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Natural flood protection: The role of Natural Infrastructure and the impact of climate change in the catchments of select cities

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Natural flood protection: The role of Natural Infrastructure and the impact of climate change in the catchments of select cities

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Thesis submitted for the degree of Doctor of Philosophy (PhD)

Department of Geography, King's College London

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Abstract

Flooding impacts a huge number of people every year and is projected to worsen as land use change and climate change progress. Restoring nature to help protect and mitigate these impacts is increasingly advocated. This thesis takes an ecosystem services approach to evaluate the flood mitigation services provided by Natural Infrastructure such as canopy, soil, wetlands, water bodies and floodplains, to select global cities now and under climate change. The study is focused on the catchments upstream of six cities: Guayaquil in Ecuador, Bogotá in Colombia, London in the UK, Nairobi in Kenya, Chennai in India and Jakarta in Indonesia. A spatially explicit hydrological modelling tool called *WaterWorld* is used to conduct the analyses. The first objective was to quantify (map and measure) the role of Natural Infrastructure in flood risk reduction under current conditions. This is achieved by calculating the water storage capacity of the Natural Infrastructure features relative to the water inputs (runoff) to generate so-called 'flood risk ratios' (FRR). The second objective was to measure how these flood risk ratios change under different scenarios of climate change as a result of projected changes in precipitation. This is achieved for three RCPs and two time periods each, for a total of six multi-GCM scenarios. The last objective examines how different forestation scenarios impact the FRR in two of the case study basins: Guayaquil and Bogotá. Different levels of forestation and geographic targeting of forestation (focusing on low-value land) are compared for their effect on the FRR. Finally, these changes are compared to the previously measured climate change FRR to determine to what extent forestation alone can mitigate climate induced flood risk.

The main findings were:

- Heavy reliance on more vulnerable green natural water storage (soils, tree canopy and wetlands) in some basins, the lack of protection for this storage, and where protected, its remoteness from downstream beneficiaries.
- The upstream basins of Nairobi, Chennai, Bogotá, and Guayaquil are projected to have increased rainfall and water balance on an annual scale compared to baseline conditions, and thus increases in FRR. In contrast, the upstream basins of London and Jakarta are projected to decrease for these same variables.
- Lowlands may have a greater role in flood risk reduction than the uplands. This is contrary to current practices of preferentially foresting uplands.

- 100% forestation (outside protected areas) will not completely offset the current flood risk ratios, i.e., there would still be more annual rainfall than the capacity to store it in parts of the landscape.
- Focusing only on reforesting areas of recent forest loss is not sufficient to achieve meaningful flood risk reduction, both currently and under climate scenarios.
- This analysis, and the methods described, can assist in establishing the amount and locations of green storage to be protected, restored, or enhanced. Equally, it points to adding additional criteria, such as natural flood protection potential, for the establishment of protected or safe-guarded land, other than species richness or habitat distinctiveness.

Most often, flood modelling and ecosystem assessments require complex data and software, technical expertise, and data rich environments for the inputs. This study has made use of a simple to use but sophisticated modelling platform that can be used in any basin globally, allowing standardised comparison between multiple basins. Taking an ecosystem approach, by measuring the contribution of Natural Infrastructure to flood regulation, is important for highlighting their importance relative to grey infrastructure, advocating for their protection, and in some cases, enhancement, as Nature-based Solutions for climate change adaptation.

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Glossary

Term	Definition
baseflow	The portion of streamflow that is sustained between precipitation events, fed to stream channels by delayed (usually subsurface) pathways (Price, 2011).
basin (hydrological)	The area drained by a river or body of water. The term is often used interchangeably with watershed or catchment.
catchment	The area drained by a river or body of water. The term is often used interchangeably with Watershed or Basin.
channel/river discharge	The volume of water flowing through a river channel. This is the total volume of water flowing through a channel at any given point and is measured in cubic metres per second (cumecs).
ecohydrology	Ecohydrology examines hydrologic mechanisms that underlie ecologic patterns and processes. The science that studies how water in all its forms links living organisms and their abiotic environment to define their function, interactions, structure, and distribution
evaporation	The loss of water from a wet surface through its conversion into its gaseous state, water vapour, and its transfer away from the surface into the atmosphere (Ward and Robinson, 2011).
evapotranspiration	Wet canopy evaporation measured as the difference between the gross rainfall (Pg) incident upon a vegetation canopy and the fraction of Pg that reaches the ground as net rainfall (Pn).
flood peak	The highest stage (largest discharge) reached during a particular flood at a given point on a river. Also known as peak discharge.
flood risk ratio	The ratio of water capacity to total storage determined in *WaterWorld* to indicate the ability of the landscape to store water.
Green Infrastructure (GI)	Vegetated Natural Infrastructure (NI)
hydraulic roughness	The measure of the amount of frictional resistance water experiences when passing over land and channel features.
hydrological regulation or (streamflow buffering)	The ability of a terrestrial ecosystem to provide a seasonal buffer of streamflow, i.e., to store water during the wet seasons and to sustain streamflow during the dry seasons.
hydroperiod	The number of days per year that an area of land is wet or the length of time that there is standing water at a location.
infiltration rate	The maximum rate at which water soaks into or is absorbed by the soil.
interception	The proportion of precipitation intercepted by the leaves and stems of the vegetation canopy and temporarily stored on its surfaces; and is evaporated back into the atmosphere before reaching the ground.
low flow	Flow of water in a stream during prolonged dry weather. Low flow are derived from groundwater discharge or surface discharge from lakes, marshes, or melting glaciers.
natural flood management (NFM)	Natural Flood Management harnesses natural hydrological processes to slow water flowing through the landscape, thereby mimicking natural environmental conditions, aspects often lost within traditional flood risk management (FRM) paradigms of moving water rapidly through the system.
Natural Infrastructure	NI is everything natural in the landscape.
occult precipitation	Refers to precipitation arriving at a location by processes that would normally go unrecorded by a standard rain gauge, in the form of fog and drizzle.

Term	Definition
peak flow	Maximum instantaneous discharge of a given stream, during the period of runoff caused by a storm, shown by the discharge hydrograph. The point of the hydrograph that has the highest flow. Measured in cubic metres of water per second (m3/s).
pixel (or grid cell)	A raster consists of a series of pixels, each with the same dimensions and shape. In the case of rasters derived from airborne sensors, each pixel represents an area of space on the Earth's surface. The size of the area on the surface that each pixel covers is known as the spatial resolution of the image.
precipitation	Precipitation is any form of moisture which falls to the earth. This includes rain, snow, hail and sleet. Precipitation occurs when water vapour cools.
runoff	see 'surface runoff'
streamflow	The amount of water flowing in a river.
streamflow buffering (or hydrological regulation)	The ability of a terrestrial ecosystem to provide a seasonal buffer of streamflow, i.e., to store water during the wet seasons and to sustain streamflow during the dry seasons.
surface roughness	The height changes in reference to the general shape of a surface. For soils, surface roughness is the shape of a surface when the topographic slope has been removed.
surface runoff (overland flow)	Part of the precipitation which flows towards a river on the ground surface. Two types: 1. when the intensity of precipitation that reaches the surface exceeds the infiltration capacity of the soil and depression storage capacity causing water to flow horizontally across land surfaces. This process is known as Hortonian overland flow. 2. when the combination of precipitation intensity and duration (and run-on from higher areas) saturates the soil and raises the water table to the surface. This process is known as saturation overland flow.
transpiration	Water taken up by plant roots from the soil which moves up the plant and then into the atmosphere principally through the leaves.
water holding capacity (WHC)	The ability of a certain soil texture to physically hold water against the force of gravity.
water yield	This is the water that remains for runoff and soil/groundwater storage after subtraction of evapotranspiration. Quantity of water which can be collected for a specified use from surface or groundwater sources in a basin during a given time interval. Water availability, either for consumptive use (e.g. drinking or irrigation) or in situ water supply (e.g. water for hydropower or fisheries).
watershed	Natural or artificial drainages on which all precipitation and emanating spring discharges collect and flow to a common outlet. See also 'basin' and 'catchment'.

Abbreviations

AOI	Area of Interest
AR4	Assessment Report Four (of the IPCC)
AR5	Assessment Report Five (of the IPCC)
AR6	Assessment Report Six (of the IPCC)
CBD	Convention on Biological Diversity
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
DEM	Digital Elevation Model
EbA	Ecosystem-based Adaptation
ES	Ecosystem Services
FLR	Forest and Landscape Restoration
FRR	Flood Risk Ratio (water capacity to total storage; the NI metric from *WaterWorld*)
GCM	General Circulation Model
GEF	Global Environment Facility
GI	Green Infrastructure
GIS	Geographic Information System
ha	hectares
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature and Natural Resources
KBA	Key Biodiversity Area
km	kilometres
NbS	Nature-based Solutions
NCP	Nature's Contribution to People
NERC	Natural Environment Research Council
NFM	Natural Flood Management
NI	Natural Infrastructure
PA	Protected Area
pcd	percent change difference
RCP	Representative Concentration Pathway
SD	Standard deviation
UNFCCC	United Nations Framework Convention on Climate Change
WRI	World Resources Institute
ZOI	Zone of Interest

Chapter 1

Research introduction and thesis overview

This chapter begins by introducing the research problem and outlining the research aim, objectives, and associated research questions. It then introduces some of the key themes and concepts relevant to the thesis, such as floods and flood risk, the 'ecosystem approach' to flood risk management, and the policy context in which these ideas sit. It describes the research importance of the topic and the contribution that this thesis provides to advancing knowledge on that topic. Finally, the chapter concludes with an overview of the thesis structure with descriptions of each chapter.

1.1 Introduction to the research problem

Floods are the most hazardous and prevalent of all natural disasters, accounting for the highest number of disaster events globally (44%) and the greatest number of people affected (1.6 billion worldwide; CRED-UNDRR, 2020). The economic cost of flood damages in the period 2000 to 2019 is estimated at $651 billion (USD) (CRED-UNDRR, 2020). The frequency and severity of floods has doubled in the last two decades (CRED-UNDRR, 2020), mostly driven by climate and land use changes, and are expected to increase further due to changes in extreme weather (IPCC, 2021). In addition, the fraction of the global population exposed to floods is growing because populations and economic activity have increased rapidly in hazard-prone areas (Ceola et al., 2014, Tellman et al., 2021) and are projected to increase further (Jongman et al., 2012; Tellman et al., 2021; Winsemius et al., 2015).

Traditional responses to prevent and mitigate the impacts of flood events have relied on hard engineering defences such as dams, levees, and seawalls. These are usually referred to as 'grey' approaches. However, there has been an increasing realisation that such approaches on their own are not sufficient to meet increasing risks, nor are they sustainable. Rather, these grey approaches need to be combined with 'green' approaches that restore, mimic or utilise nature and/or its processes. These nature-positive and ecosystem-based approaches are gaining in popularity and have many associated terms depending on the context, such as nature-based solutions, ecosystem-based adaptation, or natural flood management. I use the term '*Natural Infrastructure*', or NI, to refer to the natural parts of the environment (further discussion on definitions is in Section 1.4). The NI components considered here are canopy cover, soil, wetlands, water bodies, and floodplains. Cities are the downstream beneficiaries

of this NI protection and where the impacts of increasing flood risk are most keenly experienced. I thus focus my investigations on the river basins[1] upstream of selected cities, (the study basins and cities are discussed in Chapter 2, section 2.7) as this is where the relevant NI is located or needed, in order to supply flood regulation benefits downstream.

But how much NI is there? Where is it? How vulnerable is it, and how will it be impacted by climate change? Can we add to or increase the NI to improve the protective capabilities now and in a future shaped by climate change? These are the questions that this thesis attempts to address (discussed further in Section 1.2).

1.2 Research aim, objectives, and questions

Research aim

The overall aim of the research presented in this thesis is ***to examine the potential of current natural infrastructure (NI) to mitigate flood risk now and under scenarios for climate change and NI restoration***. I do this for six hydrological basins of different sizes and landscape characteristics, dispersed across the globe and focused upstream of medium to large cities.

To address the aim of this thesis, I have set the following three principal research objectives and associated research questions:

Objective 1: Quantify the role of upstream rural natural flood storage in providing flood risk mitigation (ecosystem) services to the study cities under current conditions.

Q1a: What is the magnitude of the water storage capacity of the NI in the upstream basins?

Q1b: Where are these natural storages, and what form do they take?

Q1c: How much of this NI storage is found in protected areas?

Q1d: How much of this NI storage is upstream of, or near to, urban areas?

Q1c: Which areas have potential annual flood risk, and what is their distribution?

[1] The terms ‘basin’, ‘catchment’ and ‘watershed’ are used interchangeably throughout the thesis.

Objective 2: Model the change in flood mitigation service provision to the study cities under different scenarios of climate change. Specifically, examine different climate change scenarios to see how they may vary the water that needs to be stored by an upstream city catchment, and therefore change flood risk.

Q2a: By how much does flood risk change under the various climate scenarios at an annual and seasonal scale?

Q2b: Are there any geographic patterns to the increases in flood risk in the study basins?

Q2c: Which climate scenarios have the greatest impact on flood risk?

Objective 3: Determine the impact of investing in additional natural infrastructure (NI). Specifically, evaluate the amount and spatial targeting of additional tree canopy cover (via forestation) needed to mitigate current and future flood risk.

Q3a: How much additional NI, in the form of tree canopy cover, is needed to reduce current levels of flood risk?

Q3b: Is there a scenario that reduces any enhanced flood risk that results from the higher precipitation projected under climate scenarios, i.e., future flood risk?

Q3c: How does spatial targeting of forestation influence current and future flood risk?

Q3d: Is there an ideal and/or realistic forestation target to recommend to NbS investors led by spatial hydrological considerations?

1.3 Floods and flood risk

As mentioned above, floods are extremely hazardous, frequent, costly, and are becoming more common and affecting more people than ever before. This makes flooding one of the key societal challenges of this century.

Below, I describe the types of flood events, drivers of flooding focusing on river flooding, and the impacts of climate change on flood risk and in watersheds.

1.3.1 Types of floods, causes and generation

Flooding is the overflow of water onto land that is usually dry. Floods are typically caused by excessive rain, snowmelt or storm surge. Table 1.1 summarises the different types of floods and their causes. On a global scale, Douben et al. (2006) showed that for the period 1985-2003 floods were mainly caused by heavy and/or long-lasting rain followed by brief torrential rain, tropical cyclones, and monsoon rains. However, the meteorological aspect is only one part of how floods are formed. There are many physical processes that interact to generate floods. These include hydrological pre-conditions (e.g., soil saturation and snow cover), meteorological conditions (e.g., the amount, intensity, and spatial distribution of

precipitation), runoff generation processes (e.g., the infiltration and lateral runoff on hillslopes), as well as river routing (e.g., superposition of flood waves; Nied et al., 2014).

Table 1.1 Types of floods, their definition, and causes.

Type	Definition	Cause
Riverine (alluvial)	When the water level in a river, lake or stream rises and overflows onto the neighbouring land.	Excessive rain. Snow and ice melt. Combined rain and melt. Ice jams. Landslides. Failure of dams and control works.
Pluvial	When rainwater builds up beyond the absorptive capacity of soil. Occurs when an extreme rainfall event creates a flood independent of an overflowing water body. Two types: surface water and flash floods. Surface water: urban drainage system is overwhelmed, and water flows out into streets and nearby structures. Occurs gradually. Flash flood: an intense, high velocity torrent of water triggered by torrential rain falling within a short amount of time within the vicinity of, or on nearby elevated terrain.	Excessive rain
Coastal and estuarine	The inundation of land areas along the coast by seawater.	Intense windstorm events occurring at the same time as high tide (storm surge), and tsunamis.
Groundwater	Occurs when water levels underneath the ground rise above normal levels approaching the surface.	Prolonged periods of rainfall.

This thesis is primarily concerned with river (alluvial) and overland surface water (pluvial) flooding and flood risk.

Key terms associated with disaster events such as floods are; ‘risk’, ‘hazard’, ‘exposure’, ‘vulnerability’, ‘prevention’, ‘mitigation’, and ‘adaptation’. I define them below in Table 1.2 in

relation to flooding using the definitions from the IPCC report on '*Impacts, Adaptation and Vulnerability*' (IPCC, 2022). Flood risk is a combination of the probability of an event happening and the consequences (impact) if it occurred.

Table 1.2 Key disaster-related terms and their definitions as defined in IPCC (2022).

Term	Definition
Risk	The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems.
Hazard	The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.
Exposure	The presence of people; livelihoods; species or ecosystems; environmental functions, services and resources; infrastructure; or economic, social or cultural assets in places and settings that could be adversely affected.
Vulnerability	The propensity or predisposition to be adversely affected. Encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm, and lack of capacity to cope and adapt.
Prevention	Stopping or hindering the flood event from occurring.
Mitigation	The action of reducing the severity or seriousness of the flood event.
Adaptation	Anticipating the adverse effects and taking appropriate action to prevent or minimise the damage they can cause; or taking advantage of opportunities that may arise.

1.3.2 Flood hazard/risk maps and mapping

Flood hazard maps identify areas affected by floods of different probabilities. They provide valuable information about the predicted effects of water depth, velocity and debris. In the UK, flood hazard maps usually show: the likely extent of flooding, depth of flooding, the direction and speed of flow, the probability of the floods occurring (Environment Agency, 2019). Flood risk maps, meanwhile, present the potential impact of floods on human health and life, economic activity and infrastructure, cultural heritage and the environment (Fischer & Stanchev, 2022).

Quantifying and mapping flood risk/hazard is important for raising awareness about areas at risk of flooding and for helping communities develop strategies for reducing these risks

through structural and non-structural measures (Fischer & Stanchev, 2022). They are also used for emergency response planning, urban and development planning, installation of mitigation and for insurance purposes (Trigg et al., 2006).

Flood hazard/risk mapping is traditionally undertaken at catchment and national scales but much of the world is still 'unmapped' for fluvial flood risk regions (Trigg et al., 2016). Where mapping exists, it often uses different and inconsistent methodologies or datasets across countries and regions (Trigg et al., 2016). Developing accurate hazards maps, and flood forecasting, often uses computational river or hydrological models and requires vast amounts of input data ranging from spatial data (e.g., land-use, digital terrain models and cross sections of rivers), meteorological and hydrological data, as well information on the existing hydrotechnical infrastructure and their operational rules. This information feeds into hydrological and hydrodynamic models to simulate how flooding spreads across the landscape (Fischer & Stanchev, 2022). Modelling is carried out for synthetic flood events with low, medium, and high probability.

Flood risk maps can be made by overlaying maps of flood extents with the locations of where assets and people are at risk, i.e., information on the elements exposed to (HR Wallingford, n.d.). This includes information about the population and their housing, social infrastructure such as schools and hospitals, transport infrastructure, industrial sites, agricultural land, protected areas and other types of assets and natural elements (Fischer & Stanchev, 2022). The flood risk maps use a qualitative approach to identify areas of low, medium or high risk (Fischer & Stanchev, 2022).

For example of the process, in the UK, the Environment Agency's national surface water flood risk maps use modelling techniques that map depressions in the ground surface and simulates some flow along natural drainage channels, rivers, low areas in floodplains, and flow paths between buildings (Environment Agency, 2019). To do this requires: hydrological (rainfall) modelling, depth-duration-frequency (DDF) curves; adjustments to calculate effective rainfall; the use of a digital terrain model (DTM) to provide a continuous model of "bare earth" topography at a horizontal grid resolution of 2m; and use of local information from local authorities to incorporate local recorded flood data and local knowledge to identify areas that are known to flood, and to highlight unexpected patterns of flooding (Environment Agency, 2019).

River flood models usually consist of: (i) a method to estimate river flow magnitude for a given probability; and (ii) a model to simulate water flow in river channels and over floodplains (Trigg et al., 2006). Programmes for national level flood modelling often use specially commissioned data collection, for example airborne laser terrain data at high resolution (1–2 m horizontal), detailed surveys of river bathymetry and long-term river flow data (Trigg et al., 2006).

1.3.3 Drivers of increased flood risk

Simplistically, the main drivers of increased flood risk are climate change and land cover change. However, there are many underlying processes that are involved. River floods are influenced by different controlling processes and associated variables, which can be grouped as follows:

1) Atmosphere - atmospheric forcing of catchment water fluxes.

2) Catchment - runoff generation and concentration.

3) Rivers - flood wave propagation, superposition of flood waves (Blöschl et al., 2015).

The processes in all three groups affect the characteristics of river floods and therefore any changes in these processes will also lead to changes in the floods themselves (Blöschl et al., 2015). The processes, variables, and drivers of change are summarised in Table 1.3.

Table 1.3 Summary of the processes, associated variables, and potential drivers of change for river floods (reproduced with permission from the author, Blöschl et al. 2015). Highlighted variables are those inputted or outputted in the WaterWorld model (discussed in detail in Chpt.2). Yellow highlight is for WaterWorld version 2. Blue highlight is for WaterWorld version 3 (not used for this research).

	Processes	Variables	Drivers of change
Atmosphere	Atmospheric forcing of catchment water fluxes.	Temperature, total precipitation, precipitation intensity/duration, snow cover and snowmelt, short- and long-wave radiation climate variables.	Natural climate variability at different time scales, anthropogenic climate change.
Catchments	Runoff generation and concentration.	Infiltration capacity, runoff coefficient, water storage capacity, evapotranspiration.	Urbanisation, transport infrastructure, deforestation, ditch construction, wildfires, agricultural management practices, drainage of wetlands and agricultural areas, construction of flood retention basins.
Rivers	Flood wave propagation, superposition of flood waves.	River morphology, conveyance, roughness, water level, runoff, floodplain storage, river channel vegetation.	In-stream channel engineering, reduction in river length, construction of dikes, groynes and weirs, operation of hydropower plants and reservoirs.

Climate change

Changes in climate fall under the 'atmosphere' category above (Table 1.3). Modelling studies indicate a clear positive correlation between atmospheric warming and increased frequency, intensity, and/or duration of extreme weather events including future flood risk at a global scale (Alfieri et al., 2015) as a result of intensification of the hydrological cycle leading to changes in precipitation. Projected increases in heavy precipitation will most likely substantially alter river flow regimes, resulting in extreme flows, and contribute to rain-generated local flooding in some catchments or regions (Eccles et al., 2019; Hirabayashi et al., 2013, 2021; Milly et al., 2002; Seneviratne et al., 2012). There is substantial variability in the estimated impact between climate scenarios (Arnell & Gosling, 2013) but there is agreement that there will be shifts in the timing of river flow regimes, especially where snowmelt is a hydrological driver (Adam et al., 2009; Arnell & Gosling, 2013). River discharges will increase by 6–61% in the coming century (Aerts et al., 2006).

Although the primary focus of this thesis is flood regulation from precipitation increases, it must be noted that climate change is also projected to result in *decreases* in precipitation and associated river flow in some parts of the world (Eccles et al., 2019; IPCC, 2021)

The latest IPCC report (2022) states that, “It is very likely that heavy precipitation events will intensify and become more frequent in most regions with additional global warming. At the global scale, extreme daily precipitation events are projected to intensify by about 7% for each 1°C of global warming (high confidence). The proportion of intense tropical cyclones (Category 4–5) and peak wind speeds of the most intense tropical cyclones are projected to increase at the global scale with increasing global warming (high confidence).”

Figure 1.1 shows three figures from the AR6 IPCC reports. The first (a) is a synthesis of observed change, since the 1950s, in heavy precipitation in the world’s regions. This shows heavy precipitation increasing in most of Northern Europe, East Asia, South Asia, Northern Australia, West Southern Africa, East Southern Africa, South-Eastern South America, Central North America, Eastern North America (IPCC, 2021). The second figure (b) is the change in annual mean precipitation compared to 1850-1900 based on simulated projections of global warming by 1.5°C, 2°C and 4°C. Precipitation is projected to increase over high latitudes, the equatorial Pacific, and parts of the monsoon regions, but decrease over parts of the subtropics and in limited areas of the tropics (IPCC, 2021). The third figure (c) shows projected changes in river flooding for the years 2071-200 relative to 1970-2000 (IPCC, 2022). There is high model agreement (high confidence) for increased flood frequency and magnitude in Asia, central Africa, western Europe, Central and South America and eastern North America, and decrease in northern North America, southern South America, the Mediterranean and eastern Europe in 2050 and beyond (IPCC, 2022).

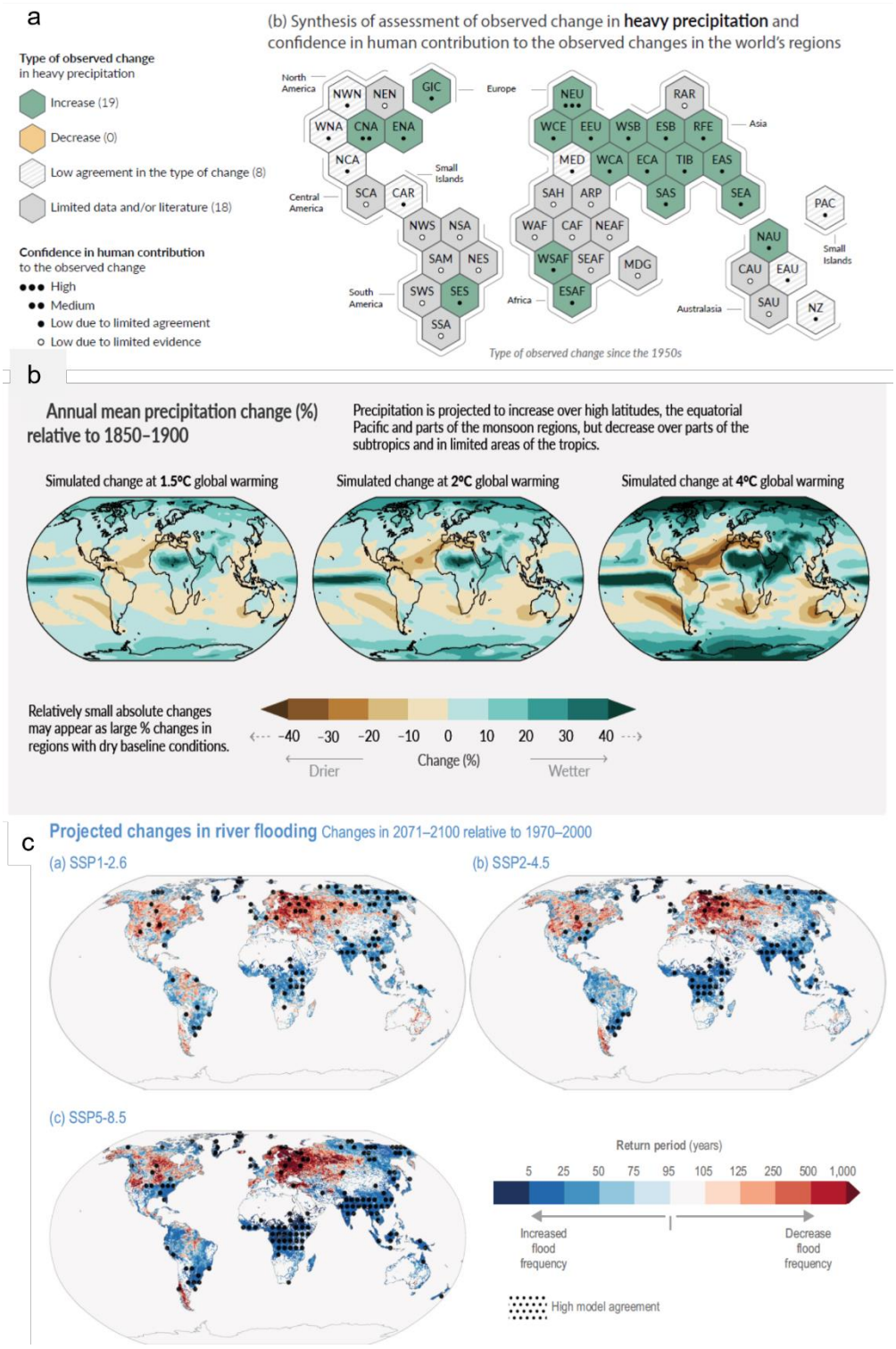


Figure 1.1 Figures from the AR6 IPCC reports showing a) synthesis of observed change in heavy precipitation (Fig. SPM3, p10 of IPCC, 2021). b) Simulated precipitation change (%) at global warming levels of 1.5°C, 2°C and 4°C (20-year mean global surface temperature change relative to 1850–1900). Simulated changes correspond to CMIP6 multi-model mean change at the corresponding global warming level (Fig. SPM5, p16 of IPCC, 2021). c) Multi-model median return period (years) in the 2080s for the 20th century 100-year river flood, based on a global river and inundation model, driven by runoff output of nine CMIP6 Models for three scenarios (Fig 4.17, p606 of IPCC, 2022).

Land cover change

Change in land use and land cover is an important driver of flood risk. Land cover change due to urbanisation, deforestation, and cultivation results in increased flood frequency and severity (Tollan, 2002). This is because land use affects two important components of runoff generation: soil moisture and infiltration. Soil moisture determines the amount of precipitation that cannot infiltrate and therefore runs off from the land surface and contributes to flooding. Runoff contribution may vary greatly between events, depending on the soil moisture at the beginning of that event. Soil moisture is controlled by evaporation and the infiltration characteristics of the soil. Increases in evaporation will reduce soil moisture, and the more permeable a soil, allowing greater infiltration, the less water will accumulate near the surface (Blöschl et al., 2015). Certain activities reduce infiltration, such as surface sealing from urban development and compaction by heavy machinery or livestock associated with certain agricultural practices. Change in land use to forest (afforestation) may increase infiltration because coarse woody roots of trees create preferential flow paths in the soil which enhance the fast flow of water from the surface into the subsurface, thus recharging the aquifers (Blöschl et al., 2015). Afforestation also increases evaporation and thus reduces soil moisture. There is therefore a complex interplay in the soil–plant–atmosphere continuum of the processes controlling flood generation (Blöschl et al., 2015).

Researchers have found that land use change effects on floods are most pronounced at small scale and for frequent flood magnitudes (Tollan, 2002) but that evidence for watershed-scale impacts from land management practices is limited (O'Connell et al., 2007). However, studying land use effects in large watersheds is challenging because factors such as soils, geomorphology, land cover and the timing of rainfall runoff across a basin will affect the downstream flood response (Schilling et al., 2014). Other researchers have found that the total area of change in land cover, as well as land management practices, are more important in generating floods than the type of land cover change, such as deforestation (Solín et al., 2011).

1.4 The 'Ecosystem Approach' to flood risk management

The ecosystem approach is a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way (CBD, 2004). It ties in with a shift in the framing and purpose of conservation which has occurred over the past 50 years, moving from an emphasis on species to ecosystems, and from a 'nature for itself' view to 'nature for people' and more recently, to a 'people and nature'

perspective (Mace, 2014). Examples of some of these 'ecosystem approaches' relevant to flood regulation are described below.

Natural Flood Management

The seriousness of the flood problem and its exacerbation due to climate and land use change has led practitioners to question whether traditional grey infrastructure is adequate to deal with current conditions or those expected in the future. There has been growing traction for 'softer', holistic, and more 'joined-up' approaches, not to replace the traditional hard measures, but to work alongside them, complement them, and extend their life (Environment Agency, 2010, 2018). These approaches are called many things depending on the country of origin and governance level. Examples include: 'Making Space for Water' (MSW); 'Room for the River' (RFR); 'Working with Natural Processes (WWNP)' (Environment Agency, 2010); 'Natural Flood Management' (NFM); 'Natural Water Retention Measures' (NWRM); 'Natural and Nature-based Features' (NNBF); 'Nature-based Solutions' (NbS); 'Engineering with Nature' (EWN); and 'Building with Nature' (BWN).

In this thesis, I will use the term Natural Flood Management (NFM) as a lower-level concept and Nature-based Solutions (NbS) as a higher-level concept where flood risk reduction is a frequently cited element or outcome.

These 'ecosystem-based' or 'nature-based' approaches to flood regulation, such as NFM, are guided by similar principles, such as restoring, utilising or mimicking nature's natural processes to slow and store excess water, with the purpose of reducing flooding, whilst achieving multiple benefits throughout the catchment. Specifically, the aim is to increase water storage, reduce the flood peak or increase the time to peak parameter by altering multiple elements of a catchment water balance by:

- promoting interception, infiltration, and groundwater storage
- enhancing water losses through evapotranspiration
- lengthening hydrological pathways
- increasing flow resistance

Actions commonly advocated as part of NFM are: protecting or enhancing soil condition; the (re)establishment of forests and woodlands; drainage and drain blocking; wetland creation; river and floodplain restoration; the creation of intertidal habitats; on-farm reservoirs/ponds;

restoring smaller watercourses to a more natural alignment; and combined measures (Environment Agency, 2010, 2018; Iacob et al., 2014; SEPA, 2013). These interventions provide, sustain, or enhance many additional benefits (known as co-benefits) such as: greater biodiversity; improved soil and water quality; carbon sequestration; reduced soil erosion; greater agricultural productivity; and improved public health and well-being (Dadson et al., 2017).

Many researchers and institutions are evaluating the effectiveness of NFM. Dadson et al., (2017) in a review of the natural science evidence concluded that, "There is clear evidence that appropriately chosen land-use and land-cover interventions can reduce local peak water flows after moderate rainfall events. The evidence does not suggest these interventions will have a major effect on nearby downstream flood risk for the most extreme events." Lane (2017) in an overview outlines potential shortcomings of the NFM approach, especially regarding the spatial scales required for an impact. Lane (2017) concludes that, "NFM may be best advocated in two situations: (1) where it can improve the effectiveness of more traditional engineering approaches to flood risk reduction; and (2) when flood management is not simply equated with flood risk reduction, and its wider benefits are identified." Despite these evaluations, Wingfield et al. (2019) assert that they remain insufficient for drawing conclusions on the effectiveness of NFM at catchment scales.

Examples of recent projects on NFM include the UK Research and Innovation (UKRI) NERC funded program "Understanding the effectiveness of natural flood management"[2] for the period 2017 to 2022, and the EU funded project, Land4FLOOD[3], which is a European research network that has been focusing on the relationship between people, land and floods, in order to better prepare for future flooding events.

I describe further aspects of NFM in Chapter 3.

Nature-based Solutions

An increasingly popular concept is that of Nature-based Solutions (NbS). There are a multitude of definitions for NbS. For illustrative purposes, I include the European Commission's definition and that of the IUCN here. The European Commission defines NbS as "*living solutions inspired by, continuously supported by and using nature, which are*

[2] https://www.ukri.org/what-we-offer/browse-our-areas-of-investment-and-support/understanding-the-effectiveness-of-natural-flood-management/
[3] https://www.land4flood.eu/

designed to address various societal challenges in a resource efficient and adaptable manner and to provide simultaneously economic, social, and environmental benefits"[4]. The IUCN defines NbS as "*actions to protect, sustainably manage and restore natural and modified ecosystems in ways that address societal challenges effectively and adaptively, to provide both human well-being and biodiversity benefits*" (Cohen-Shacham et al., 2016).

The NbS concept is related to many other established 'ecosystem-based' or 'nature-based' approaches, such as ecosystem-based adaptation (EbA), ecosystem-based disaster risk reduction, natural infrastructure, green and blue infrastructure, forest and landscape restoration, and natural climate solutions (Chausson et al., 2020; Cohen-Shacham et al., 2016; Potschin et al., 2016). It shares a common focus on multi-functional benefits such as ecosystem services and aims to address societal challenges (Cohen-Shacham et al., 2016; Stafford et al., 2021). Potschin et al. (2016) and Cohen-Sacham et al. (2016) advise using NbS as an umbrella concept under which all these approaches reside. See Figure 1.2 for an illustration of NbS as an umbrella concept. Cohen-Sacham et al. (2016) in their IUCN report, propose that NbS approaches can be classified into:

I. Ecosystem restoration approaches (e.g., ecological restoration, ecological engineering and forest landscape restoration).

II. Issue specific ecosystem-related approaches (e.g., ecosystem-based adaptation, ecosystem-based mitigation, and ecosystem-based disaster risk reduction).

III. Infrastructure-related approaches (e.g., natural infrastructure and green infrastructure approaches).

IV. Ecosystem based management approaches (e.g., integrated coastal zone management and integrated water resources management).

V. Ecosystem protection approaches (e.g., area-based conservation approaches including protected area management).

[4] https://ec.europa.eu/info/research-and-innovation/research-area/environment/nature-based-solutions_en



Figure 1.2 Depiction of Nature-based Solutions as an umbrella term for ecosystem-based approaches (from Cohen-Sacham et al., 2016).

By definition, NbS needs to have a problem that it is addressing. However, the latest IUCN Global Standard for NbS points out that the problem cannot be biodiversity loss only, as that is conservation (IUCN, 2020b). To be a NbS, the problem addressed needs to be something else, in addition to having biodiversity benefits (IUCN, 2020). The NbS approach and tools are popular with researchers and practitioners as they are seen to be able to address the dual global crises on biodiversity loss and climate change. Some research has shown that NbS could provide around 30% of the cost-effective mitigation needed by 2030 to stabilise warming to below 2°C (Griscom et al., 2017), leading the authors to coin the phrase 'natural climate solutions'. NbS can also provide protection against the impacts and long-term hazards of climate change, i.e., nature-based adaptation to climate change.

For this thesis, I am interested in how NbS can be used to solve, or alleviate, the problem of increased flood risk, either current and/or future climate induced. Following Short et al. (2019), NbS will refer to the top-level approach and NFM to the actual interventions.

Ecosystems as infrastructure: Green Infrastructure and Natural Infrastructure

Infrastructure is usually defined as all elements of interrelated systems that provide goods and services essential to enabling, sustaining or enhancing societal living conditions. Typically, it has referred to only human-made assets, and human capital, but scientists and conservationists have suggested that ecosystems should also be considered as a type of infrastructure (da Silva & Wheeler, 2017). In a history of the concept, Da Silva and Wheeler (2017) report that 'ecological infrastructure' was the first term to refer to ecosystems as infrastructure in 1984. The term 'green infrastructure' was first introduced in 2004 and has been widely adopted. 'Natural infrastructure' and 'blue infrastructure' are more recently coined terms.

Green infrastructure (GI) and Natural Infrastructure (NI) are elements or components of NbS and NFM. These terms are often used interchangeably and are beset with a wealth of different definitions. The two approaches share many of the same principles and objectives, including connectivity, multifunctionality, and smart conservation (Cohen-Shacham et al., 2016; EEA, 2011). A commonly used definition of GI is: "... *a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services. It incorporates green spaces (or blue if aquatic ecosystems are concerned) and other physical features in terrestrial (including coastal) and marine areas. On land, GI is present in rural and urban settings"* (European Commission, 2013). 'Natural' GI refers to green infrastructure that is not constructed or modified by humans. Examples of GI include green roofs, permeable vegetated surfaces, green alleys and streets, urban forests, public parks, community gardens, and urban wetlands.

A simple definition of NI is "*natural habitat or constructed natural spaces that supply crucial benefits to urban residents*" (McDonald, 2015). Although I propose that the residents need not be urban, and that 'urban residents' could be changed to 'people'. Another useful definition is that NI refers to "*the conditions of the landscape that provide functions to mediate and regulate shocks and disturbances that threaten human well-being*" (Tellman et al., 2018). The difference between NI and GI perhaps lies in the scale and settings applied. Some researchers state that a GI approach is used at both an urban and a landscape scale, but focused 'within, around and between urban areas' (Tzoulas et al., 2007) or should be entirely restricted to urban areas (Mathews et al. 2015). In contrast, an NI approach is primarily used at a landscape scale (Cohen-Shacham et al., 2016).

For the purpose of this thesis, I will take a much simpler view: NI is everything natural (as it includes water bodies) and GI is all vegetation-related NI.

Ecosystem services

A separate but related concept that runs through those described above is that of '*ecosystem services*'. Ecosystem services (ES) are the goods and services provided by ecosystems for the benefit of people. Although first conceptualised in the mid-1960s and early 1970s (de Groot et al., 2002), 'ecosystem services' gained widespread recognition in 1997, firstly from a book edited by Gretchen Daily on *Nature's Services* (G. C. (editor) Daily, 1997), and secondly from a *Nature* paper that estimated the current economic value of 17 ecosystem services for 16 biomes (Costanza et al., 1997). The term became prominent following the Millennium Ecosystem Assessment report (MA, 2005) and has continued to dominate both policy and research endeavours. The growth and relevance of the ES concept over twenty years is described in a paper published by some of the original authors of that first paper in 1997 called "Twenty years of ecosystem services: How far have we come and how far do we still need to go?" (Costanza et al., 2017).

Recently, a new term, 'Nature's Contribution to People' (NCP), was introduced as a supra-concept to ES. NCP is defined as "*all the positive contributions, losses or detriments, that people obtain from nature' to capture both beneficial and harmful effects of nature on people's quality of life*" (Díaz et al., 2015; Pascual et al., 2017). NCP does not differ greatly from ES, despite some reframing and novel conceptualisations (Kadykalo et al., 2019), so will not be discussed further.

Types and categories of ecosystem services

The habitat, biological or system properties or processes of ecosystems are referred to as ecosystem functions. Ecosystem goods (such as food) and services (such as waste assimilation) represent the benefits (or occasionally disbenefits) human populations derive, directly, or indirectly from ecosystem functions. Ecosystem goods and services together are called ecosystem services (Costanza et al., 1997).

The classification of ES is continually being reworked and adapted but are consistently grouped into four primary categories: provisioning, regulating, supporting and habitat, and cultural services. Table 1.4 provides a comparison between four of the main ES classification systems with their differences and similarities (from Costanza et al., 2017). In

some cases, a single ES is the product of two or more ecosystem functions, whereas in other cases a single ecosystem function contributes to two or more ES. Many are interdependent.

Table 1.4 Comparison of four main ecosystem services classification systems (reproduced from Table 2 of Costanza et al., 2017). Highlighted services are the ones of interest in this thesis.

Category	Costanza et al. 1997	Millennium Ecosystem Assessment 2005	TEEB 2010	CICES (v.4.3)
Provisioning services	Food production	Food	Food	Biomass -nutrition
	Water supply	Fresh water	Water	Water
	Raw materials	Fibre etc Ornamental resources	Raw materials Ornamental resources	Biomass -fibre, energy & other materials
	Genetic resources	Genetic resources Biochemicals and natural medicines	Genetic resources Medicinal resources	Biomass - Mechanical energy
Regulating & Habitat services	Gas regulation	Air quality regulation	Air purification	Mediation of gas- & air-flows
	Climate regulation	Climate regulation	Climate regulation	Atmospheric composition & climate regulation
	Disturbance regulation (storm protection & flood control)	Natural hazard regulation	Disturbance prevention or moderation	Mediation of air & liquid flows
	Water regulation (e.g. natural irrigation & drought prevention)	Water regulation	Regulation of water flows	Mediation of liquid flows
	Waste treatment	Water purification and waste treatment Erosion regulation	Waste treatment (esp. water purification) Erosion prevention	Mediation of waste, toxics, and other nuisances Mediation of mass-flows
	Erosion control & sediment retention Soil formation	Soil formation [supporting service]	Maintaining soil fertility	Maintenance of soil formation and composition
	Pollination	Pollination	Pollination	Life cycle maintenance (incl. pollination)
	Biological control	Regulation of pests & human diseases	Biological control	Maintenance of pest- and disease-control
Supporting & Habitat services	Nutrient cycling	Nutrient cycling & photosynthesis, primary production 'Biodiversity'		
	Refugia (nursery, migration habitat)		Lifecycle maintenance (esp. nursery)	Life cycle maintenance, habitat, and gene pool protection
Cultural	Recreation (incl. eco-tourism & outdoor activities)	Recreation & eco-tourism	Recreation & eco-tourism	Physical and experiential interactions
	Cultural (incl. aesthetic, artistic, spiritual, education, & science)	Aesthetic values	Aesthetic information	
		Cultural diversity	Inspiration for culture, art, & design Spiritual experience	
		Spiritual & religious values		Spiritual and/or emblematic interactions
		Knowledge systems	Information for cognitive development	Intellectual and representative interactions
		Educational values		

It is important to highlight that the services are an output of the ecosystem functions, which rely on, or are a result of, ecological complexity, ecosystem structure and process. This is summarised by De Groot et al. (2002) in this typology to be used in assessment: ecosystem structure and process -> ecosystem function -> ecosystem goods and services -> values (socio-cultural, economic, ecological). For example, the ecosystem function which regulates hydrological flows results in the service of water regulation, which humans value for storm protection, flood control, and drought recovery.

Why is the ecosystem service framework useful?

There has been huge uptake and traction of the ecosystem services concept (sometimes referred to as a 'framework') by the scientific, policy and conservation communities, resulting in novel approaches for research, conservation, and development (Brauman, 2015; Carpenter et al., 2009; G. C. Daily & Matson, 2008). The ecosystem services framework provides a way to assess trade-offs among alternative scenarios of resource use and landscape change and can account for gains and losses to different beneficiaries at different spatial scales (Brauman et al., 2007).

Costanza et al. (2017) state in their review on the last twenty years of ecosystem services, that the ES concept/approach/framework has been valuable for: i) becoming an effective bridge between ecological and economic approaches and creating a more transdisciplinary ecological economics; and for ii) challenging the conventional approach to growth and development while paving the way for a different approach to prosperity based on wellbeing.

1.5 Policy context

In this section I describe some of the international policies and frameworks that form the context and underpin the work of this thesis. The first part begins with the broader sustainability focused policies. The second part focuses on policies specific to tree planting and forestation, as this is pertinent to the mitigation intervention used in Chapter 5.

1.5.1 Global sustainability policies

Sustainable Development Goals

In 2015, the United Nations General Assembly adopted the 2030 Agenda for Sustainable Development (United Nations, 2015) with 17 Sustainable Development Goals (SDGs)[5] at its

[5] https://sdgs.un.org/goals

core. These "are *an urgent call for action by all countries - developed and developing - in a global partnership. They recognize that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve our oceans and forests*."

The Sustainable Development Goals (SDGs) were adopted by the United Nations' General Assembly in 2015 as part of the 2030 Agenda for Sustainable Development (United Nations, 2015). The purpose of the SDG is to be a "*comprehensive, far-reaching and people-centred set of universal and transformative Goals and targets" to be implemented by 2030, "committed to achieving sustainable development in its three dimensions – economic, social and environmental – in a balanced and integrated manner*", building upon the achievements of the Millennium Development Goals "*and seeking to address their unfinished business*" (United Nations, 2015).

There are 17 goals with a number of associated targets. The work described in this thesis contributes to three of the SDGs and four targets (Fig 1.3):

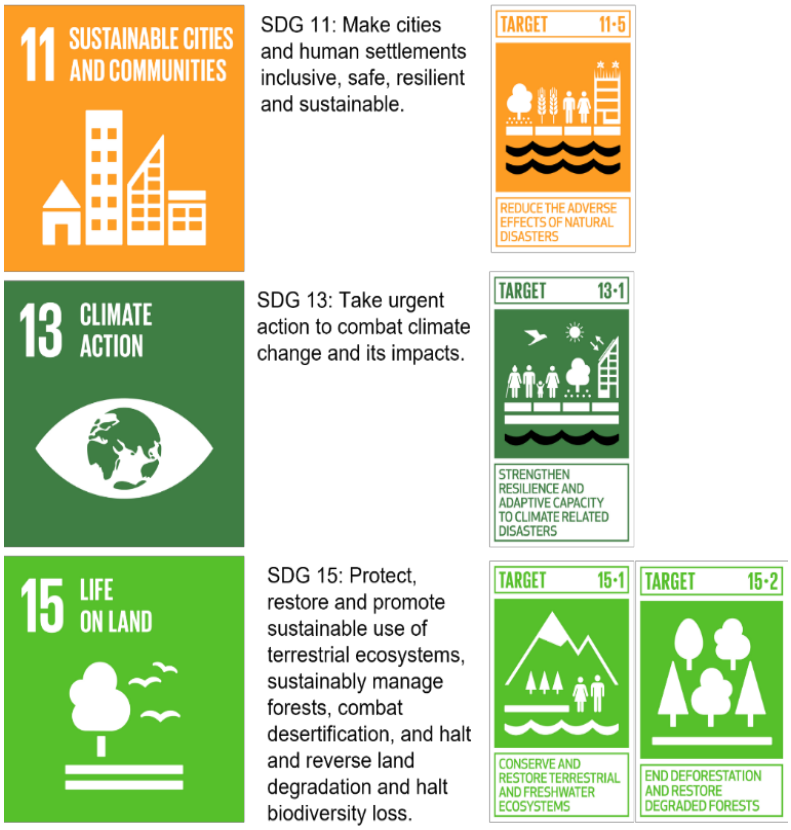


Figure 1.3 The three Sustainable Development Goals (SDGs) and associated targets that are relevant to the work carried out for this thesis.

Sendai Framework for Disaster Risk Reduction 2015–2030

The Sendai Framework for Disaster Risk Reduction 2015–2030[6] was adopted at the Third United Nations World Conference on Disaster Risk Reduction in 2015. Its purpose is to "*declare our determination to enhance our efforts to strengthen disaster risk reduction to reduce losses of lives and assets from disasters worldwide*" in light of "*the increasing impact of disasters and their complexity in many parts of the world*". The Sendai Framework has seven global targets:

1. Substantially reduce global disaster mortality by 2030, aiming to lower the average per 100,000 global mortality rate in the decade 2020–2030 compared to the period 2005–2015;
2. Substantially reduce the number of disaster-affected people globally by 2030, aiming to lower the average global figure per 100,000 in the decade 2020–2030 compared to the period 2005–2015;
3. Reduce direct disaster economic loss in relation to global gross domestic product (GDP) by 2030;
4. Substantially reduce disaster damage to critical infrastructure and disruption of basic services, among them health and educational facilities, including through developing their resilience by 2030;
5. Substantially increase the number of countries with national and local disaster risk reduction strategies by 2020;
6. Substantially enhance international cooperation to developing countries through adequate and sustainable support to complement their national actions for implementation of the present Framework by 2030;
7. Substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030.

By focusing on flood risk reduction, the research in this thesis will contribute towards targets 1-4.

[6] https://sustainabledevelopment.un.org/frameworks/sendaiframework

Convention on Biological Diversity- Global Biodiversity Framework

The post-2020 global biodiversity framework is developed by the Convention on Biological Diversity (CBD)[7] and "*... builds on the Strategic Plan for Biodiversity 2011-2020 and sets out an ambitious plan to implement broad-based action to bring about a transformation in society's relationship with biodiversity and to ensure that, by 2050, the shared vision of living in harmony with nature is fulfilled.*" It is currently in draft, due to be finalised and adopted in December 2022. The framework has 21 action-oriented targets for urgent action over the decade to 2030. Target 8 and Target 11 (outlined below) are relevant to the research in this thesis.

Post-2020 Global Biodiversity Framework Target 8: Minimise the impact of climate change on biodiversity, contribute to mitigation and adaptation through ecosystem-based approaches, contributing at least 10 GtCO2e per year to global mitigation efforts, and ensure that all mitigation and adaptation efforts avoid negative impacts on biodiversity.

Post-2020 Global Biodiversity Framework Target 11. Maintain and enhance nature's contributions to regulation of air quality, quality and quantity of water, and protection from hazards and extreme events for all people.

UNFCCC Finance for Climate Adaptation

The United Nations Framework Convention on Climate Change (UNFCCC) established an Adaptation Fund in 2001 to finance concrete adaptation projects and programmes in developing country Parties to the Kyoto Protocol[8] that are particularly vulnerable to the adverse effects of climate change. At COP26, the UN Climate Change Conference in 2021, new financial pledges were made to the Adaptation Fund (totalling over USD 350 million) and to the Least Developed Countries Fund (LDCF) (totalling over USD 600 million)[9].

1.5.2 Policy context for tree planting and forest restoration

In this section, I undertake an overview of global and regional policies that are pushing international, regional, and national drives to increase forest cover. Although placed here in

[7] https://www.cbd.int/

[8] The Kyoto Protocol operationalizes the United Nations Framework Convention on Climate Change by committing industrialised countries and economies in transition to limit and reduce greenhouse gases (GHG) emissions in accordance with agreed individual targets. https://unfccc.int/kyoto_protocol

[9] https://unfccc.int/process-and-meetings/the-paris-agreement/the-glasgow-climate-pact/cop26-outcomes-finance-for-climate-adaptation

the introduction, this section's purpose is to provide background for Chapter 5 which focuses on reforestation/afforestation as mitigation.

Currently many governments and organisations around the world are creating ambitious policies and implementing initiatives to increase tree cover. This is being driven by the growing urgency of the combined climate and biodiversity crises. Improving or altering water regulation is often not a primary driver for increasing forest cover but is considered an important co-benefit. Below, I outline some of the main policy instruments for increasing tree cover and provide context for the current global forestation expansion goals. The aim is to examine the potential scales of forestation envisaged and financial incentives (generators of funding) for these schemes, in order to provide context for possible scenario choices made in Chapter 5.

Policy instruments

There have been numerous international and regional commitments made around forests and tree planting in the last 15 years. In Table 1.5, I outline the most prominent pledges, with the proviso that these are merely pledges with no legal obligation. I also report on the uptake in the regions that are of interest to my study: Ecuador, Colombia, Kenya, UK, India and Indonesia. Progress on meeting these targets is discussed at the end of the section.

Table 1.5 An overview of tree planting and restoration commitments at the international and regional level.

Commitment	Overview	Uptake in my regions of interest
	International	
The Bonn Challenge	The Bonn Challenge was launched by the Government of Germany and International Union for the Conservation of Nature (IUCN) in 2011 with a global goal to bring 150 million hectares (ha) of degraded and deforested landscapes into restoration by 2020 and 350 million hectares by 2030 (IUCN, 2020a). It was later endorsed and extended by the New York Declaration on Forests at the 2014 UN Climate Summit. IUCN is the Secretariat of the Challenge. The Bonn Challenge utilises the Forest Landscape Restoration approach. The Challenge surpassed the 150-million-hectare milestone for pledges in 2017 and in 2020, 210 million hectares had been pledged by 74 governments, private associations and companies. Tracking the implementation of the pledges is via The Bonn Challenge Barometer[10]. Progress on meeting these goals is discussed below.	Pledged: Colombia: 1,000,000 ha, Ecuador: 500,000 ha, Kenya: 5,100,000ha, India: 21,000,000 ha, Indonesia: 1,000,000 ha. The UK is not listed as having made pledges as part of the Bonn Challenge.
REDD and UNFCCC REDD+	Deforestation and its climate impacts became known as REDD[11], reducing emissions from deforestation and degradation, at the 2007 UN Framework Convention on Climate Change (UNFCCC) in Bali, Indonesia (decision 2/CP.13). REDD+ is a mechanism developed by Parties to the UNFCCC to create a financial value for the carbon stored in forests by offering incentives for developing countries to reduce emissions from forested lands and invest in low-carbon paths to sustainable development.	The Forest Carbon Partnership Facility (FCPF)[12] Readiness Fund helps countries set up the building blocks to implement REDD+. A FCPF REDD+ Country Participant is a developing country located in a subtropical or tropical area that has signed a Participation Agreement to participate in the Readiness Fund. Of my study regions, Kenya, Colombia, and Indonesia are Country Participants.
United Nations Decade on Ecosystem Restoration	The United Nations Decade on Ecosystem Restoration runs from 2021 to 2030 and aims to halt the degradation of ecosystems and restore them to achieve global goals[13]. It is led by the United Nations Environment Programme and the Food and Agriculture Organisation of the United Nations. In 2020,	India has made commitments to restore 21 million hectares of deforested and degraded land and sequester 2.5 to 3 billion tons of CO_2 equivalent through additional forest and tree

[10] https://infoflr.org/bonn-challenge-barometer
[11] https://www.un-redd.org/
[12] https://www.forestcarbonpartnership.org/
[13] https://www.decadeonrestoration.org/about-un-decade

Commitment	Overview	Uptake in my regions of interest
	the World Economic Forum instigated an ambitious global tree-planting programme—the 1t.org platform—to support the UN Decade on Ecosystem Restoration 2021–30.	cover[14].
New York Declaration on Forests (NYFD)	In 2014, over 200 endorsers, including national governments, multinational companies, local community organisations, non-government organisations, and financial institutions declared ambitions to halt natural forest loss by 2030, restore 350 million hectares of degraded landscapes and forestlands, improve governance, increase forest finance, and reduce emissions from deforestation and forest degradation as part of a post-2020 global climate agreement (*New York Declaration on Forests - Forest Declaration*, 2022). However, a progress report has found that a majority of forest nations have not embedded those goals in their latest climate pledges to the UN (Gerretsen, 2021).	
COP26	The 26th UN Climate Change Conference of the Parties (COP26) was held in Glasgow, UK in 2021. Protection of forests, not merely 'conservation', was emphasised at COP26. One of the outcomes was the Glasgow Leaders' Declaration on Forest and Land Use, whereby leaders from 141 countries committed to halt and reverse forest loss and land degradation by 2030 by strengthening their efforts to conserve and restore forests and other terrestrial ecosystems and accelerate their restoration (UN Climate Change Conference UK 2021, 2021). COP26 saw increased financial commitment for forests, such as the Global Forest Finance Pledge, which commits to collectively provide US$12 billion for forest-related climate finance between 2021-2025 for the protection, restoration and sustainable management of forests. In addition, the United States of America launched the Forest Investor Club and Forest Finance Risk Consortium (FFRC) which includes a network of leading public and private financial institutions and other investors and aims to unlock and scale up	India was not one of the countries that signed the Glasgow Leaders' Declaration on Forest and Land Use.

[14] https://www.1t.org/india

Commitment	Overview	Uptake in my regions of interest
	investments that support sustainable, climate-aligned outcomes in the land sector (Abisoye, 2021).	
30x30	30 by 30 is a worldwide initiative for governments to designate 30% of Earth's land and ocean area as protected areas by 2030.	Colombia, Ecuador, India, Indonesia, Kenya, and the UK have pledged to 30x30.
	Regional commitments	
African Forest Landscape Restoration Initiative (AFR100)	AFR100 is a country-led effort to bring 100 million hectares of land in Africa into restoration by 2030. It aims to accelerate restoration to enhance food security, increase climate change resilience and mitigation, and combat rural poverty. AFR100 contributes to the Bonn Challenge, the African Resilient Landscapes Initiative (ARLI), the African Union Agenda 2063, the Sustainable Development Goals and other targets.	Kenya has committed to restore 5.1 million ha.
Initiative 20x20 in Latin America and the Caribbean	Initiative 20x20 is a country-led effort in Latin America and the Caribbean to protect and restore 50 million hectares of forests, farms, pasture, and other landscapes by 2030[15]. To date, 18 Latin American and Caribbean countries and three regional programs have committed to improve more than 52 million hectares of land and there is US$3.09 billion in private sector investment.	Both Colombia and Ecuador are signed up country members with Colombia pledging 1 million ha and Ecuador 0.5 million ha (the same as for the Bonn Challenge).
ECCA30 in Europe, Caucasus and Central Asia	ECCA30[16] aims to restore 30 million hectares of land in Europe, the Caucasus and Central Asia, by 2030. It is a regional initiative to secure additional commitments and accelerate the implementation of the Bonn Challenge, the Land Degradation Neutrality, and land and forest-based targets of the Paris Agreement.	

[15] https://initiative20x20.org/restoring-latin-americas-landscapes
[16] https://infoflr.org/bonn-challenge/regional-initiatives/ecca30

National commitments and progress

Colombia

Colombia has committed, via the Bonn Challenge and Initiative 20x20, to plant or restore one million hectares of forest by 2020. InfoFLR[17], a website that collates information, news and resources on Forest Landscape Restoration (FLR) around the world, and managed by the IUCN, summarises the commitments and national restoration targets for many countries. It states that Colombia[18] has a total restoration target of 2,017,984 hectares and a potential of 14 million ha for forest plantations. Proposed actions include the implementation of programs for rehabilitation, restoration and recovery of forest ecosystems. Several projects are listed as being funded by the Global Environment Facility (GEF). Of note is one located in the Magdalena Basin, in which our study basin is located, titled: Sustainable Management and Conservation of Biodiversity in the Magdalena River Basin (submitted Jan 2013 – 60-month duration) (Project code: 4849) focused on watershed restoration. Financing includes a $6.3 M grant and $25 M in co-financing adding up to $31.3 M. In 2022, Colombia secures $245 million USD of public and private finance to permanently protect 32 million hectares of iconic Colombian landscapes and seascapes[19]. Colombia is the first country in the west to meet the 30% goal for ocean protection[20]. Bezos Earth Fund grants $5M to the UN Environment Programme World Conservation Monitoring Centre (UNEP-WCMC) to catalyse support to countries from the Congo basin (Congo, Democratic Republic of the Congo, Gabon) and the Andes region (Bolivia, Colombia, Ecuador, Peru) for the 30x30 ambition[21].

Ecuador

From 2001 to 2021, Ecuador lost 902kha of tree cover, equivalent to a 4.7% decrease in tree cover since 2000[22]. In 2014, Ecuador committed 500,000 hectares to forest landscape restoration and conservation as part of the Bonn Challenge and the 20x20 Initiative[23]. In 2015, 44,000 people in Ecuador made it into the Guinness Book of World Records by planting 647,250 trees of 216 species of trees across 2,000 hectares of land in 150 locations, ranging from the Pacific coastal region to the Amazonian basin to the high Andean mountains[24].

[17] https://infoflr.org/index.php/
[18] https://infoflr.org/countries/colombia
[19] https://wwf.panda.org/wwf_news/?5909466/Colombia-WWF-and-partners-announce-245M-agreement-to-permanently-protect-vital-systems-of-nations-protected-areas
[20] https://worldwarzero.com/magazine/2022/07/on-a-high-note-colombia-meet-30x30-ocean-protections-pledge/
[21] https://www.unep-wcmc.org/en/news/towards-30x30--new-grant-supports-major-progress-for-protected-and-conserved-areas
[22] https://www.globalforestwatch.org/
[23] https://infoflr.org/index.php/countries/ecuador
[24] https://ourworld.unu.edu/en/what-every-country-can-learn-from-ecuador

India

India originally pledged to restore 13 million ha by 2020 as part of the Bonn Challenge, but in fact claims to be on track to restore 26 million ha of degraded land by 2030[25]. Meanwhile, the World Resource Institute (WRI) has calculated that India has nearly 140 million hectares of potential for forest protection and landscape restoration (Chaturvedi et al., 2018). The same report states that India, between 2011 and 2016, allocated more than US$16 billion to improving forest and tree cover, through public financing (Chaturvedi et al., 2018).

Indonesia

Indonesia committed 1,000,000 hectares as part of the Bonn Challenge and has a total restoration target of 29,294,990 hectares according to InfoFLR[26]. In 2012, the government committed to reforest 2 million hectares of degraded land annually[27]. Pharmaceutical company, AstraZeneca, via its AZ Forest programme commits to planting 20 million trees in Indonesia by 2025[28].

Kenya

The Kenyan government has set a constitutional target to increase Kenya's forest cover from the current 7.2% to 10% forest cover, requiring 2 billion trees, by 2022 (Republic of Kenya, 2019). This is part of its commitment to restore 5.1 million ha of degraded landscapes as a contribution to the AFR100 (Republic of Kenya, 2019). Organisations like the International Tree Foundation aim to plant 20 million trees in Kenya through forest restoration and agroforestry[29].

United Kingdom (UK)

The devolved UK governments have individual aspirations for increasing forest cover; England from 10% to 12% by 2060, Scotland from 17% to 21% by 2032 and Wales aims to plant "at least 2000 hectares per annum from 2020 to 2030 and beyond" (Ares et al., 2021).

In the UK, the government has a target of planting 30,000 hectares of trees annually from 2025 in order to meet its net zero emission target for 2050[30]. But in 2020, only 13,660 hectares of new trees were planted, resulting in calls to radically step-up efforts. The

[25] https://www.thehindubusinessline.com/news/national/india-will-achieve-land-degradation-neutrality-by-2030-says-prime-minister-narendra-modi/article34816460.ece
[26] https://infoflr.org/index.php/countries/indonesia
[27] https://news.mongabay.com/2014/12/indonesias-ambitious-plan-to-reforest-2m-ha-annually/#:~:text=President%20Joko%20Widodo's%20election%20campaign,Bold%20plans%20indeed.
[28] https://www.astrazeneca.com/media-centre/articles/2020/az-forest-indonesia-20-million-trees-to-be-planted-by-2025.html
[29] (https://internationaltreefoundation.org/20milliontrees/
[30] https://publications.parliament.uk/pa/cm5802/cmselect/cmenvfru/356/report.html

government has created many new grants to help fund the tree planting programme[31]. Additionally, many NGOs have set their own targets for tree planting. Friends of the Earth plans to double Britain's forest cover to 26%[32]. The Woodland Trust wants to plant 50 million trees over the next five years[33]. The National Trust has called for 20m this decade[34].

Corporations and private entities

In bids to offset their own carbon emissions, many corporations are embarking on mass tree planting projects. For example, BrewDog, the craft beer company, pledges to plant a tree for every multipack of beer sold (via a third-party charity) but has also bought 809 hectares (2,000 acres) of Scottish highland to plant 1 million trees, with the ambition to remove twice as much carbon from the air than it emits each year (Clark, 2020).

In a bid to understand the corporate dimension of tree planting, WWF undertook research among the Global Fortune 500 companies with headquarters in France, Switzerland and the UK (Mansourian & Vallauri, 2020). They found that 100% of the 28 French companies, 93% of the 14 Swiss companies and 85% of the 20 British companies in the Global Fortune 500 list planting trees (overall a total of 58 out of 62 companies). A total of at least 190 million trees were reported to have been planted between 2000 and 2018 by the 58 companies analysed (Mansourian & Vallauri, 2020).

Conservation-minded major landowners are also undertaking mass restoration and tree planting projects. For example, Danish billionaires Anders and Anne Holch Povlsen, who own more than 80,000 hectares in Scotland, are removing sheep and intensively culling red deer in order to allow native woodland and species to regenerate. They are also planting 1.5 million trees[35].

[31] https://www.gov.uk/government/news/39-million-to-drive-innovative-tree-planting
[32] https://friendsoftheearth.uk/trees
[33] https://www.woodlandtrust.org.uk/press-centre/2020/10/50-million-trees-to-tackle-climate-change/
[34] https://www.theguardian.com/environment/2020/jan/09/national-trust-plant-20-million-trees-uk-net-zero-emissions
[35] https://www.theguardian.com/uk-news/2019/mar/21/danish-billionaires-anders-and-anne-holch-povlsen-say-plan-is-to-restore-scottish-highlands

Large NGOs' restoration investments

Priceless Planet Coalition, a coalition between Mastercard, Conservation International (CI) and World Resources Institute (WRI), will employ a forest restoration model dedicated not only to the planting of 100 million trees by 2025 but also to the regrowing of forests[36].

Trillion Trees[37] is a joint venture of three of the world's largest conservation organisations: WWF, BirdLife International and the Wildlife Conservation Society. It is a vision for a trillion trees to be restored, saved from loss, and better protected around the world, by 2050. Of my countries of interest, Trillion Trees is working in Kenya, Colombia, and Ecuador.

Lack of progress on goals

The commitments to tree planting and forest restoration outlined above indicate a huge amount of political will and ambition. However, investigations into what progress has been made towards these goals indicates that there is a shortfall of 'on-the-ground' implementation, and that globally we are not on track to meet the goal of restoring 150 million hectares of forest. The NYDF Assessment progress report (NYDF Assessment Partners, 2020) states that, "Since 2000, approximately 26.7 million hectares of forest landscapes have experienced tree cover gain (20.5 Mha reforestation, 6.2 Mha afforestation), representing 18 percent of the 2020 goal. Since 2011 (start of the Bonn Challenge), 3.1 million hectares have undergone forest restoration (2.4 Mha reforestation, 0.7 Mha afforestation). After the launch of the Bonn Challenge and NYDF, the average rate of forest restoration decreased from approximately 2 million hectares per year between 2000-10, to less than 1 million hectares per year after 2011."

Type of forestation restoration

The NYDF Assessment Report (NYDF Assessment Partners, 2019) also analysed what type of restoration occurred, either 'regeneration', 'active ecological restoration', 'timber plantation or woodlot', 'agroforestry', or 'afforestation' where it occurred and the time period (Fig. 1.4). Since 2011 (start of the Bonn Challenge), a majority of the forest cover gain through FLR activities occurred in North America (USA) (1.4 Mha), Latin America (0.75 Mha), and SubSaharan Africa (0.70 Mha). Most restoration types since 2011 were active ecological restoration (24%), woodlots (unspecified kinds of timber plantations, 22%), natural and assisted regeneration (20%), agroforestry (16%), and afforestation (15%) (Fig. 1.4).

[36] https://www.mastercard.us/en-us/vision/corp-responsibility/priceless-planet.html
[37] https://trilliontrees.org/

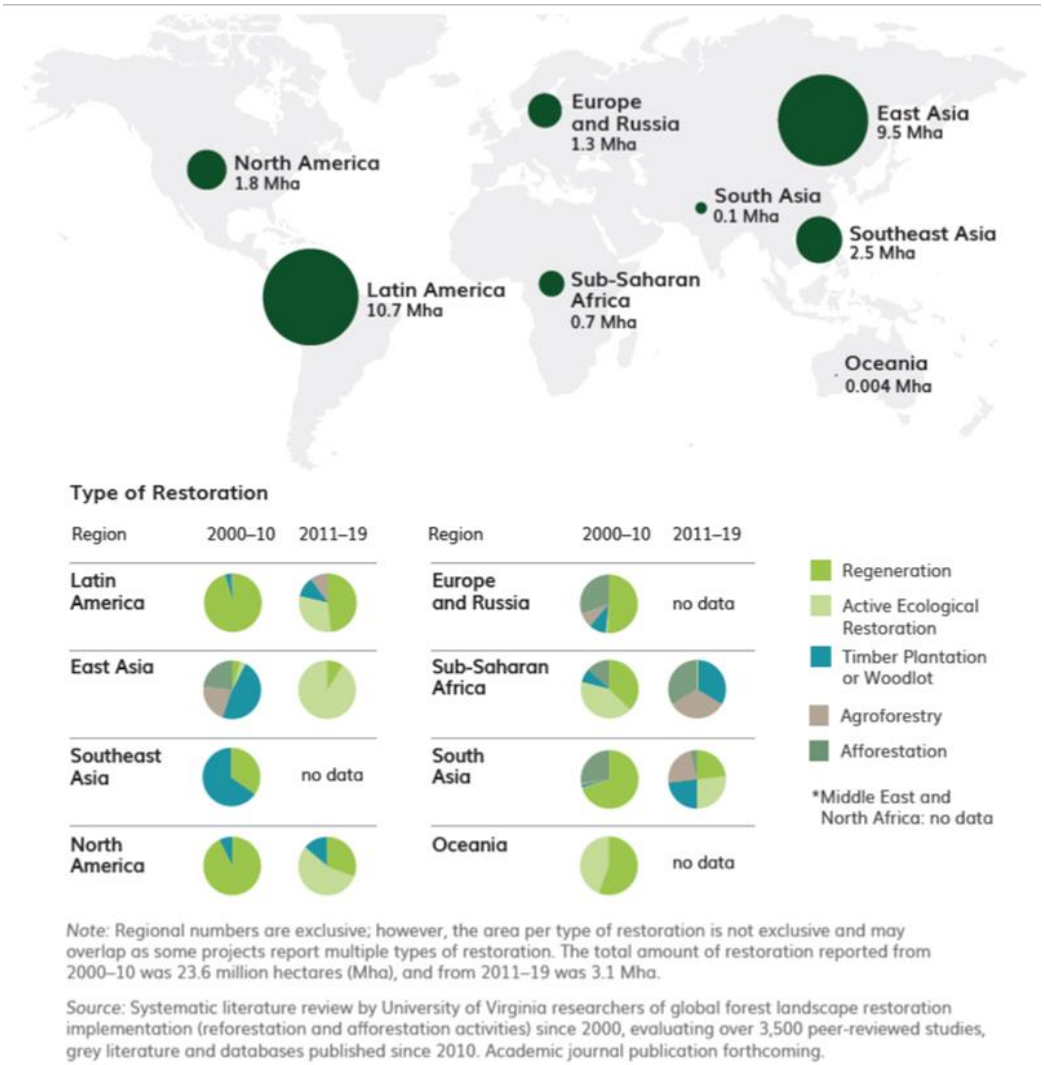


Figure 1.4 Increase in forest area through forest landscape restoration (forest cover gain through reforestation and afforestation activities) from 2000–19 in million hectares, and by region, time period, and type of restoration (from Figure 7, NYDF Assessment Partners, 2019).

Lack of finance

A major reason for the lack of implementation is a lack of finance for the initiatives. It is estimated that since 2010 countries have spent only 0.5%-5% of what is needed to protect and restore forests ($2.4 billion a year compared to the $460 billion per year that is estimated to be required; NYDF Assessment Partners, 2019). A significant number of country targets are conditional on international climate finance, highlighting the need for continued support to forest countries (NYDF Assessment Partners, 2019). A lot of funding is also channelled into administration and management rather than to on-the-ground works.

Critique of tree planting schemes

Tree planting and FLR schemes, such as REDD+ and *One Trillion Trees*, are often criticised for not only *not* fulfilling tree quotas but also for having no specific goals on, or way to

monitor, the much-acclaimed biodiversity co-benefits (Pascual et al., 2022). In particular, single-issue initiatives, like *One Trillion Trees,* are not viewed favourably by conservation groups as they encourage planting on grasslands and other sensitive ecosystems. REDD+ is widely recognised as neglecting the social risks associated with the approach, and has demonstrated mixed social outcomes, with few examples of social co-benefits across multiple dimensions (Pascual et al., 2022).

1.6 Research significance and contribution

The research presented in this thesis is situated between two major societal problems and a potential solution: increasing flood risk and climate change (Fig.1.5), and natural infrastructure, which has the potential to buffer the impact of both. Climate change intensifies the hydrological cycle, which exacerbates flood risk in some regions. Land cover change influences surface water runoff, which contributes to flood risk. Land cover change also impacts greenhouse gas emissions that can either exacerbate or ameliorate climate change, depending on the direction of change. Cities, through expansion and/or demand for resources, create pressure for land use change. This thesis aims to investigate the role that natural infrastructure (NI) has in buffering the impact of flood risk, how climate change will affect that influence, and if adjusting land cover towards greater tree cover contributes to reducing the impact of flood risk and climate induced flood risk.

Taking an ecosystem services approach by measuring the contribution of NI to flood regulation is important for highlighting their importance relative to grey infrastructure, advocating for their protection, and in some cases, enhancement of green NI through nature-based solutions to better adapt to climate change. The information from this research can be used by city planners, environmental agencies, NGOs and investors etc. to plan and prioritise their response to flood risk, associated land cover change decisions and areas for restoration and/or protection.

What this thesis does not do is investigate how the changes in land use and land cover will impact climate change, or how cities impact on land use change. Those relationships and processes are outside the scope of this thesis.

1.7 Thesis overview and guidance to the reader

1.7.1 Thesis overview

This thesis comprises six chapters, described below:

Chapter One

Chapter one provides a brief introduction to the research problem and rationale for the work. It outlines the research aim, objectives, and associated research questions. It then introduces some of the key themes and concepts relevant to the thesis such as floods and flood risk, the 'ecosystem approach' to flood risk management, and the policy context in which these ideas sit. It describes the research importance of the topic and the contribution that this thesis makes. Finally, the chapter concludes with an overview of the thesis structure with descriptions of each chapter.

Chapter Two

Chapter two provides the research overview for the thesis and has two parts. Part one gives an overview of the current state of knowledge on key themes. It focuses on hydrological ecosystem services, particularly those related to water flow regulation, and presents an umbrella literature review on the use of forests as a Nature-based Solution for flood alleviation. Part two discusses some of the methodological background, such as a comparison of ecosystem modelling approaches, background to climate change modelling, and a description of the *WaterWorld* model. Finally, the chapter provides a description of the study basins.

Chapter Three

Chapter three is a published research article. It was published in the journal *Science of the Total Environment* in 2019. It is presented here in its published form. This article addresses Objective 1. It determines the current state of natural water storage in five of the six basins and describes in detail the natural infrastructure flood metric used to calculate current (baseline) flood risk in the study basins. The baseline flood risk in these basins is mapped, and the influence of geographic patterns is discussed.

Chapter Four

Chapter four addresses Objective 2. This chapter describes the impacts of climate change on relevant hydrological variables and the change in flood risk (as determined by the natural infrastructure flood metrics) as a result of the climate scenarios in all six basins. It also looks for geographic patterns and the influence of the specific climate scenarios.

Chapter Five

Chapter five addresses Objective 3. This chapter sets-up various land-use change scenarios based on increasing forestation in two of the study basins, Bogotá and Guayaquil. It calculates how flood risk will change as a result of these forestation scenarios and then overlays these with the climate scenarios to determine if there are areas where forestation can act as a nature-based solution. This chapter focuses on how forestation extent and spatial-targeting based on low-value land will affect flood risk.

Chapter Six

Chapter six synthesises the conclusions from Chapters 3 to 5. This chapter describes the extent to which the objectives have been met and recommends avenues for further research.

1.7.2 Guidance to the reader

This thesis deliberately focuses on multiple natural water storage types. There are three empirical chapters in this thesis: Chapters three, four and five. Chapter three and four focus on all/multiple natural water stores, whereas Chapter five focuses on only canopy water storage and how increasing that storage via re/afforestation impacts flood risk. However, the literature on afforestation is vast (it is a much greater established research area compared to the other stores) and so it seemed wise to delve more deeply into that subject matter. Thus, Chapter one and Chapter two have sections on tree planting/forest policy and an umbrella review of the impact of afforestation to provide background to Chapter 5 and which may lead the reader to believe that this thesis is primarily concerned with canopy water stores, but that is not the case.

Chapter 2

Research and methodological context

This chapter provides in-depth background on two themes and methodological context for the research. It is divided into two parts: Part one provides an introduction to Hydrological Ecosystem Services (HES), and a review of the use of forests for water regulation; Part two summarises modelling approaches for hydrology, ecosystem services and climate change. It also introduces the *WaterWorld* model used for this research and describes the study basins.

Part one: Hydrological Ecosystem Services and Forests

This section explores more fully concepts introduced in Chapter 1. It begins by focusing on hydrological ecosystem services, their definition and relationship to flood regulation and mitigation. Finally, it focuses on forestation as a flood mitigation intervention by describing the hydrological concepts of how forests regulate flow, and finally, undertakes an umbrella literature review (review of systematic reviews) looking at the impact of afforestation on water regulation, specifically for flood risk mitigation.

2.1 Hydrological ecosystem services

In this thesis, I will focus on hydrological ecosystem services, which encompass the benefits to people produced by terrestrial ecosystem effects on freshwater (Brauman et al., 2007). Brauman et al. (2007) organised hydrologic ecosystem services into five broad categories:

1. Diverted water supply - *provisioning service* - provides water for municipal, agricultural, commercial and industrial, as well as power generation.
2. *In-situ* water supply – *provisioning service* – water for hydropower, water recreation, transportation, fish and other freshwater products.
3. Water damage mitigation – *regulating service* – mitigation of flood damage, of sedimentation of water bodies, of saltwater intrusion into groundwater and of dryland salinization.
4. Provision of water related *cultural services* – provision of spiritual, aesthetic, and tourism values.

5. Water-associated *supporting services* – includes provision of water for plant growth and to create habitats for aquatic organisms.

Each of these services is defined by attributes of quantity, quality, location and regulation of timing, and magnitude of flow (see Table 2.1). Under various scenarios of these attributes, some services are improved at the expense of others, resulting in trade-offs. Hydrologic attributes (quantity, quality, location and timing) are directly impacted by ecosystems as water moves through the landscape. Ecosystem processes enhance or degrade the supply of hydrologic services, with vegetation often being the driving force in ecosystem effects on water (Brauman et al., 2007).

To summarise: eco-hydrologic process (refers to what the ecosystem does) -> hydrologic attribute (is the direct effect of the ecosystem in terms of quantity, quality, location and timing) -> hydrologic service (results in what the beneficiary receives).

Important components of these attributes of quantity, quality, location and timing are water retention, water yield, natural water infiltration and sediment regulation (Vigerstol & Aukema, 2011). For my focus on flood mitigation and buffering, the components of water retention and water yield are the most important considerations.

Water retention is a key component of water quantity. Retention provides a buffer for both water supply shortages and flooding. This is achieved by features of the hydrologic cycle acting as a distributed reservoir of water that is released over time (Vigerstol & Aukema, 2011). Water retained by the landscape in the upper basin allows water supply to prolong further into the dry season when water is scarce and thus valued more. Water retention during a storm event reduces flood damage by flattening the flood peak. Holding water on the landscape also aids in replenishing groundwater, the source of baseflow for many streams (Vigerstol & Aukema, 2011).

Water yield is another important component of water quantity, contributing to water availability, either for consumptive use (e.g., drinking or irrigation) or in situ water supply (e.g., water for hydropower or fisheries). The distribution of water in the hydrologic cycle can be changed due to management decisions that alter land use change. Therefore, if the

landscape yields more water due to a land use change, another component of the hydrologic cycle, such as groundwater, may be losing water (Vigerstol & Aukema, 2011). A critically important component of water yield is the seasonal timing of runoff patterns for individual storms. Water yield in conjunction with water retention helps determine patterns and timing of flooding events (Vigerstol & Aukema, 2011).

Table 2.1 Summary of attributes of hydrologic ecosystem services (based on Brauman et al., 2007).

Hydrologic attribute	Description	Example	Role of ecosystems	Metrics
Water quantity	Refers to the amount of water available for drinking, agriculture or describes the volume of flood waters.	For services such as water supply, an increase in water quantity is beneficial but is not beneficial for the service of flood mitigation.	Ecosystems do not create water but do modify the amount of water moving through a landscape. The main effect of ecosystems is to reduce available water quantity through direct use of water by plants.	Researchers evaluate changes in surface flow and groundwater storage after natural or human-induced alterations to land cover. Measured as surface water output and reported as annual watershed yield.
Water quality	Refers to the measure of chemicals, pathogens, nutrients, salts and sediments in surface and groundwater.	Changes in quality can occur seasonally, daily or move through a watershed over years. Terrestrial ecosystems can add and remove a variety of contaminants to flows above and below ground.	Ecosystems with intact groundcover and root systems are generally good at improving water quality. Removal of vegetation increases erosion and allows nutrients and other impurities to build up in the ecosystem.	Measures include changes in annual average concentration, changes in total maximum daily load, and relative and absolute changes in concentration.
Location of delivery	Water is useful only if users have access to it, and likewise it can be harmful if it ends up in the wrong place, such as in homes or over crops.	Riparian vegetation can direct water flow in a streambed and prevent water moving from the river to the floodplain.	Ecosystems affect the location of water above and below ground, as well as its distribution within a watershed. Ecosystems affect the location of water mainly by the process of infiltration.	
Timing of delivery	Refers to when water is available, and the regulation of peaks and troughs.	Precipitation is not uniformly spread through the year which can make runoff either unusable or even a hazard. Timing also encompasses predictability of flows.	Ecosystems regulate timing by: •water use by plants which may be synchronised with the growing season •maintaining an areas hydro-period •vegetation mediates flow paths •floodplains and wetlands reduce flooding by absorbing and slowing floodwaters.	Information is needed about the duration, seasonality, and predictability of absolute and relative changes in flood peaks and low flows.

Flood risk regulation and mitigation

Flood regulation addresses the ecosystem's capacity to lower flood hazards caused by heavy precipitation events (Stürck et al., 2014). This is generally achieved in the landscape by reducing the runoff fraction and through storage and slow release of rain water from the soil and aquifers (Eigenbrod et al., 2011). Key environmental variables that impact rainfall-runoff responses include: the physical characteristics of river catchments; the land cover/land use types and specific variations in evapotranspiration rates; vegetation-soil interactions and modifications of the surface roughness; and soil hydraulic properties such as infiltration capacity and the water holding capacity (WHC) of the soil (Stürck et al., 2014).

The onset, duration and magnitude of a flood hazard are highly dependent on precipitation intensity, duration and extent, making for different flood types (i.e., rainy-fluvial floods, flash floods, snowmelt-fluvial floods (Nedkov & Burkhard, 2012; Stürck et al., 2014). The flood regulative effect of the above-mentioned environmental variables may, therefore, depend considerably on the underlying precipitation event and prior weather conditions (Stürck et al., 2014).

The flood regulating function of ecosystems can be either preventive or mitigating. In the preventive function, the ecosystem service plays its role before the occurrence and can even prevent it. For instance, the ecosystems, such as forests, redirect or absorb parts of the incoming water (from rainfall), reducing the surface runoff and consequently the amount of river discharge (Nedkov & Burkhard, 2012). The mitigating function occurs after the flood has already formed. The ecosystems (i.e., floodplains and wetlands) provide retention space for the water surplus to spill, thus reducing the flood's destructive power (Nedkov & Burkhard, 2012).

Ecosystem service provision to cities

Since cities contain the largest concentration of people, i.e., beneficiaries, they are where the greatest proportion of ecosystem service flows reach their end-point. Quantifying the magnitude of these flows, spatial distribution, threats and vulnerabilities to these flows, is thus important.

Generally, the origination of resources to cities is from ecosystems and landscapes outside of cities and, in some cases, quite spatially distant from the city. Some early work on

ecological footprints of cities found that each city is dependent for its growth and survival on an area of productive ecosystems two to three orders of magnitude larger than the geographic area of the city itself (Rees, 1997). However, despite this dependence on remote regions, cities still depend on their immediate hinterlands for the provision of water, the most important and largest material transfer into urban ecosystems (Decker et al., 2000). Likewise, cities are dependent on the immediate landscape, in addition to more remote natural features in the water basin, for protection or buffering from floodwaters.

Cities represent 'exposure', i.e., the people and assets that could be adversely affected by the hazard. In this research, I focus on the hazard potential (of flood risk) and will not be modelling future changes in exposure. This is because my focus is on the mitigation of the biophysical elements of risk, not the socioeconomic aspects and their adaptation. The research in this thesis will focus on the flood damage mitigation benefits provided by the landscape via Natural Infrastructure (NI) to cities.

2.2 Forestation as flood risk mitigation

So far, I have discussed concepts and topics broadly relevant to this thesis. Now, I will take an in-depth account of the use of forests and forestation as a flood risk mitigation intervention, as I model this in Chapter 5. The purpose of this section is to outline the ecohydrological principles of how trees regulate flows, summarise the evidence from the scientific literature for using forestation as a flood risk reduction intervention, and distil current best practice in locating forestation schemes for the least negative impact on biodiversity and landscape properties.

Forestation, either afforestation, reforestation, restoration or regeneration, is one of the most commonly advocated nature-based solutions (NbS) particularly for climate mitigation/adaptation or flood control. This is largely due to the multiple ecosystem services associated with extensive tree cover such as erosion control (Bonnesoeur et al., 2019; Labrière et al., 2015), habitat for wildlife/biodiversity (Brockerhoff et al., 2008), carbon storage and sequestration (Cannell, 1996; Lewis et al., 2019; Soepadmo, 1993), water quantity, quality and regulation (Baillie & Neary, 2015; Dudley & Stolton, 2003), micro-climate regulation such as air surface cooling (Mildrexler et al., 2011; Moss et al., 2019; Rahman et al., 2020) and air pollutant filtration (Diener & Mudu, 2021; Nowak et al., 2014). Although increasing tree cover for the purpose of carbon sequestration and storage for

climate mitigation is of acute global interest, doing so for the purpose of flood risk reduction (or mitigation) is also advocated, critiqued and debated (Calder & Aylward, 2006; Dadson et al., 2017; FAO-CIFOR, 2005; Hankin et al., 2017; Lane, 2017; Page et al., 2020; Wingfield et al., 2019; World Bank, 2017). Despite many reviews on this topic, the link between forests and river flooding remains inconsistent (Calder & Aylward, 2006; Stratford et al., 2017). Large-scale tree-planting also has many drawbacks (if not done correctly) such as decreased water yield and decreasing low flows and has resulted in increasing calls for caution, temperance and better project planning (Brancalion & Holl, 2020; Forsyth, 2021).

I use the general term '*forestation*' as the catch-all term to refer to the establishment of forest (defined as tree cover greater than 10%) by plantation (tree planting by humans for a specific purpose) or assisted natural regeneration or natural regeneration on areas that either had forest in the past or not (as in Bonnesoeur et al., 2019). Specifically, '*afforestation*' will refer to the establishment of forest by manual aid or natural regeneration on land that did not previously have forest (for at least 50 years), whereas '*reforestation*' or '*restoration*' is forestation in previously deforested (recently forested) areas. Afforestation and reforestation is the artificial establishment of trees (usually by planting seedlings/saplings) and so usually has a high build cost. Regeneration and restoration usually do not involve any manual planting but can either take a "do nothing" approach or could involve mild intervention such as removing grazing pressure, improving soil conditions, and/or facilitating seeding of preferred species. The distinction between types for forestation approaches are summarised in Table 2.2 and are relevant for this review but used in a much simpler form in the modelling used in Chapter 5.

Table 2.2 Comparison and definitions of the key terms related to forestation practices.

Term	Active/ passive planting	Definition
Afforestation	Active or Passive	The establishment of forest by manual aid or natural regeneration on land that did not previously have forest (for at least 50 years).
Reforestation	Active	Forestation in previously deforested (recently forested) areas.
Restoration	Passive	Forestation in previously deforested (recently forested) areas.
Natural regeneration	Passive	Allowing forest systems to spontaneously regrow without any tree planting or other assisted regeneration practices.
Assisted natural regeneration	Active	Aims to accelerate natural regeneration and/or guide successional trajectories through activities that enhance tree growth, via the exclusion of threats (i.e., grazing, fire, invasive plants) that had previously prevented the natural regrowth of a forested area from seeds already present in the soil, or from natural seed dispersal from nearby trees.
Enrichment planting	Active	The strategic re-establishment of key tree species in a forest that is ecologically degraded due to lack of certain species, without which the forest is unable to naturally sustain itself.
Agroforestry	Active	The intentional mixing and cultivation of woody perennial species (trees, shrubs, bamboos) alongside agricultural crops in a way that improves the agricultural productivity and ecological function of a site.
Forest Landscape Restoration (FLR)	-	An approach that aims to restore ecological integrity at the same time as improving human well-being through multifunctional landscapes. The three key objectives of FLR include carbon sequestration, biodiversity recovery and sustainable livelihoods.

2.3 Eco-hydrological concepts on forests and flooding

The ecohydrological processes and mechanisms by which forests are thought to alleviate flooding can be categorised as those that either slow, store or lose the water inputs as summarised in Table 2.3 and illustrated in Figure 2.1. Specifically, tree planting (or forests more generally) can influence flooding, and has potential as a flood risk/peak reduction intervention, through: (i) increased soil infiltration capacity; (ii) enhanced soil drying resulting from higher transpiration; (iii) increased ground-surface roughness leading to detention storage and increased infiltration opportunity; (iv) enhanced wet-canopy evaporation, (v) increasing available canopy and soil storage capacity, and (vi) slowing and spatial redistribution of sub-canopy throughfall (Page et al., 2020; Stratford et al., 2017).

Important key hydrological concepts are defined in the Glossary.

Table 2.3 The mechanisms and processes by which forests are thought to regulate water flow.

Slowing	Storing	Loss/Gain
Interception (slowing - redistribution in time and space - of rainfall rate through canopy).	Increased soil storage capacity. Influenced by infiltration rates and soil water retention capacity. More organic matter and tree roots, and less soil disturbance, allows forest soils to hold more water.	Evaporation - from tree surfaces, i.e., interception (loss to atmosphere).
Ground surface (greater surface/hydraulic roughness compared to open habitats which has a slowing effect on flood flows) through enhanced storage and opportunity time for infiltration and evaporation.	Increased canopy storage capacity. Interception (temporary storage on vegetation surface).	Transpiration - evaporation from within the leaf (loss to atmosphere) enhances soil drying.
Throughfall and stemflow slows rainfall rate through the canopy.		Capture of occult precipitation (is important for cloud forests).
Increased soil infiltration rates.		Metabolic tree use (very low).

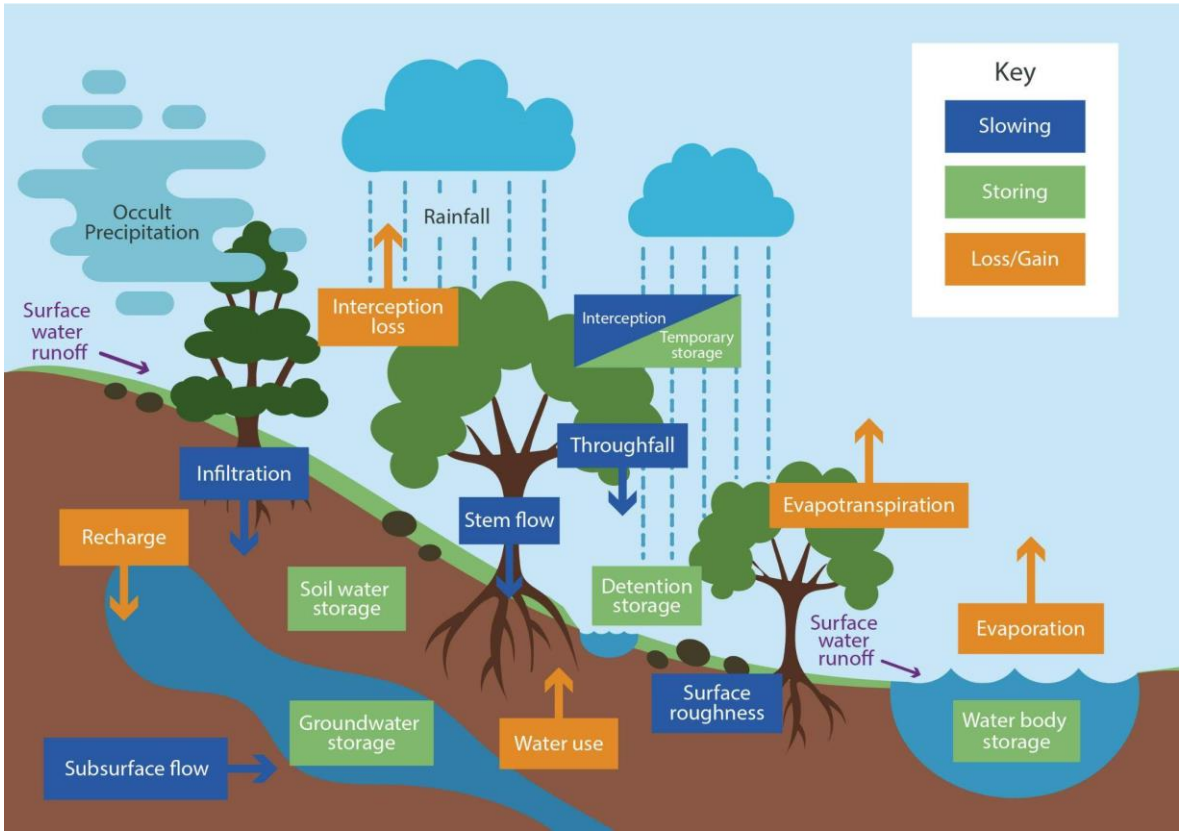


Figure 2.1 Conceptual model of how trees slow, store and lose water within the landscape as part of the hydrological cycle. WaterWorld v2 captures most of these processes/variables, except for surface roughness, interception, stem flow and throughfall, groundwater storage, infiltration and recharge. (Concept by the author, illustration by Cecily Church).

In terms of water use, the size and longevity of trees set them apart from other types of vegetation. Trees, by definition, are usually greater than 5 m in height. Morris & Benyon (2005) identified three main factors influencing the water use by trees: (1) climatic factors: humidity, solar radiation, air temperature, and wind; (2) water availability: rainfall, irrigation, soil water, and groundwater; and (3) tree factors: leaf area, rooting depth, maturity, and size. Hydrological fluxes in any given area of the forest will be significantly impacted by the species, age and spatial distribution of the trees (Cooper et al., 2021).

Factors such as forest extent, forest fragmentation, forest type, forest age, catchment size, and management regime also influence the hydrological response (Stratford et al., 2017). Climatic effects can be difficult to separate from those of terrain or land-use, especially as the main factors influencing major flooding given a large rainfall event are: (i) event characteristics; (ii) the geomorphology of the area (affecting infiltration and flow concentration); and (iii) preceding rainfall (Bruijnzeel, 1990, 2004; FAO-CIFOR, 2005;

Hamilton & King, 1983). The intensity and the amount of time since the last significant rainfall event can have a marked effect on the amount of water stored within the soil and canopy and therefore available for evaporation (Cooper et al., 2021).

To measure the effects of forests on flooding, researchers typically look at the changes in flow metrics such as runoff, channel discharge, flood peak, peak flow and water yield. In addition to directly influencing the hydrological flux, trees will also indirectly affect water runoff and flood flows by changing the physical properties of the soil (therefore affecting infiltration and soil water storage), changing the surface and hydraulic roughness of the area, which will affect surface flows during rainfall, and reducing erosion and therefore downstream siltation (Bruijnzeel, 2004; Chandler et al., 2018; Wiśniewski & Märker, 2019). Indirect measures look at the intermediary processes such as infiltration, interception or evapotranspiration from which we can make inferences about the effect on flow regulation. Ideally, the comparison in measures would be between two states, forested and un-forested, with everything else held constant. However, this is problematic due to the long time frames needed (30+ years), and so studies tend to be either immediately before/after deforestation, or paired catchment studies (in which similar catchments with different land use are monitored), or utilise modelling (particularly in large catchments).

2.3.1 Umbrella Literature Review

Direct evidence for how forests contribute to attenuating flooding is still uncertain. One established view is that forests only protect against floods at very local scales and for small storm events (Calder & Aylward, 2006; Dadson et al., 2017; FAO-CIFOR, 2005). For instance, Dadson et al. (2017), after reviewing a number of UK studies, concluded that under sustained winter rainfall, soil saturation will occur and little mitigation of high flood flows would be expected. However, Cooper et al.'s (2021) review concluded that when applied with 'due diligence and measured consideration', appropriately planted and managed woodlands in the UK can mitigate flood risk and delay flood peaks, both temporally and spatially. Another UK modelling study found that widespread afforestation only provided a modest reduction in extreme flood flows (and may inadvertently reduce water availability, particularly in drier areas; Buechel et al., 2022). A systematic review of nature-based solutions for hydro-meteorological risk reduction reported on a study that found that native mountain forests could be used to reduce hydro-meteorological risk such as flash floods and landslides (Casteller et al., 2018; Ruangpan et al., 2020). A study in India examined the association between forest cover and flood damage and found that as forest cover rises in

proportion to total geographical area, flood damage in the form of the number of human lives lost and people affected due to floods, are likely to reduce (Bhattacharjee & Behera, 2018).

An examination of the literature on forestation impacts on water/ flooding showed that there are thousands of published papers and many, fairly recent, systematic reviews. Thus, I decided to do a review of the systematic reviews, i.e., an umbrella review (also known as overviews of reviews, review of reviews, a summary of systematic reviews or a synthesis of reviews). Umbrella reviews specifically refer to compiling evidence from multiple reviews into one accessible and usable document[38]. These are very common in the medical and public health literature but less so in the environmental and ecological science literature.

The purpose of this umbrella review is to gather evidence on the effects of afforestation and eco-hydrological variables associated with flood risk. The results may help to inform possible mitigation scenarios that will be used in Chapter 5. The key question that I aim to address in this umbrella review is: "***Under what conditions does afforestation lead to the greatest changes in flood risk reduction***?" Additional sub-questions considered are: i) what effect does scale of the intervention (afforestation) have; ii) what effect does the type of planting or tree species have; and iii) what effect does the pre-intervention land cover type have?

Method

Search protocol

A framing exercise defined the boundaries of the study (Table 2.4), specifically using the population, interventions, comparisons, and outcomes (PICO) framework to develop the search strings (Collaboration for Environmental Evidence, 2013; Koricheva et al., 2013).

[38] https://guides.mclibrary.duke.edu/sysreview/types

Table 2.4 The PICO elements to determine the question and scope underpinning the search string and study selection criteria.

Population/ Target (the subject or unit of study)	**Intervention (exposure applied or investigated)**
Included: catchments/watersheds/river basins, landscape scale areas, systematic reviews	Included: tree planting (afforestation, reforestation), natural regeneration
Excluded: small plots, reservoirs, lakes, non-review articles, narrative reviews	Excluded: deforestation, existing canopy, small-scale interventions, sediment load
Comparison (control with no intervention)	**Outcomes (the effect of the intervention)**
Included: unforested land Excluded: deforested land	Included: quantified change in hydrological metrics such as flow regulation, flood control/protection, risk reduction Excluded: perceptions, sediment reduction, qualitative or inferred change in water metrics

Two searches were conducted, one focusing on afforestation and flood or water, and the other incorporating nature-based solutions, ecosystem services and ecosystem-based adaptation to see where forestation may be included in a bundle of interventions. The search terms used are described in Table 2.5. The search was for original articles in English for all dates and was conducted on 21 and 24 July 2021. The search was done using Scopus, Web of Science, and Google Scholar.

Table 2.5 Search terms and exclusion criteria used in two literature searches.

	Search 1	**Search 2**
Search terms	Forest OR "tree planting" *OR* afforestation *OR* reforestation *OR* "forest restoration" *AND* *hydrolog* *OR* water *OR* flood* *AND* review *AND NOT* quality Title only	Nature-based solutions OR NBS OR Ecosystem services OR Ecosystem-based Adaptation AND flood* OR water quantity OR *hydro* OR water yield OR risk reduction AND tree* OR tree planting OR afforestation OR reforestation AND review Title, abstract and keywords Review documents only
Exclusion criteria	Papers that reviewed hydrological variables in response to forest cover loss, such as deforestation or harvesting, were excluded, as were those that dealt with conceptual models or where quantitative values for hydro-physical variables were not synthesised or reported.	

Study Selection/ Screening

The screening protocol is outlined in Figure 2.2. Screening was based on six criteria: tree planting; peer review; review paper; systematic review; flood regulation reporting; and scale.

Initial screening determined if the paper described impacts of forestation, and if it was a peer-reviewed article. Further screening determined if it was a review paper and then whether it was a systematic review or meta-analysis (narrative reviews were excluded). In-depth screening of full papers evaluated whether the papers reported on a synthesised result for an eco-hydrologic value that could be associated with flood regulation as a result of forestation. Further, only studies that reported results at a catchment or landscape scale were included, if it was evident.

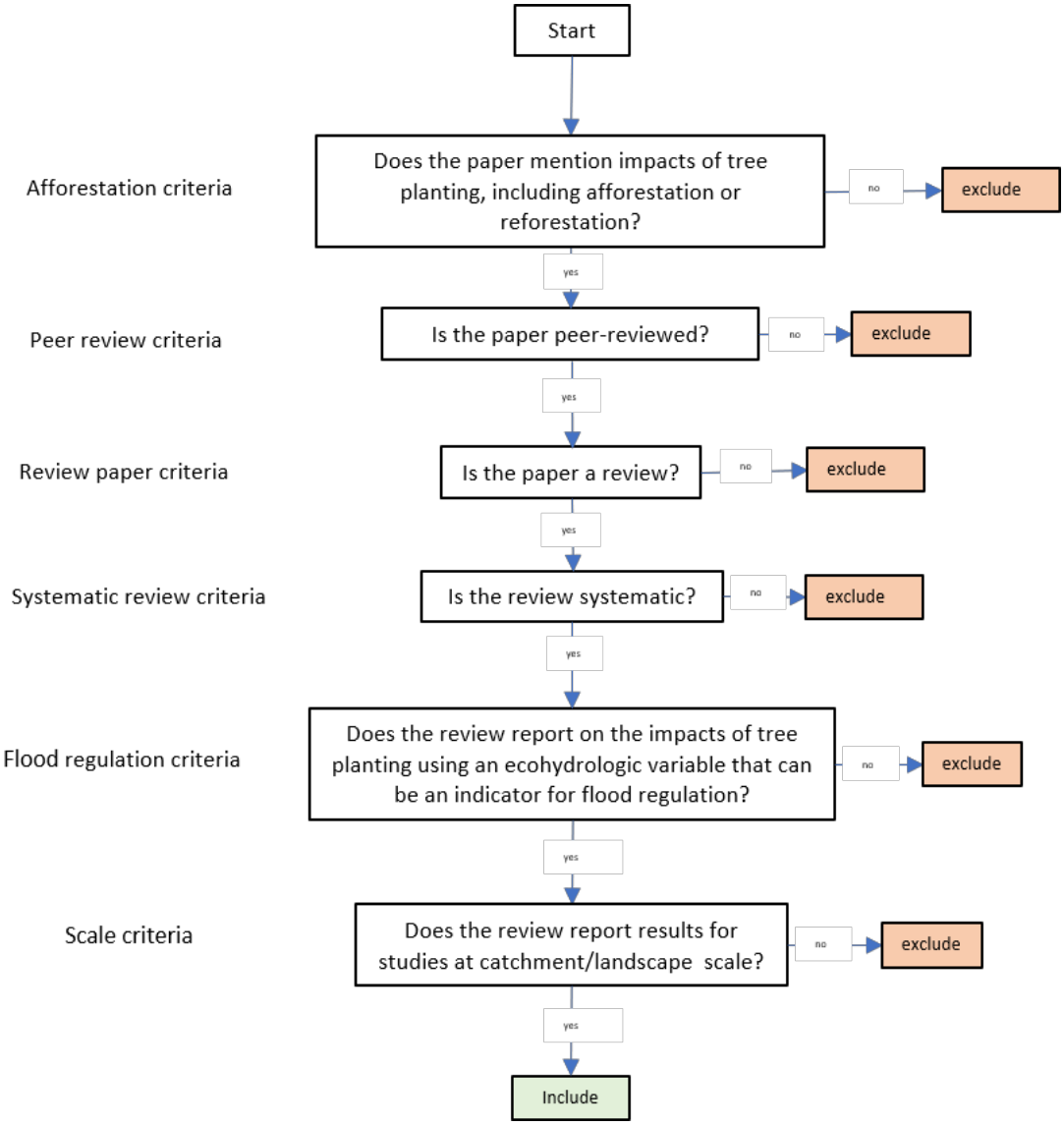


Figure 2.2 Screening criteria based on six criteria: tree planting, peer review, review paper, systematic review, flood regulation reporting, and scale.

Data extraction

Information was collected on the following: the type of review, number of studies included in the review, the geographical region covered, the planting type (afforestation, reforestation, regeneration, mixed etc), the type of vegetation/ land cover present pre-intervention, the hydrological variable reported, the magnitude of the change and whether the outcome would result in flood risk reduction.

Results

Search results

Search 1 returned 41 results for Web of Science, 45 for Scopus and 14 papers were chosen from a Google Scholar search. Search 2 search returned 125 results for Web of Science, and 24 for Scopus. After initial screening, 49 unique papers were selected for further screening. 22 papers were excluded for being narrative rather than systematic reviews. The final full-text screening resulted in eight selected papers, which in turn reviewed 825 papers/studies between them (Table 2.6). The earliest review is from 2005 and the latest from 2021. **Table A1 in Appendix A lists all removed reviews.**

Table 2.6 The final reviews included in this overview with the number of studies covered and the main purpose of their review.

Review paper (first author_date)	Number of studies	Main aim/purpose of the review
Farley_2005	26	Quantified the change in streamflow (runoff and low flow) associated with afforestation of grassland, shrubland and pasture, globally.
Ilstedt_2007	14	Synthesised results on the effects of afforestation in the tropics on soil infiltration.
Zhang_2017	312	Provided a generalised relationship between forest cover change and annual runoff response at multiple spatial scales.
Filoso_2017	167	Provided an assessment of the state-of-the-science regarding the effects of forest cover expansion and restoration on water yields.
Carrick_2018	7	Combined results of existing studies on flood mitigation to evaluate the strength of evidence that tree cover reduces flood risk.
Bonnesoeur_2019	155	Synthesised the consequences of forestation on hydrological services in the Andes.
Lozano-Baez_2019	11	Synthesised the available information on the recovery of infiltration in tropical and subtropical forests restored by tree planting.
Acreman_2021	133	A systematic review of the available evidence for nature-based solutions to water-related risks in Africa.

Topic and geographic distribution of the reviews

The selected papers were divided between either sole systematic reviews (3) or those that combined systematic approach with meta-analysis (3) but also included two meta-analyses (Fig. 2.3a). Three of the reviews took a global scope while the others were regional, focusing on the Tropics or Sub-tropics or continents such as Africa or South America (Fig. 2.3b). One paper was regional in scope focusing on Western Europe (Carrick et al., 2019) and another focused on the Andes region of South America (Bonnesoeur et al., 2019). Four of the eight review papers covered a range of forestation types, including afforestation, reforestation, deforestation and regeneration. Three reviews covered afforestation only, and one paper focused on reforestation only (Fig. 2.3c). A wide range of hydrological variables were utilised in the review with runoff and infiltration variables being the most used (Fig. 2.3d). Some papers focused only on one variable, whilst others looked at multiple hydrological variables, but only those that have an effect on flood risk reduction were captured.

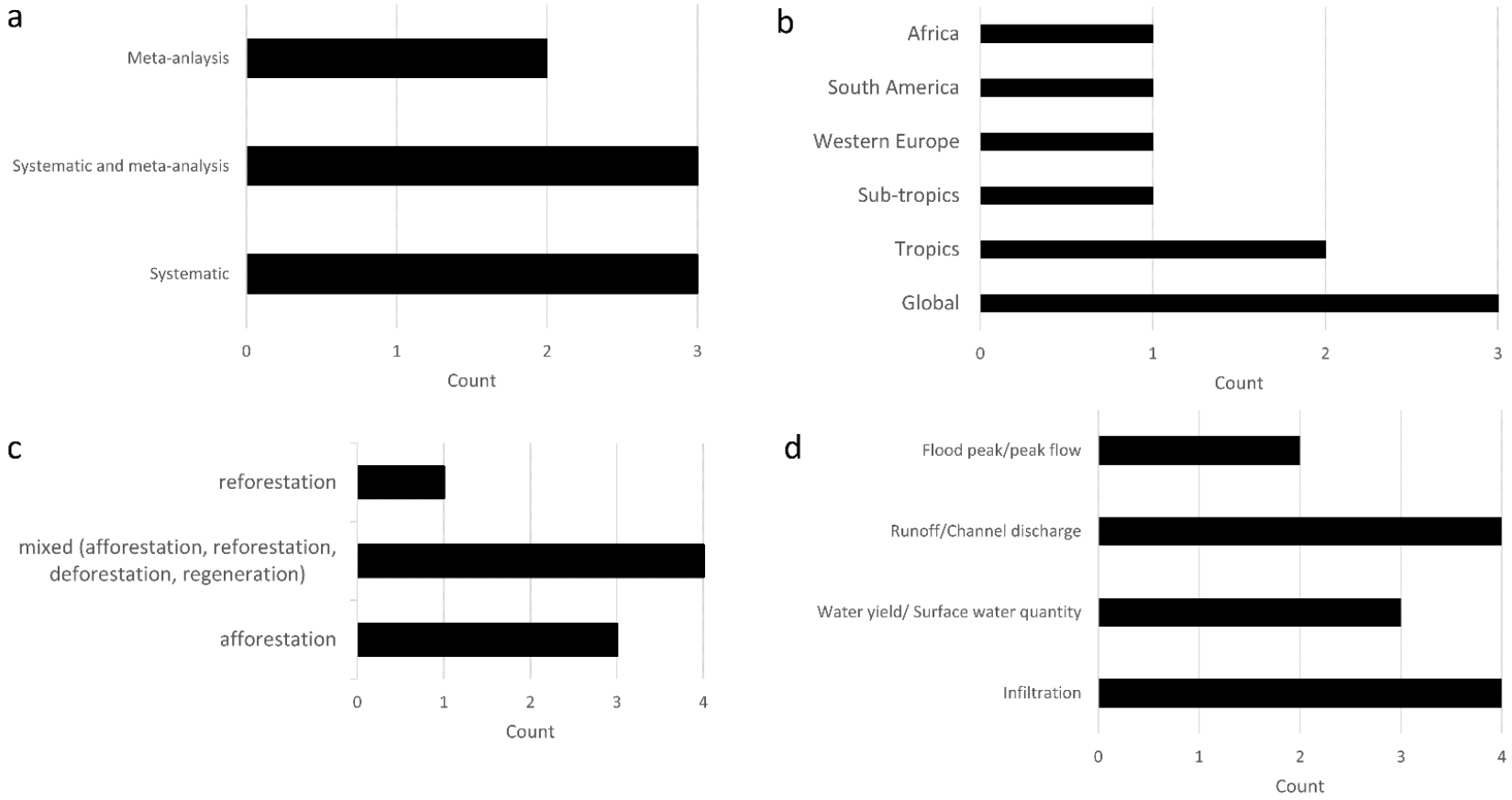


Figure 2.3 The selected review papers summarised in terms of (a) the type of review, either meta-analysis, systematic and meta-analysis, and systematic, (b) the geographic range covered by the review, (c) the type of tree planting covered, whether afforestation, reforestation, deforestation, regeneration or a combination (mixed), and (d) the hydrological metric reported.

Hydrologic variable results and effect on flood risk

Table 2.7 summarises the synthesised results from the reviews on the effect of forestation on hydrological variables directly relating to flood risk, such as runoff, discharge, peak flow and flood peak. If these variables decline, then the inferred assumption is that flood risk will decline. Water yield is a common variable examined in relation to effects of afforestation. It refers to the amount of water available after extraction for resource use. Other variables, such as infiltration, have an indirect influence on flow regulation. The greater the infiltration capacity (the maximum rate at which water soaks into or is absorbed by the soil), the greater the ability to regulate flows. Table 2.8 summaries the results for infiltration.

I have interpreted these direct and indirect variables to indicate whether they would result in an increase, decrease or no change/marginal change in flood risk based on the assumption that: decreases in runoff, flood peaks, peak flows and channel discharge are associated with a decrease in flood risk, while increases in infiltration rate/capacity are associated with a decrease in flood risk and vice versa (Table 2.7 and Table 2.8).

Table 2.7 Hydrological variables of flooding examined in the selected review papers, reported direction of change in the variable after tree-planting, and its interpreted effect on flood risk.

Review paper (author_year)	Variable	Comparator (method and intervention type)	Reported direction of change	Inferred effect on flood risk
Farley_2005	Annual runoff	Paired catchment: aff grassland to current grassland	↓ aff grasslands ↓ aff shrublands	⇩
Zhang_2017	Annual runoff	Pairs, quasi-paired, modelling, statistical: Afforestation, regrowth (in small watersheds) or reforestation and forest cover loss	↓ Large watersheds ↓ Small watersheds	⇩ ⇨
Filoso_2017	Water yield/ channel runoff Peak flow/flooding frequency	Mixed methods: Forest restoration, forestry, afforestation, reforestation, regrowth	↓ 80% of studies ↓ 82% of studies	⇩
Carrick_2018	Channel/river discharge	Experimentation, before/after/control: afforestation/tree planting	- / ↓	⇩
Bonnesoeur_2019	Peak flow	plantation forests, natural forest regrowth, natural regeneration and secondary succession	↓ 100% of studies agreed (to certain rainfall intensity)	⇩
Acreman_2021	Surface water quantity	afforestation (35) and restoration (2)	↓ 91% of afforestation studies ↓ 100% of reforestation studies (2 studies)	⇩
	Flood peak/magnitude		- (variable effects; 4 studies)	⇨

Table 2.8 Hydrological variables of intermediary processes examined in the selected review papers, reported direction of change in the variable after tree-planting, and its interpreted effect on flood risk.

Review paper	Variable	Comparator	Reported direction of change	Inferred effect on flood risk
Ilstedt_2007	Infiltration	Before/after: aff/agroforestry on former agric land	↑	⇩
Filoso_2017	Infiltration capacity	Mixed methods: Forest restoration, forestry, afforestation, reforestation, regrowth	↑ 83% of studies	⇩
Bonnesoeur_2019	Infiltration	plantation forests, natural forest regrowth, natural regeneration and secondary succession	↑ for grazed grassland	⇩
Lozano-Baez_2019	Infiltration		↓ 39% compared to reference forest ↑ 291% compared to agricultural soil ↑ 182% compared to pasture soil ↑ 57% bare soil	⇩

Of the six reviews reporting on direct variables relating to flood risk, all six reported results that are indicative of forestation decreasing flood risk for at least one hydrological variable or situation. Two of the studies had neutral or variable results, the first in small watersheds (Bonnesoeur et al., 2019) and the second, for the flood peak/magnitude variable but for only four case studies (one increase, one decrease and two no effect; Acreman et al., 2021). For the indirect variables, i.e., infiltration, all four studies reported an increase in infiltration capacity or rate, thus supporting the inference of a decrease in flood risk from forestation.

Influence of land use/ vegetation-type on hydrological responses to afforestation

The prior land-use or vegetation type may play a role in the eco-hydrological function after afforestation. Five of the review papers reported the land use/covers prior to forestation or compared different land-uses to afforestation. Only one, Farley et al (2005), explicitly compared different vegetation types prior to, and post intervention. They found that annual runoff reduction was greater when grasslands were afforested (44% reduction) compared to shrublands (31% reduction; Farley et al., 2005). For some papers, it was unclear if the compared effects were between land uses rather than before/after-effects. Lozanao-Baez et al. (2019) reported that restored forests had greater infiltration rates compared to agricultural sites, then pasture then bare soil (but lower rates compared to reference forests). Ilstedt et al.'s (2007) review focused on afforestation on agricultural land (pasture, grassland and permanent cultivation) and found that infiltration capacity increased on average approximately three-fold after afforestation or planting trees in agricultural fields. Bonnesoeur et al. (2019) compared the impact of forestation over grazed grassland to native forests in the Andes. They found that the saturated infiltration rate increased by eight in forestation over grazed grassland but was three times lower than the rate in native forests (Bonnesoeur et al., 2019).

Key message: Infiltration rate increases after forestation of grasslands but not as well as that of native forests.

Effect of tree species type used in forestation

The type of tree species used for forestation, whether native or non-native, broadleaf or conifer, could impact eco-hydrological variables associated with afforestation. Six review papers explicitly reported on the tree type and made comparisons between the tree species/types and their effects on eco-hydrological function.

Farley et al. (2005) found that Eucalypts reduced runoff to a greater extent than Pines in afforested grasslands (75% and 40% reduction respectively). Zhang et al. (2017) compared broadleaf, coniferous and mixed forests in both large and small watersheds. They found that there was significant difference in the sensitivity of annual runoff between coniferous forests and broadleaf-dominated or mixed forests. In large mixed and broadleaf dominated watersheds, 1% forest cover change can result in 0.80% and 0.74% change in annual runoff, respectively, while in large coniferous dominated watersheds, that value is only 0.24%. In small broadleaf and coniferous dominated watersheds, 1% forest cover change can result in 0.73% and 0.71% change in annual runoff, while in small mixed watersheds that value is

only 0.33% (Zhang et al., 2017). Filoso et al. (2017) found in their review that the majority of studies (46%) were based on forest stands of non-native tree species as opposed to native species. They found that all reported forest types showed a reduction in water yield but the magnitude of water yield reduction reported in studies with native, non-native, and mixed forest types varied significantly ($F = 9.76$; $p < 0.001$). Bonnesoeur et al.'s (2019) review found that native forests generated less surface runoff than any other land use type, and both native forests and exotic tree plantations decrease peak flow (except during extreme rainfall events). They concluded that exotic tree plantations may have a slightly lower capacity to buffer peak flow than native forests, as native forests had slightly lower surface runoff and slightly higher soil water storage capacity than exotic tree plantations (Bonnesoeur et al., 2019). Also, exotic tree plantations, and to a lesser extent natural forests, have a lower water yield compared with non-forested land uses in most Andean regions (Bonnesoeur et al., 2019). The studies in Lozano-Baez et al.'s (2019) review indicate that both exotic and native tree plantations on degraded soils positively affected infiltration recovery. Acreman et al.'s (2021) systematic review showed that in 32 afforestation case studies (out of 35) downstream surface water quantity declined. Those studies comprised 30 with non-native species and two studies with mixed forest types. Of the remaining three, two were neutral (unspecified and non-native tree types) and one (unspecified tree type) showed an increase in downstream water quantity. Two reforestation (natural tree regrowth without planting) case studies reported a significant decrease in runoff generation, which continued for 20 years (Acreman et al., 2021).

The differences between native versus exotic tree plantations on other eco-hydrological variables not associated with flood reduction, such as low flow, was also reported in the reviews. Bonnesoeur et al. (2019) found that exotic tree plantations reduce low flow, except in degraded lands, and decrease soil moisture.

Key message: Native forests and broadleaf forests have greater impact on annual runoff change than non-native or coniferous forests.

Effect of catchment size and/or intervention size

Only two of the selected papers explicitly reviewed the effect of catchment size on eco-hydrological responses to afforestation. Zhang et al.'s (2017) systematic review compared large (>1,000 km^2) and small (<1,000 km^2) watersheds. They did not find a statistically significant relationship between forest cover change and annual runoff response in small watersheds, but there was a significant negative relationship between forest cover change and annual runoff response in large watersheds. Overall, they conclude that in small

watersheds, forest type (mixed, broadleaf or coniferous) is the important factor affecting annual runoff response, while in large watersheds, hydrological regime (rain dominated vs snow dominated) is the more important factor (Zhang et al., 2017).

The systematic review by Filoso et al. (2017) found that more than 50% of case studies are from small catchments (<10 km^2), whilst less than 25% of the total number of studies were of large catchments (>1,000 km^2). Their meta-analysis focused on water yield and found no water yield gains in any of the studies but did find that spatial scale was influential. Their results showed a significant inverse correlation between the magnitude of water yield reduction and catchment size. They conclude that the larger the temporal or spatial scale, the smaller the decrease in water yield but caution that the catchment sizes reported in studies "did not necessarily reflect the size of the forest intervention, making it difficult to determine if the scale of the intervention was driving factor determining changes in water yields or if the results were an artefact of differences in the percentage of restored forest cover within the catchments of the studies selected" (Filoso et al., 2017).

Key message: There is a negative relationship between forest cover change and annual runoff response in large watersheds.

Negative effects of afforestation

In the systematic reviews studied, the predominant negative effect of afforestation reported was on low flow and water yield/ water quantity. Farley et al.'s (2005) analysis demonstrated that afforestation of grasslands and shrublands typically results in a loss of one-third to three-quarters of streamflow on average. The lag time between planting and runoff response is also short. They estimate that in a region where natural runoff is less than 10% of mean annual precipitation, afforestation should result in a complete loss of runoff, and where natural runoff is 30% of precipitation, it will likely be cut by half or more when trees are planted (Farley et al., 2005). They caution that afforestation could cause or intensify water shortages in many locations. Zhang et al.'s (2017) review also determined that large-scale afforestation in water-limited environments will inevitably exacerbate water scarcity. Filoso et al. (2017) concluded that in most cases, forest restoration will likely lead to a decrease in annual water yields, baseflow and ground flow, at least for a short time after. Likewise for the Andean region, Bonnesoeur et al.'s (2019) systematic review confirmed that of other global scale reviews: exotic tree plantations, and to a lesser extent natural forests, have a lower water yield compared with non-forested land uses. As with the other papers, the concern is that in dry regions of the Andes, afforestation is likely to worsen water scarcity (Bonnesoeur et al., 2019). In Africa, Acreman et al.'s (2021) review found that more than 70% of case

studies of afforestation show decreases in surface water resource quantity greater than 60%. Several studies also reported a 100% decrease from afforestation. Acreman et al. (2021) states that, “The general trend was for increasing water resource quantity as the percentage of the catchment covered by forests decreases and decreasing water resource quantity as the percentage of the catchment forested area increased. Changes in water resource quantity were generally greater for non-native than for native species.”

Key message: Forestation leads to declines in water yield and could lead to water scarcity in dry regions.

Discussion and conclusion

Assumptions and limitations of this umbrella literature review

More reviews could have been included in this umbrella literature review if deforestation was included in the eligibility criteria. Discounting reviews that used deforestation as the main comparator was deliberate, as the assumption that those papers make is that effects of deforestation are the inverse of tree planting. However, this is a simplification of the eco-hydrological processes that occur after a harvest/cut (Carrick et al., 2018); site preparation, cultivation, drainage, road construction, and logging can prevent the recovery of soil characteristics.

The search terms used did not incorporate ‘regeneration’, ‘rewilding’ or ‘natural flood management’. Including these may have picked up a few more studies, however since the focus of this review is on the use of tree planting and forests as an intervention, it is assumed this will cover ‘regeneration’, which was represented in some of the reviews. The term 'rewilding' doesn't appear to be much used in the forest academic literature, instead, ‘natural regeneration' is the preferred term. ‘Natural flood management’ (NFM) is a UK centric concept that encapsulates a suite of interventions, of which afforestation is one. Although there are papers which review the evidence for effectiveness of NFM practises, including increasing tree cover (for example Dadson et al., 2017), these are not systematic reviews, so were not included. However, many of the findings from Dadson et al. (2017) are referred to in Chapter 3 and do not detract from the findings here.

Focusing on peer-reviewed review articles meant that grey-literature reviews were excluded. An example is Stratford et al.’s (2017) report for the Centre for Ecology and Hydrology (CEH) titled “Do Trees in UK Relevant River Catchments Influence Fluvial Flood Peaks?” This systematic review captured 72 studies that focused on the effects of both increasing

and decreasing tree cover on flood peaks. They found broad support that increasing the amount of tree cover results in a decreasing flood peak (Stratford et al., 2017). However, this was more evident for studies based on model outputs. When the observation-based statements were considered in isolation there remained a majority of statements showing increasing cover to decrease flood peaks but notable numbers supporting the opposite effect or no influence, resulting in no overall significant difference (Stratford et al., 2017). With regard to flood magnitude, all statements that distinguish between small and large flood events indicated that the peak flows of small flood events are reduced by increasing tree cover. However, the majority of statements from observed case studies reported that the peak flows of large flood events are not influenced by the presence or absence of trees in the catchment (they note this is based on a small number of case studies). As with Filoso et al. (2017), they also remark on the paucity of 'observed' studies examining the effects of tree cover on large flood peaks and in large catchments, to test and validate models.

Water yield was a commonly used metric in the selected review papers, but it was not often properly defined and was sometimes used interchangeably with other variables, such as runoff. In other instances, water yield seemed to refer to water supply available for human use but with no description of how this was measured.

In conclusion, this umbrella literature review has found that all the systematic review papers selected were in agreement on the direction of change for the hydrological variables they selected, and that these are indicative of forestation resulting in reduction of flood risk. Importantly, there were key patterns to the conditions in which this effect was stronger. For example:

- Infiltration rate increases after forestation of grasslands but not as well as that of native forests.
- Native forests and broadleaf forests have a greater impact on annual runoff change than non-native or coniferous forests.
- There is a negative relationship between forest cover change and annual runoff response in large watersheds.
- Forestation leads to declines in water yield and could lead to water scarcity in dry regions.

2.3.2 Spatial prioritisation criteria for forestation interventions

Whether positive or negative, it is known that afforestation has highly site-specific impacts on water resources, water management, soil and land conservation, biodiversity, and/or food security, which are dependent upon climate, soil types, topography, land uses, population densities, existing infrastructures, and trade-offs with coexisting demands for water (Trabucco et al., 2008). It is thus important to carefully plan where to place forestation interventions so that they provide maximum benefit (for multiple ecosystem services) without causing unintended harmful impacts. This requires balancing multiple ecological and social goals to prioritise where to increase tree cover regionally and globally (Holl and Brancalion, 2020).

Below, I gather and summarise a sampling of the best recommendations from the literature on forestation placement.

Recommendations for forestation placement:

- FLR initiatives across the Andes should prioritise degraded soils in order to optimise societal benefits (Bonnesoeur et al., 2019). i.e., focusing on land that cannot produce high agricultural yields whilst regenerating soils and reducing soil erosion.
- Tree plantations must be avoided on páramo and puna grasslands (even if degraded), and restoration of native grassland should be preferred given the excellent water supply, hydrological regulation and erosion mitigation of these grassland ecosystems (Bonnesoeur et al., 2019).
- Avoid planting any trees, whether native or not, in areas not naturally forested, e.g. in grasslands, or savannas. Doing so would not meet the IUCN definition of a nature-based solution as it could have negative impacts on biodiversity (Acreman et al., 2020).
- In plantation landscapes, to mitigate reduction of water supply to downstream users, a system of mosaic management of tree plantation and native forests and grasslands can be adopted across the landscape (Bonnesoeur et al., 2019; Ferraz et al., 2013). In other words, it is best not to forest entire catchments upstream of dams or cities.
- Plant multiple tree species. Higher levels of multiple ecosystem services are found in forests with more tree species (Gamfeldt et al., 2013).
- Avoid land that is currently used, or in the future could be used, for food production. Large-scale afforestation requires land that is most likely also needed to provide

other land-based services such as food production, which may affect food security (Doelman et al., 2020).

- Position in the catchment: Riparian and floodplain woodland is found to be particularly effective at reducing peak flood magnitude (Broadmeadow & Nisbet, 2004; Burton et al., 2018; Dixon et al., 2016).
- Consider the type, duration, and intensity of land-use prior to forest restoration. Land-use history has a great influence on infiltration recovery after tree planting (Lozano-Baez et al., 2019).
- Aim to maximise biodiversity recovery. Restoring biodiversity facilitates other objectives, such as carbon sequestration, ecosystem services and socio-economic benefits (di Sacco et al., 2021).
- When selecting appropriate areas for reforestation: Avoid previously non-forested lands, connect or expand existing forest, and be aware of displacing activities that will cause deforestation elsewhere (di Sacco et al., 2021).
- Whenever possible, follow the forest planting hierarchy:
    1. Protect primary forests and their biodiversity.
    2. Ecological restoration of degraded forests. It has been demonstrated that, in the long term, restored native forests maximise biomass and capture far more carbon while conserving biodiversity (Díaz et al., 2009; Lewis et al., 2019).
    3. Regenerate forests naturally where they have been cleared. Site next to primary forest patches.
    4. Tree planting schemes must not displace local communities, food production or ecological restoration efforts. Mass tree planting may cause some soil erosion or compaction in the short term, whereas natural regeneration may avoid this issue (Acreman et al., 2021).

Based on the above, I have summarised the type of land cover and/ or land use to either avoid or target when creating spatial prioritisation criteria for tree planting (Table 2.9).

Table 2.9 Land to avoid, and land to target, for forestation placement.

Avoid this land	Target this land
Land used for food production	Degraded forests (for restoration)
Non-forested biome such as grassland, savanna, non-forested wetland or peatland	Previously forested
Dry and water scarce areas	Adjacent to existing primary forest
Land for human habitation/ urban expansion	Degraded soils

Part two: Data and methodology

Part two of this chapter provides the background on the methodical strategy used to answer the research questions. It introduces hydrological models, ecosystem service models, basics of climate modelling, the *WaterWorld* model, and provides a rationale and brief description of the basins investigated in this thesis.

2.4 Hydrological models and modelling

2.4.1 Differences between observed and modelled data

Data can be divided into 'empirical' and 'virtual' data (Franke, 2023). Empirical data consists of two major variants: observational and experimental. Observational data is data gathered by observing and recording what happens passively. Experimental data is data recorded in a strict regime of manipulation-and-observation, i.e., a scientific experiment. Virtual data is often data obtained from computer simulation studies, or data generated as predictions of a model, which we can use to test whether that model is any good (Franke, 2023). In hydrological studies, observational data is collected by 'instrumenting' a catchment. This involves placing devices to measure variables into the physical environment and recording the measurements over time. The instruments are often expensive and subject to malfunction meaning that often only small catchments are experimentally instrumented in detail. Large catchments are usually gauged with some kind of discharge measurements (but little else).

Thus, to study large catchments or many catchments at a time, over spans of time, requires using computer models to simulate physical processes, generating so-called 'virtual data'. This modelled or virtual data comes with its own inherent shortcomings. They are simplifications of the real-world and the outputs will always be inaccurate even if the assumptions and input data reflect, or are at least representative of, conditions believed to be true (Loucks et al., 2005). Differences between model output and observed values can result from either natural variability, and/or by both known and unknown errors in the input data, the model parameters or the model itself (Loucks et al., 2005), resulting in different types of 'uncertainty'.

2.4.2 Hydrological models

To address the research aim for this thesis, "*to examine the potential of current natural infrastructure (NI) to mitigate flood risk now and under scenarios for climate change and NI restoration*", and the associated objectives, requires the use of a hydrological model that

includes the capability of implementing scenarios of land use and climate change. A number of hydrological models exist for a range of temporal and spatial resolutions. The choice of model is therefore highly dependent on the application. Spatially distributed models allow for simulation of land use changes and use of spatially distributed data, such as remotely sensed data, which has the advantage that these models are easier to implement in ungauged basins. Another important distinction between hydrological models is whether they are transient (i.e., dynamic) or equilibrium (i.e., static) models. Dynamic models use time series data and update at every time-step, whereas equilibrium models calculate a state for a given time-period. For the modelling carried out in this thesis, only equilibrium models have been considered since the focus is on the relative change between a future period and a baseline period.

Table B1 in Appendix B gives an extensive overview of some of the most widely used, spatially distributed hydrological models and ecosystems service models, and their main characteristics. Most models tend to be either primarily hydrological in function or ES focused, but not both. Although some hydrological models have been adapted to quantify and visualise water-related ES. Vigerstol & Aukema (2011) compare examples of two classes of models for freshwater ecosystem services: SWAT and VIC, as examples of traditional hydrological models, and InVEST and ARIES, as ES specific models. They compared key inputs, outputs, services modelled, usability, and interpretability. They conclude that hydrological tools give more detail, but ecosystem services tools are more accessible (Vigerstol & Aukema, 2011). A selection of models is summarised in Table 2.10 (but see Table B1 in Appendix B for more detail and examples).

Table 2.10 Summary of the type, description, pros and cons of different hydrological and ES models.

Model	Type	Description	Pros	Cons
SWAT	Traditional hydrological	Continuous-time, semi-distributed, process-based river basin model. Outputs describe water movement from evapotranspiration to subsurface flow to volume of water applied for irrigation. Also detailed output on movement of nutrients through a watershed.	Long term trends. Users can specify land management practices.	Requires detailed data inputs, time to learn the model, & expertise in hydrology. Not for onetime events.
VIC	Traditional hydrological	Large-scale gridded hydrologic model. Where water yield and stream flow are main variables of interest. Model estimates water movement between the atmosphere, ground surface, soil layers and subsurface by precipitation, evapotranspiration, infiltration and runoff. ES: Water yield	Most appropriate for large river basins. Used for studying the effects of climate changes on streamflow generation	Less useful for comparing across several services. Not intended for study areas smaller than a river basin.
InVEST	ES specific	Models and maps a suite of ES across the landscape to elucidate general patterns and changes in ES caused by land cover changes or climate change impacts. Simple (tier 1) and complex (tier 2) models. Freshwater ES: nutrient filtration, hydropower, irrigation, avoided reservoir sedimentation, storm peak mitigation.	Trade-off scenarios. Examining changes in ES provision under different land use changes. Relatively quick assessment of services across the landscape.	Inability to account for seasonal or sub-seasonal variability, groundwater and water resource infrastructure that redistributes water flow.
ARIES	ES specific	Allows users to evaluate trade-offs between ES and to identify hidden stakeholders who may benefit from services within area of interest. ES: flood control, sediment regulation, subsistence fisheries, salmon yield, nutrient filtration, water supply, and several non-water related services.	Visualising ecosystem service dynamics. Trade-offs. Flow characteristics between provider and user. Can generate scenarios to explore changes in ES provision and use based on changes in ES supply or demand. Climate change scenarios.	Lack of transparency of the model code due to complexity. Very data demanding.
WaterWorld	Traditional hydrological	A spatially explicit, physically based global model for water balance. Capable of producing a hydrological baseline representing the mean water balance for 1950–2000 and allows users to apply ensemble scenarios for climate change or land cover change. NI metrics.	Well suited to heterogeneous environments with little or no available data. All data contained within, so no need for external data input.	Poor or no documentation for many features.

To decide on the most suitable model(s) to be answer the research question, the following criteria and considerations were taken into account:

- The model should be spatially distributed and include upstream-downstream links in order to simulate land cover changes;
- The model has to be able to simulate the impacts of changes in climatic conditions and be applicable in un-gauged basins, so a purely empirical rainfall/ runoff model would be inappropriate;
- For the purposes of this study, a monthly time-step is sufficient since our focus is long-term flood risk not short-term flood dynamics; and
- The model should allow for easy implementation of land use and climate change scenarios.

I have chosen to use the *WaterWorld Policy Support System* (PSS)[39] (Mulligan, 2013b) as it meets all the criteria above, and due to its ability to undertake all four tasks of hydrological modelling, ES modelling, climate modelling and land use/ cover change within the same modelling platform. I describe *WaterWorld* in more detail in Section 2.7.

2.5 Ecosystem services models and modelling

2.5.1 Methods for modelling and mapping ecosystem services

Ecosystem services (ES) are assessed at different stages: i) by measuring generation of ecosystem processes, ii) by quantifying the magnitude of attributes or intermediate service levels and, iii) by assessing the amount of final service benefit (Brauman et al., 2007).

A quantitative review that focused specifically on urban ES found that various models are used to value ES demand and provisioning. These include biophysical, empirical, GIS-based, statistical and survey-based models and less widely applied approaches such as qualitative studies, causal loops and look-up tables (Haase et al., 2014). GIS-based models are useful for demand and provision analyses because spatial data, such as land cover and land use data, can serve as an indicator for estimating quantities of the particular urban

[39] http://www.policysupport.org/waterworld

ecosystem services associated with vegetation types, soil and other landscape features (Haase et al., 2014).

Important factors to consider in mapping of ecosystem services are: i) scale: local, regional, national or global, ii) resolution, iii) type and number of ecosystem services, iv) uncertainty, v) stakeholders - ES providers, ES receivers and intermediaries (Pagella & Sinclair, 2014), and vi) synergies and trade-offs. The inconsistency in methods to quantify and map services has led to criticisms and calls to standardise a methodological approach for quantifying and mapping ecosystem services (Bagstad et al., 2013; Crossman et al., 2013; Martínez-Harms & Balvanera, 2012; Seppelt et al., 2012).

Examples of studies that have mapped and modelled hydrologic ecosystem services

A number of studies have mapped flood mitigation/ regulation within the ecosystem services framework. The studies tend to examine a number of ecosystem services simultaneously, use a wide range of indicators from land cover/ land use types to biophysical factors such as slope and elevation, and at many spatial scales. **I summarise a range of studies at large scales, from regional to global, with a focus on the methods used in Table B2 (Appendix B)**.

2.5.2 Ecosystem modelling tools

The growth in the field of ecosystem services has resulted in a large variety of decision-support tools to support more systematic ecosystem services assessment. The tools differ in their approaches to economic valuation, spatial and temporal representation of services, and incorporation of existing biophysical models (Bagstad et al., 2013).

Choosing which tool to use can be challenging. Some studies have evaluated tools by comparing them against set criteria (Bagstad et al., 2013) and others by running them for the same study site and comparing the results (Bagstad et al., 2013; Dennedy-Frank et al., 2016; Sharps et al., 2017). In a comparison of 17 ecosystem services tools against eight evaluative criteria, Bagstad et al. (2013) reports that most tools are currently too resource intensive for routine use in public- and private-sector decision making. In the same paper, they apply five spatially explicit modelling tools – InVEST, ARIES, EcoAIM, EcoMetrix, and ESValue – to the same study area. The results were too incomparable to draw direct

quantitative comparisons, particularly about whether the tools "agreed" on the relative impacts of development at alternative sites (Bagstad et al., 2013). Dennedy-Frank et al. (2016) compared annual water yield using InVEST and SWAT for two catchments in the United States. They found that the models provided similar estimates of the spatial distribution of water yield in one catchment, but very different estimates of the spatial distribution of water yield in the other, probably due to the differences in baseflow contribution in the two sites and the fact that InVEST doesn't measure storage dynamics (Dennedy-Frank et al. 2016). In the study by Sharps et al. (2017), comparing ARIES, InVEST and LUCI, they found that the modelling tools provided broadly comparable quantitative outputs, but that each has its own unique features and strengths, and therefore the choice of tool depends on the study question.

2.6 Modelling climate change

Global Circulation Models (GCMs)

Climate change is modelled using Global Circulation Models (GCMs). GCMs are complex mathematical representations of the major climate system components and their interactions. They were originally built using fundamental equations of physics to account for the conservation of energy, mass, and momentum and how these are exchanged among different components of the climate system (Randall et al., 2007). GCMs have increased in complexity over time and today simulate many aspects of the climate system, such as atmospheric chemistry and aerosols, land surface interactions including soil and vegetation, land and sea ice, and increasingly even an interactive carbon cycle and/or biogeochemistry (Hayhoe et al., 2017; Randall et al., 2007). GCMs use scenarios (such as representative concentration pathways (RCPs), see below) as input to produce trajectories of future climate change, including global and regional changes in temperature, precipitation, and other physical characteristics of the climate system.

Coupled Model Intercomparison Project - CMIP

With the ever-increasing power in computing, the number of GCMs incorporating an expanding number of earth-system processes and greater spatial resolution has increased. The results of individual climate model simulations using the same inputs can differ from each other over shorter time scales ranging from several years to several decades. These differences are the result of normal, natural variability, as well as the various ways models characterise various small-scale processes(Hayhoe et al., 2017). Some models perform better than others for certain regions or variables. With so many institutions and modelling

centres producing models, comparing them can be difficult if they have not been set-up in a systematic way using agreed-upon protocols. The differences may be because the models are different or because they were set up in a different way. To address this, the Coupled Model Intercomparison Project (CMIP) was set up to provide a framework for climate model experiments, allowing scientists to analyse, validate and improve GCMs in a systematic way[40].

CMIP falls under the direction of the Working Group on Coupled Modelling, as part of the World Climate Research Program[41]. To date, there have been six large model intercomparison projects coordinated by CMIP. Most have been extensively used in the Intergovernmental Panel on Climate Change (IPCC) assessment reports. CMIP5, was used in support of the 5th assessment report (AR5) of the IPCC, published in 2013 and 2014. CMIP6, was used in support of the 6th assessment report (AR6) of the IPCC, published in 2021. This thesis uses the models from CMIP5.

Downscaling

The spatial scales used and outputted by GCMs (200 km to 300 km) do not allow us to understand the regional detail of climate change at local scales. Downscaling is the process of taking the information from large scales to output able to make predictions at local scales. Downscaling approaches are either dynamical or statistical. Dynamical downscaling requires running high-resolution climate models on a regional scale (higher spatial resolution), using observational data or lower-resolution climate model output as a boundary condition[42]. These models are often called Regional Climate Models (RCMs). These models use physical principles to reproduce local climates but are computationally intensive. Statistical downscaling is a two-step process consisting of, i) the development of statistical relationships between local climate variables (e.g., surface air temperature and precipitation) and large-scale predictors (e.g., pressure fields), and ii) the application of such relationships to the output of global climate model experiments to simulate local climate characteristics in the future[43].

Scenarios - representative concentration pathways (RCPs)

The climate change scenarios used in this study are representative concentration pathways (RCPs) developed for AR5 and used with the CMIP5 ensemble of GCMs (see above). The RCPs are not emissions scenarios; they are radiative forcing scenarios. These pathways are

[40] https://www.carbonbrief.org/qa-how-do-climate-models-work

[41] https://www.wcrp-climate.org/wgcm-cmip

[42] https://climatefutures.org.au/projects/what-is-downscaling/

[43] https://gisclimatechange.ucar.edu/question/63

defined in terms of the concentration (i.e., the level) of carbon in the atmosphere, not the volume of carbon emissions (van Vuuren et al., 2011). The four RCPs are numbered according to the change in radiative forcing (from +2.6 to +8.5 watts per square metre) that results by the year 2100 (Fig. 2.4; van Vuuren et al, 2019). Each scenario consists of a specific radiative forcing projection and makes assumptions about future population, GDP, energy use, land use/cover change etc. based on the radiative forcing. The scenarios include one mitigation scenario leading to a very low forcing level (RCP2.6), two medium stabilisation scenarios (RCP4.5/RCP6) and one very high baseline emission scenario (RCP8.5) (Fig. 2.4; van Vuuren et al., 2011). RCP 8.5 is considered to be the 'worst-case' scenario however in many studies it has been used as the 'business-as-usual' scenario, although there is some debate about the accuracy of this assertion (Hausfather & Peters, 2020; Schwalm et al., 2020).

In terms of land use/ cover change, the RCPs cover a very wide-range of land-use scenario projections, such as increases or decreases in cropland and grassland due to factors such as, global population changes, bio-energy production, reforestation programs, etc. (van Vuuren et al., 2011). However, these projections will be very coarse. This study did not incorporate any additional future LUC assumptions for the specific study basins, besides the LUC projections incorporated within the RCP scenarios.

For this study, RCP 4.5, RCP 6.0 and RCP 8.5 were used; RCP 2.6 was excluded as it was deemed unrealistic to achieve and because we are interested in highlighting areas of high/ increased impact. Table 2.10 lists the climate models used for each RCP scenario as part of CMIP5 in the *WaterWorld* modelling platform.

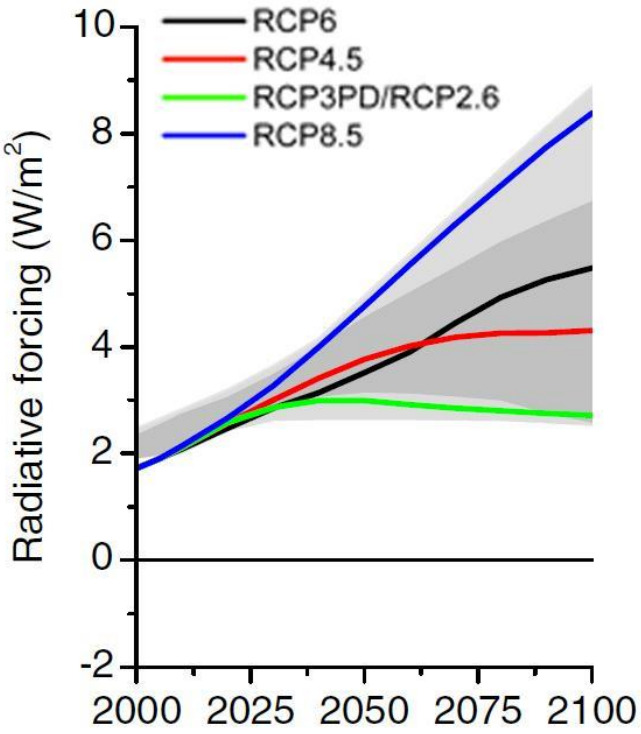


Figure 2.4 Radiative Forcing of the Representative Concentration Pathways (from van Vuuren et al., (2011)).

Table 2.10 The CMIP5 climate models used for RCP 4.5, 6.0 and 8.5.

CMIP5 climate models	RCP 4.5	RCP 6.0	RCP 8.5
IPSL_CM5A-LR Institut Pierre Simon Laplace	x	x	x
GFDL-ESM2G Geophysical Fluid Dynamics Laboratory	x	x	
MIROC5 Atmosphere and Ocean Research Institute (The University of Tokyo)	x	x	x
MIROC-ESM Japan Agency for Marine-Earth Science and Technology et al.	x	x	x
GISS-E2-R NASA Goddard Institute for Space Studies	x	x	x
MIROC-ESM-CHEM Japan Agency for Marine-Earth Science and Technology et al.	x	x	x
BCC-CSM1 Beijing Climate Center, China Meteorological Administration	x	x	x
HadGEM2-ES Met Office Hadley Centre	x	x	x
CCSM4 National Center for Atmospheric Research	x	x	x
NorESM1-M Norwegian Climate Centre	x	x	x
HadGEM2-AO National Institute of Meteorological Research/Korea Meteorological Administration	x	x	x
MRI-CGCM3 Meteorological Research Institute	x	x	x
MPI-ESM-LR Max Planck Institute for Meteorology (MPI-M)	x		x
CNRM-CM5 Centre National de Recherches Meterologiques	x		x
INMCM4 Institute for numerical Mathematics	x		x
HadGEM-CC Met Office Hadley Centre	x		x
ACCESS1-0 CSIRO (Commonwealth Scientific Industrial and Research Organisation, Australia) and BOM (Bureau of Meteorology, Australia)	x		x
CESM1-CAM5-1-FV2-Centre National de Recherches Meterologiques	x		
GFDL-CM3 Geophysical Fluid Dynamics Laboratory GFDL-ESM2G	x		x
Total	**19**	**12**	**17**

2.7 The WaterWorld Policy Support System

2.7.1 How it works

WaterWorld v2.92 (V2) was used for the research in this thesis. The *WaterWorld Policy Support System (PSS)* is a web-based water resources, ecosystem services and flood risk policy support tool that can be used to test the consequences of implementing land and water related policies on these aspects of hydrology. The system can be applied anywhere globally with all data provided by the system and runs on either 1-square km or 1-hectare resolution using an extensive global detailed spatial database and spatial models, as well as scenario generating tools for climate, land use and land/ water management change. The underlying hydrological model in the system is the FIESTA model (Mulligan & Burke, 2005) which is a spatially explicit model designed to calculate a water balance, and particularly well suited to data poor environments and incorporating many aspects not well represented in other models. Specifically, physically based representations of wind driven rainfall, cloud water interception, snow and ice and land cover and vegetation functional type dependent actual evapo-transpiration (ET). The model uses some 140 input data layers which include terrain (SRTM, Farr & Kobrick, 2000), climate (WorldClim, Hijmans et al., 2005) and land cover (either Landsat or Sentinel Hansen et al., 2006; Mulligan, 2013a, 2021). Climate variables are incorporated as long term (50 year) monthly means and a water balance is calculated for a total of 48 time-steps for twelve months, with four time-steps in each month representing a typical diurnal cycle. Finally, the water balance is accumulated downstream along a stream flow network to obtain potential runoff (refer to the V2 model documentation for the full detail; (Mulligan, 2013b, 2022). See Figure 2.5 for a conceptual representation of how the water balance model in *WaterWorld* works.

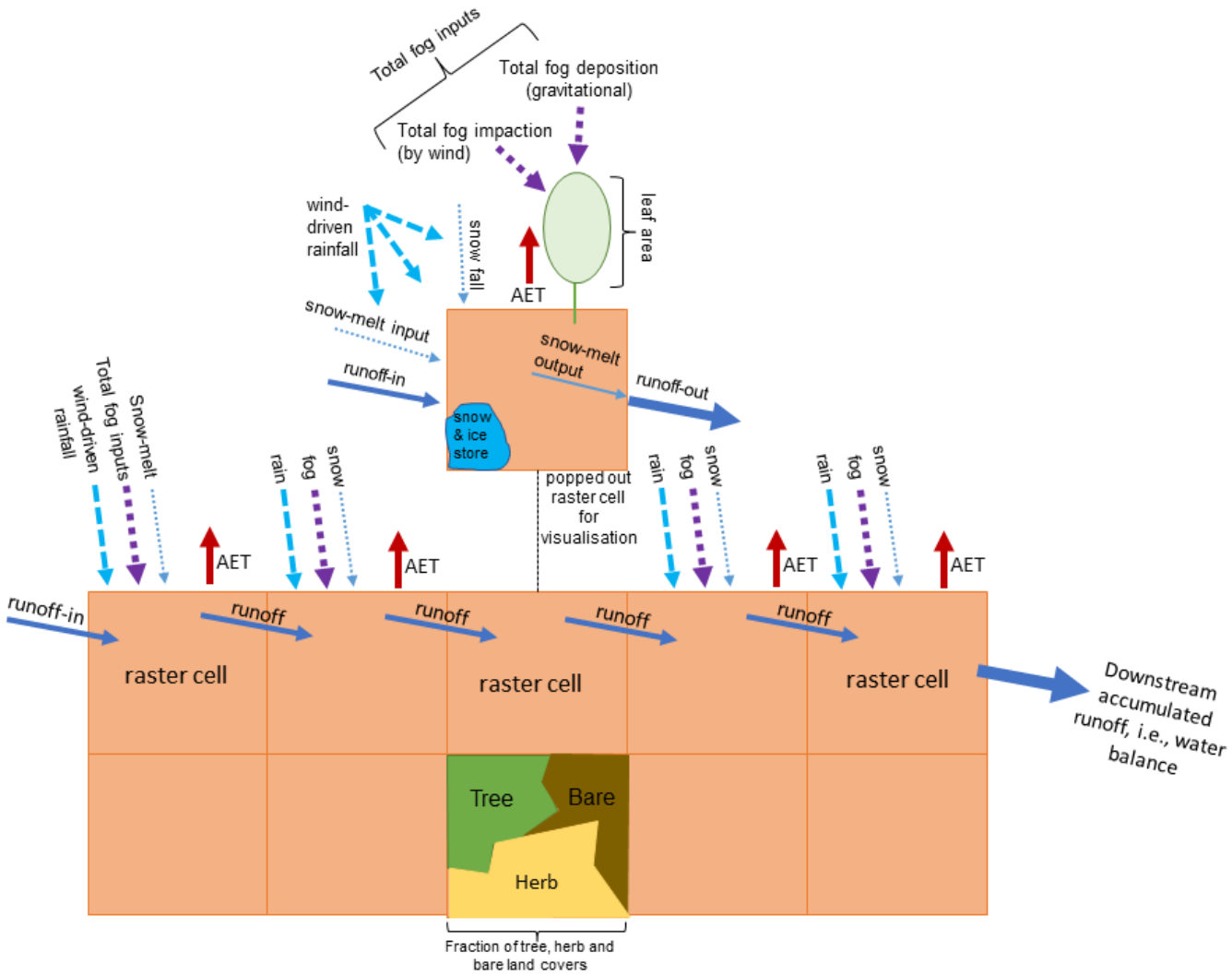


Figure 2.5 Conceptual representation of the WaterWorld water balance model. Mulligan (2013b) describes the process as follows: WaterWorld is a raster-based model that calculates inputs of wind-driven rainfall and fog, combines these with an energy driven assessment of potential evapotranspiration (PET), then modifies PET by the available leaf area to calculate actual evapotranspiration (AET). Wind-driven rainfall plus fog (Cloud Water Interception – CWI) inputs minus AET determines the water balance. This can be cumulated downstream using a drainage direction network calculated by the system globally from the hole-filled 1 km SRTM or the 90 m SRTM data using the D8 algorithm. Each raster cell of the model is split into tree, herbaceous and bare For each month, wind speeds are corrected for topographic exposure and the wind speed in each cell determines the proportion of rainfall that falls as direct vertical precipitation and the proportion that is wind-driven, falling at an angle with respect to the terrain and thus having greater inputs to windward slopes than leeward ones. Fog is present if the lifting condensation level occurs at ground level (according to atmospheric vapour pressure and temperature lapse rates) and at a frequency each month determined by the MODIS observed cloud frequency for the month and time of day. Where fog is present, the wind speed also determines the proportion of fog that falls under gravitational processes as fog deposition (which occurs to all leaf areas) versus the proportion that is driven onto vegetation by wind as fog impaction which tends to occur on wind-exposed surfaces only. WaterWorld V2 has snow input, surface snow and ice store and snowmelt added to runoff.

WaterWorld can carry out detailed and process-based analysis of hydrological services. The V2 hydrological modelling is focused on above ground hydrological fluxes such as precipitation (rainfall, fog input), ET and water balance. Though *WaterWorld V3* incorporates subsurface hydrology, it was not used in this study as for much of the research period, it was still in beta. The *WaterWorld V2* model is also capable of estimating Cloud Water Interception (Fog Water Inputs). *WaterWorld* uses monthly and diurnal datasets of mean precipitation, temperature, relative humidity, sea level pressure, wind direction and cloud frequency to quantify total hydrological inputs and outputs. The model calculates monthly and annual total average rainfall (wind-corrected), fog input, ET rates and the water balance. To calculate actual ET rates of different land cover types, the model also uses data on net radiation, topography, and cloud frequency.

Since the research is exclusively focused on water related ESs, the process-based model is essential to understand the marginal change in hydrological attributes. *WaterWorld* is provided with the best available, and high-resolution datasets which makes application rapid, and the models can be used to assess an ES baseline but also to apply various plausible scenarios for land use, land management and climate change.

2.7.2 Verification and validation

Key aspects of *WaterWorld* have been verified and validated by the modelling team in several studies (see Bruijnzeel et al., 2011; Mulligan & Burke, 2005) and has been applied and tested widely throughout Latin America and parts of tropical Africa and Asia. Mulligan & Burke (2005) tested ET estimates against measured field data for montane forest and pasture sites. These indicated agreement within 1.4% of AET for the pasture site and 10.4% for the more spatially variable forest site. Bruijnzeel et al. (2011) tested the wind driven rain and CWI components relative to field data at 15 sites throughout the tropics with good agreement, particular at low wind speeds. They found that at high wind speeds it is impossible to separate the fog and wind-driven rainfall components in measured canopy water balances since canopies capture wind driven rain in very different ways to raingauges (Bruijnzeel et al. 2011) and thus validation of CWI becomes difficult. Mulligan & Burke (2005) also tested catchment-scale modelled accumulated water balances (runoff) against flows recorded in the GRDC database for 17 catchments covering more than half of Costa Rica, with climates varying from hyper-humid in the Atlantic to semi-arid in the Pacific north-west areas of the country. For catchments with high quality rainfall data the model performed well

but for some others, although the model results and the flow data were in general agreement, the model would underestimate measured flows, especially in highly exposed areas with few raingauges and would overestimate flows in dry, cloud-free lowlands. Mulligan (2013b) summarises that given the uncertainties in the input datasets, particularly rainfall and also in the validation runoff dataset, it is difficult to say to what extent the uncertainty in these (un-calibrated) model results arises from uncertainties in input data, or uncertainties in model structure, or uncertainty in the runoff estimates of the validation dataset. This is a common challenge with large scale modelling (Mulligan 2013b).

Some newer metrics, such as the natural infrastructure flood metrics may not be 'validatable' at the global scale since they model properties that are not necessarily field-measurable at the landscape scale (e.g., flood risk mitigation by natural infrastructure) and may not necessarily correspond with in-situ measurable quantities, such as flood frequency since flood frequency depends on other factors than mitigation by natural infrastructure.

2.7.3 Uncertainty and sensitivity

There are three versions of the *WaterWorld* model (versions 1, 2, 3) each with increasingly sophisticated process modelling. It is possible to run any of the three and compare model structural uncertainty. There are also alternative maps for many of the input data layers (land cover, climate, etc). The same analysis can be run with these and compared for input data uncertainty. A variety of scenarios or policy options can be easily run to understand scenario/policy option trends and uncertainty. The *WaterWorld PSS* also has a sensitivity analysis function to understand sensitivity of outputs to unit change in inputs and allows the user to examine values at the pixel, zonal or map scale, including the changes to input and intermediate values that determine a change in output.

A sensitivity analysis was carried out on the Natural Infrastructure (NI) input parameters to see how changing these by set amounts changed the results for the total storage capacity generated. **These results are presented in Appendix C.** They show that small changes in the input parameters change the output in an expected manner, and will not significantly alter the qualitative findings of this thesis.

2.7.4 Natural Infrastructure metrics as flood risk indicators

The Natural Infrastructure (NI) metrics are a feature of *WaterWorld* aimed at providing a type of flood risk/hazard indicator based on the water storage capacity of natural landscape features, i.e., NI, relative to the accumulated annual runoff. The NI metrics were incorporated into *WaterWorld* in 2014/15 and the work of this thesis is the first extensive use and 'road-testing' of the metrics, other than that done by the developer. They are fully described in the documentation for the model (Mulligan, 2016) and in Chapter 3, which is a published journal article (Gunnell et al., 2019).

The NI metrics in *WaterWorld* differ to typical flood risk and hazard maps, such as those described in Chapter 1 (Section 1.3.2), in many ways. The main difference is that the NI metrics are based on natural water storages (such as canopy, soil, wetland, floodplain and waterbody) and are not event based, so do not calculate flood risk based on magnitudes or intensities or frequencies or probabilities of rainfall events. They also do not account for previous flood events or inundation extents. However, their purpose is different. The NI metrics do not aim to forecast flood events or hazard zones but rather use the ecosystem service approach to show where in the landscape there is a sufficient or deficient supply of natural water storage capacity to account for the runoff generated from rainfall on an annual basis. This will allow land managers to plan where to enhance or install new NI for the purpose of flood risk mitigation.

The advantage of these NI metrics, and their application via *WaterWorld*, is that the data input requirements, computer processing power, and modelling expertise required are greatly reduced compared to that needed for traditional flood hazard/risk mapping, thereby making the metric easier to generate output and more accessible.

A limitation of the approach is that it does not account for urban drainage systems and is thus unsuitable to use in urban areas. In addition, the floodplain storage does not consider areas where the floodplain is disconnected from the watercourse, usually through the use of dykes and levees. This will mainly be an issue in built-up areas. This may be difficult to deal with at coarse resolutions but may be accommodated by setting the floodplain storage to 0 (in the input box of the model) where this is known to be the case.

2.8 Study-basins

In this section, I describe the rationale for my choice of study basins and provide a summary of key economical, population and geographical information for each country and city of choice.

The six river basins[44] investigated in this thesis are upstream of the cities of Bogotá in Colombia; Chennai in India; Guayaquil in Ecuador; Jakarta in Indonesia; London in the United Kingdom; and Nairobi in Kenya.

2.8.1 Rationale for study basin choice

Eccles et al. (2019) in their review on riverine flooding, note a paucity of studies in Latin America, Africa, Australia, in small to mid-sized catchments, and in rapidly urbanising catchments in the developing world. I thus selected cities that matched those broad criteria and these below:

1. A wide geographic distribution globally, focusing on different continents.
2. Diversity of city size and basin size.
3. Known flooding problem within the city.[45]
4. Equal number of inland versus coastal cities.

In addition, the exact city basins were chosen partly because research groups within the department have done precious work in these locations, know the stakeholders and/or has access to data for these basins. The London basin is an outlier but was included as it was hoped that we could use the extensive monitoring and gauging associated with it for verification purposes. Unfortunately, this was not possible due to time constraints and fell outside the scope of this thesis due to the work involved.

2.8.2 Descriptions of study basins

Key facts on each study basin's city of interest, country and recent flood history are summarised in Table 2.11, as well as in Table 1 of the research article in Chapter 3.

[44] In this thesis, the terms 'basin', 'catchment' and 'watershed' are used interchangeably.
[45] Most flooding in the cities is urban flooding. Earlier intentions for this research included looking at mitigating flood risk in cities.

Table 2.11 Comparison of each study basin's country, city and recent flood history.

Country	City	Flood disaster recent history
Colombia Upper-middle income country Fourth largest economy in Latin America Land area: 1,141,748 km^2 Population of 47.7 million 76% is urban Rich natural resources endowment including oil, coal, gas, iron, and gold. Agribusiness (particularly coffee) and manufacturing (e.g., the car industry) are also relatively well developed Climate: Colombia has a diverse range of climate zones, including tropical rainforests, savannas, steppes, deserts and mountain climates.	**Bogotá** • Capital city of Colombia. • Located on a high plateau in the Northern Andes mountains. • Elevation: ~2,640 m • Area of 1,587 km^2 • Population: 8,034,649 • Climate: relatively cool climate that is constant through the year.	• Heavy rainfall causes urban flooding most years. • The World Bank funds a flood control project for the Rio Bogotá which utilises a combination of traditional methods such as levees and NbS[46].
India • Population of 1.39 billion (2021) • Covers an area of 32,87,263 km^2 • Tropical climate marked by relatively high temperatures and dry winters. • Major industries are: telecommunications, automotive and pharmaceutical.	**Chennai** • Capital city of the Indian State of Tamil Nadu. • Located on the Coromandel Coast off the Bay of Bengal. • It is the fourth largest city in India. • Elevation: avg. 6.7 metres • Area: 1,189 km^2 (Chennai Metropolitan Area) • Population: 8,653,521 • Two major rivers flow through Chennai, the Cooum River (or Koovam) through the centre and the Adyar River to the south. • Climate: dry-summer tropical wet and dry.	• Nov-Dec 2015 severe flooding in the region, declared a disaster event. • Dec 2021 more heavy floods. • Caused by combination of heavy rains and man-made conditions such as water releases from dams, blocked drains and development over wetlands.

[46] https://www.worldbank.org/en/results/2021/04/09/restoring-a-long-lost-relationship-with-rio-Bogotá

Country	City	Flood disaster recent history
Ecuador • Located in the western corner at the top of the South American continent. • One of seventeen megadiverse countries in the world. • Land area 272,045 km^2 • Population: 17,715,822 (2021) Great variety in the climate, largely determined by altitude.	**Guayaquil** • Second largest city in Ecuador and also the nation's main port. • Located on the west bank of the Guayas River, which flows into the Pacific Ocean at the Gulf of Guayaquil. • Tropical savanna climate. • Area 344.5 km^2 (city)/ 2,493.86 km^2 (metro) • Elevation: 4 m • Population: 3,113,725 Climate is tropical. Wet season is hot, oppressive, and overcast and the dry season is warm, muggy, and partly cloudy.	• March 2021 heavy urban flooding. • Jan 2022 heavy flooding and landslides in Guayas province. Described as, "... one of the most vulnerable cities to flooding in the world" due in part to the tide that comes up the estuary as well as "an intense rainy season".[47]
Indonesia • Diverse archipelago nation • Went from upper-middle income to lower-middle income status as of July 2021, due to the Covid pandemic. • Land area: 1,904,569 km^2 • Population: 270,203,917 (2020) • Climate: tropical - wet season and a dry season - with no extremes of summer or winter.	**Jakarta** • Capital (for now) and largest city of Indonesia. • Located on the northwest coast of the island of Java. • Primary challenges include rapid urban growth, ecological breakdown, gridlocked traffic, congestion, and flooding. • Sinking up to 17 cm (6.7 inches) per year. • Area covers 7,062.5 km^2 • Population: 10,562,088 • Elevation: Jakarta lies in a low and flat alluvial plain, ranging from −2 to 50 metres with an average elevation of 8 metres. • Climate: tropical monsoon climate.	• Increased risk of flooding because: the city lies in a lowland area through which 13 rivers flow, it is sinking, and the rising of sea levels. • Jan 2020, Feb 2021, Dec 2021 - severe flooding leaves much of the city submerged. • Flooding is the major reason why the government is moving the capital city from Jakarta to Nusantara. • Jakarta has been described as "the region's most vulnerable city to climate disasters such as flooding"[48].

[47] https://www.tudelft.nl/infrastructures/onderwijs/studentenprojecten/flood-prevention-guayaquil-ecuador
[48] https://citymonitor.ai/government/infrastructure/new-jakarta-nusantara-flooding

Country	City	Flood disaster recent history
Kenya • Located in Eastern Africa. • Middle income country. • Major industries are telecoms, finance services, agriculture, forestry, fishing, and tourism. • Land area: 580,367 km^2 • Population: 54,985,698 (2021) • Climate varies from tropical along the coast to temperate inland to arid in the north and northeast parts of the country.	**Nairobi** • Capital and largest city of Kenya. • Located south central part of Kenya, adjacent to the eastern edge of the Rift Valley. • Area covers 32,715.5 km^2 • Population: 10,400,676 • Elevation: 1,795 m • Climate: subtropical highland climate.	• The Nairobi River flows through the city • April 2018, May 2021, Nov 2021, July 2022 heavy urban flooding • Flood risk in Nairobi is aggravated by poor drainage and development in flood-prone areas.
United Kingdom • Located off north-western coast of the continental mainland of Europe. • Major industries are retail, hospitality, professional services, business administration and finance. • Land area: 242,495 km^2 • Population: 67,326,569 Climate: temperate climate, with generally cool temperatures and plentiful rainfall all year round.	**London** Capital and largest city of England and the United Kingdom. Located on the River Thames in south-east England at the head of a 80 km estuary down to the North Sea. Area covers: 1,569 km^2(Greater London) Population: 9,425,622 (Greater London) Elevation: 11 m (avg) Climate: temperate oceanic climate. Summers are generally warm, sometimes hot. Winters are generally cool with little temperature variation.	• London is at risk of tidal flooding from the River Thames; flooding from other rivers, such as the Ravensbourne or Quaggy; surface water and groundwater. Jul, Sept and Oct 2021 flash floods, sewer flooding and surface water flooding.

Chapter 3

Evaluating natural infrastructure for flood management within the watersheds of selected global cities (published paper)

3.1 Chapter summary

This chapter addresses Objective 1 of the thesis: it attempts to quantify the role of upstream rural natural flood storage in providing flood risk mitigation (ecosystem) services to the study cities under current conditions. It was published as a research article in the journal Science of the Total Environment in March 2019 as part of a Special Issue on 'Ecosystem Services in a Changing Environment'. It was first submitted to the journal in August 2018 and was accepted for publication after one round of revisions. It is presented here in its published form which means that the section headings do not match the rest of the thesis. It is available open access via this link: https://doi.org/10.1016/j.scitotenv.2019.03.212.

This paper provides the foundation for the rest of the thesis. It introduces the *Natural Infrastructure* flood metrics from *WaterWorld* and applies it to five of the six study basins. The Nairobi basin was excluded as the basin was too small to adequately present some of the necessary information at the 1km^2 resolution used. The paper quantifies the current natural water storages in the study basins and measures the baseline flood risk ratios from which the succeeding chapters will measure change from. It also attempts to infer the influence of various geographic patterns to the results.

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Evaluating natural infrastructure for flood management within the watersheds of selected global cities

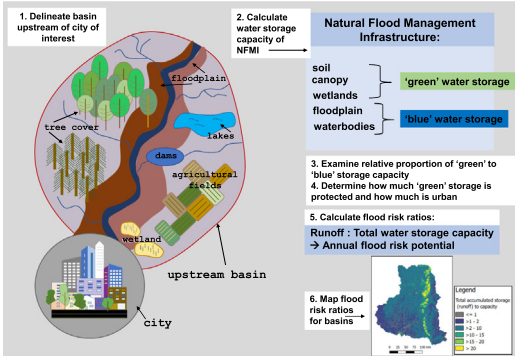
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HIGHLIGHTS

- Natural water storage metrics are applied to upstream basins of five global cities.
- Strong reliance on forest, soil and wetland storage is found in four basins.
- Little of this storage is protected making it vulnerable to land-use modification.
- The basins show different patterns of flood risk magnitude and spatial distribution.

GRAPHICAL ABSTRACT



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ABSTRACT

Cities are dependent on their upstream watersheds for storage and gradual release of water into river systems. These watersheds act as important flood mitigation infrastructure, providing an essential ecosystem service. In this paper we use metrics from the WaterWorld model to examine the flood management-relevant natural infrastructure of the upstream watersheds of selected global cities. These metrics enable the characterisation of different types, magnitudes and geographical distributions of potential natural flood storage. The storages are categorised as either green (forest canopy, wetland and soil) or blue (water body and floodplain) storages and the proportion of green to blue indicates how different city upstream basin contexts provide different types and levels of storage which may buffer flood risk. We apply the WaterWorld method for examining flood risk as the ratio of accumulated modelled annual runoff volume to accumulated available green and blue water storage capacity. The aim of these metrics is to highlight areas where there is more runoff than storage capacity and thus where the maintenance or restoration of further natural infrastructure (such as canopy cover, wetlands and soil) could aid in storing more water and thus better alleviate flood risks. Such information is needed by urban planners, city authorities and governments to help prepare cities for climate change impacts.
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1. Introduction

Cities depend on their surrounding peri-urban and rural ecosystems for a variety of ecosystem services, in particular, flood regulation and control. This is the ecosystem's capacity to reduce flood risk or

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disturbance thereby providing a regulating service and benefit of enhanced safety to human life and human constructions (de Groot et al., 2002). Flood risk results from heavy or prolonged precipitation events leading to reduced infiltration into the soil and increased surface runoff across the land surface into surface waters (streams, rivers, lakes and reservoirs). Lowering flood risk is generally achieved by reducing the surface runoff volume through i) increased infiltration into the soil, ii) storage (in either natural or built infrastructure), and iii) slow release of water by canopies, water bodies, soil and aquifers. Ecosystems can regulate floods by *preventing* their occurrence, such as by redirecting or absorbing precipitation, reducing surface runoff and river discharge; or *mitigating* their impact by providing retention space for surplus water and thereby lowering flood volumes and destructive power (Nedkov and Burkhard, 2012).

The ecosystem service of flood regulation (prevention and mitigation) is of growing importance due to the projected increases in frequency, intensity and duration of extreme precipitation events under current and future climate change (Frei et al., 2006; IPCC, 2014; Rao et al., 2014; Revi et al., 2014) and due to increased exposure of increasingly valuable assets in urban areas near to rivers.

Ecosystem services are, by definition, a function of supply and demand (there is no service without demand for it). Urban areas, and in particular cities, are high *demand* areas for the flood regulation service due to high concentrations of people and infrastructure, and for their tendency to be in low-lying areas close to river crossings and fertile agricultural lands. Despite this demand for the service, urban areas are disadvantaged in that flood regulation services are particularly sensitive to increases in agriculturalisation, urbanisation, and subsequent loss of relevant ecosystems (Chin, 2006; Eigenbrod et al., 2011; Hunt and Watkiss, 2010). The hydrological impacts of urbanisation result from a reduction in perviousness resulting in reduced infiltration and surface retention, thus increasing the proportion of storm rainfall that goes to runoff, leading to larger and more frequent floods. However, floods affecting urban areas can either be generated locally or elsewhere in the watershed; it is therefore important to consider the role of ecosystems not only within the urban areas themselves, but in the entire landscape of the watershed (Depietri et al., 2012). Indeed, the *supply* of the flood regulation service, which either prevents or mitigates floods, will mostly be generated by ecosystems upstream of the urban areas. For this reason, in this study we focus on the river basins (watersheds) upstream of our cities of interest.

1.1. Measuring and mapping flow regulation as an ecosystem service

Measuring and mapping ecosystem services usually requires identifying an indicator or proxy that represents the service. Key environmental variables that impact rainfall-runoff responses include 1) the physical characteristics of river catchments, particularly altitude and slope; 2) variation in evapotranspiration rates, vegetation-soil interactions and modifications of the surface roughness across different land cover/land use types; and 3) soil hydraulic properties such as infiltration capacity and the water holding capacity (WHC) of the soil. The onset, duration and magnitude of a flood hazard are highly dependent on precipitation intensity, duration and extent, creating different flood types (e.g. rain based fluvial (river) floods, pluvial (rainfall-generated overland flow from high-intensity rainfall) floods, snowmelt-fluvial floods. The flood regulative effect of the above mentioned environmental variables may, therefore, depend considerably on the precise characteristics of the underlying precipitation event and prior weather conditions (Stürck et al., 2014). The consideration of all these different factors alongside the role of topography in determining where will be inundated makes flood modeling complicated and onerous, requiring many input datasets and specific skills. Even then the results may not be very accurate or informative.

Applying an ecosystem services approach allows us to focus on mapping the supply of the service versus the potential demand for the service. Areas where service capacity is exceeded and therefore compromised will help pinpoint where action is needed. Several studies have mapped flood regulation/mitigation within the ecosystem services framework. These studies tend to examine multiple ecosystem services simultaneously, use a wide range of indicators from land cover/land use types, to biophysical factors such as slope and elevation, and consider many spatial scales.

For example, Chan et al. (2006) in their regional study explored the trade-offs and opportunities for aligning conservation goals for biodiversity with six ecosystem services in California. For the flood control part of the study, their model identified the areas important for maintaining a natural flooding regime and reducing the risk of extreme flood events attributable to impervious surfaces in a watershed. The feature value in the model varied with land cover in various categories and distance to the floodplain to reflect the flood-mitigation contribution of vegetation in floodplains, wetlands, the riparian zone, and beyond (Chan et al., 2006). Tratalos et al. (2007) looked at a bundle of ecosystem services along a rural-urban gradient in five UK cities. To measure surface water runoff they used the SCS-CN method which calculates the maximum potential rainfall retention of the catchment based on the soil type and land cover for a specific storm event (Tratalos et al., 2007). Egoh et al. (2008) in a study to develop national-scale maps of selected ecosystem services in South Africa used groundwater contribution to surface runoff as the most direct measure of the water regulation function of a catchment. Data on the percentage contribution of groundwater to baseflows were obtained per quaternary catchment and expressed as a percentage of total surface runoff (Egoh et al., 2008).

Studies focusing solely on flood regulating services are rare. Nedkov and Burkhard (2012) claim to have conducted one of the first ecosystem service assessments exclusively focusing on flood regulating ecosystem services at a landscape scale. They examined water retention functions of vegetation and soil cover and modelled peak river flows and land cover types for a river basin in Bulgaria, mapping both supply and demand for the service. Stürck et al. (2014) also focused only on flood regulation services but at the continental scale of Europe. They estimated the effects of five environmental variables (catchment type, precipitation types, catchment zone, soil water holding capacity and crop factor) on discharge volumes following precipitation events. These studies required complex data inputs, often at the local or regional scale, making it difficult and onerous to replicate for other sites and allow cross-comparison.

In response to this challenge, we apply recent metrics developed and documented by Mulligan (2016) as part of the WaterWorld Policy Support System. These metrics utilise the ecosystem service approach by distinguishing between the potential service (as the storage volume) and the realised service (the storage volume in relation to the volume of storage required to house the annual runoff). WaterWorld uses in-built global datasets, thus minimising user input and need for expert skills, and allowing for standarised comparisons. It can also be applied for any terrestrial site on the globe at either 1 ha or 1 km^2 resolution.

1.2. Natural flood storage and natural flood management

Typical approaches to flood management have relied on 'hard' engineered solutions involving 'grey infrastructure'. In recent years there has been a move to use green infrastructure, or "nature-based solutions" which either use or are inspired by natural processes. These interventions can be completely "green" (i.e. consisting of only ecosystem elements) or "hybrid" (i.e. a combination of ecosystem elements and hard engineering approaches). Nature-based solutions aimed at mitigating flood risk are referred to as "nature-based flood protection" (World Bank, 2017) or "natural flood management".

Natural flood management (NFM) refers to strategies and practices to utilise or restore 'natural' land cover and channel-floodplain features within catchments, by storing or slowing down flood waters in order to increase time to peak flow and reduce flood peak (SEPA, 2013). NFM has

gained a lot of attention recently, particularly in policy agendas across Europe, as it is recognised as a means to reduce flooding while delivering a wide range of other benefits, such as biodiversity, water quality, recreation and resilience to climate change (Iacob et al., 2014; SEPA, 2013).

Understanding how catchments store water can yield important insights into how catchments release water (McNamara et al., 2011). In our study we use estimates of the water storage capacities of canopy cover, soil, wetlands, floodplains and water bodies as the components of natural 'green' infrastructure relevant to mitigating flood hazard to downstream cities. We refer to these landscape components as 'natural flood management infrastructure'. We have not used groundwater since this is a store that contributes directly to river baseflows and thus flood peaks. It is also not a storage capacity that is subject to reduction as a result of land use and management.

Forests and other vegetation types (canopy cover in the WaterWorld model) reduce runoff through i) enhanced *infiltration* via their root networks which increase soil macroporosity, and by ii) *interception* of rainwater by temporarily storing it on surfaces, such as leaves, branches, trunks, and stems of trees, as well as on the herb and litter layer, and evaporate it back into the atmosphere, such that it never reaches the ground (Attarod et al., 2015). Canopy water storage capacity thus refers to that temporary store of water from interception, defined as the amount of water left on a saturated canopy when evaporation is negligible, and rainfall and canopy drainage has ceased (Attarod et al., 2015). The tree structure, type of species, climatic factors, and rainfall intensity are known to control the size of canopy water storage capacity. Forests and vegetation also contribute to water loss more directly through transpiration where water is taken up by the plants and subsequently lost through leaf surfaces to the atmosphere. These losses occur on different time scales; for example, canopy interception loss is relevant during and immediately after a storm event, while transpiration plays a role in managing soil moisture in the days or weeks between storm events (Berland et al., 2017).

Due to this important role of forests and canopy cover on the hydrological cycle, forest loss (deforestation) is considered to exacerbate the impact of floods by increasing runoff due to reductions in the interception of rainfall and the evaporation of water from the tree canopy, coupled with reductions in the infiltration rate of soils (Bradshaw et al., 2007). Conversely, afforestation (foresting a previously unforested area, or reforesting a deforested area) is considered to be a significant strategy for NFM. For these reasons, several flood-affected nations like Costa-Rica, China, India, Nepal and Bangladesh have invested heavily in forest protection or reforestation (Laurance, 2007) and the UK is conducting many NFM-based planting experiments; though there has also been some criticism of this 'flood and forests' discourse (see FAO-CIFOR, 2005; Calder and Aylward, 2006).

Soil aids flood regulation through infiltration and storage with different soil types having different capacities to store moisture, depending on their particle size distribution, porosity, level of compaction, soil depth, organic content and other factors. Coarser, sandier soils will have greater infiltration capacity and therefore prevent runoff that can exacerbate flash floods, but soils with greater levels of silt and clay (and therefore a higher surface area of particles) have greater water retention capacity once the water has entered the soil.

Floodplains, wetlands and waterbodies such as lakes and reservoirs aid flood regulation mostly through their storage function. However, floodplain 'roughness' can also affect the rapidity of flow (known as conveyance), so that the more 'rough' or disrupted the floodplain the slower the runoff. Riparian woodlands and wetland vegetation provide important flood regulation services by acting as a roughness element to surface water flow, slowing the water down and helping to prevent it entering the channel too rapidly, as well as through the usual evapotranspiration processes of vegetation. Riparian zones also help to store water on upstream floodplains during flood conditions, mitigating impacts downstream.

1.3. Flood potential metrics utilising water storage capacities of natural infrastructure

Our study applies the WaterWorld realised flood mitigation index which highlights areas where there is more downstream cumulated annual surface runoff than downstream cumulated surface water storage capacity. This indicates where there is potential for overtopping of storage, and thus flooding, on an annual basis. Upstream of these areas can be targeted for maintenance or installation of further natural infrastructure (such as improved canopy cover, wetlands and soil) to aid in storing more water and thus better mitigating flood risk. They can also be considered of high risk, and assets to be insured and adapted accordingly.

We demonstrate the use of natural infrastructure flood metrics that are globally applicable and require low-data inputs (fully described in Mulligan, 2016) for the upstream basins of five global cities: Chennai, Jakarta, Bogotá, London, and Guayaquil, by 1) mapping the magnitude and types of 'natural' storages in these basins, 2) determining how much of this storage is found in protected areas (and thus possibly less likely to be negatively impacted by land use change) and upstream of/near to urban areas (and thus possibly more at risk), and 3) using the WaterWorld realised flood mitigation metric (which compares accumulated annual runoff to storage capacity) to determine areas of potential annual flood risk. The aim is to highlight areas that are providing flood mitigation services and to understand which may be at risk from changes in land-use and land-cover management.

2. Materials and methods

2.1. Study areas

Two inland city upstream basins (Bogotá in Colombia and London in the UK) and three coastal city upstream-basins, (Chennai in India, Guayaquil in Ecuador and Jakarta in Indonesia), were selected representing a mix of continents and climatic conditions. The size of their upstream basins also vary, as do the size and characteristics of the cities themselves: four of the cities (London, Bogotá, Chennai and Jakarta) are considered "very large", with over 8 million people, and one, Guayaquil, is considered "medium" sized, with 2.7 million people (United Nations, 2018). We deliberately chose a very diverse set of basins to apply this method in order to better understand the variety of green infrastructure and flood-risk contexts. Our intention was not to validate the WaterWorld metrics, but rather to apply them in contexts of low data availability and compare findings between city-basin contexts to explore the range of outcomes.

2.2. Hydrological model

We chose to use metrics from the WaterWorld (V2) hydrological model as it uses in-built global datasets thus requiring no data inputs from the user and enabling standardised comparisons across disparate basins and regions. WaterWorld (Mulligan, 2013) is a fully distributed, process-based hydrological model that utilises remotely sensed and globally available datasets to support hydrological analysis and decision-making at national and local scales across the globe. The model includes modules for rainfall distribution based on wind interaction, fog inputs based on cloud cover and potential and actual evapotranspiration based on climate and vegetation cover (MODIS Vegetation Continuous Fields; Sexton et al., 2013; Hansen et al., 2006). Runoff is calculated as the downstream accumulation of water balance along a drainage network calculated from a digital elevation model. The model's equations and processes are described in more detail in Mulligan and Burke (2005), Mulligan (2013) and Mulligan (2016). The model parameters are not routinely calibrated to observed flows as it is designed for application in low data environments and for hydrological scenario

analysis using a physically-based model. (Mulligan, 2013). WaterWorld (V2) was used at 1-km spatial resolution.

2.3. Selection of upstream catchments

WaterWorld, was used to delineate basin boundaries by selecting points on watercourses upstream of the city region, resulting in a study basin containing the entire upstream basin before it enters the main urban area. WaterWorld uses a D8 routing algorithm and the HydroSHEDS flow network (Lehner et al., 2006) applied at 1 km spatial resolution for this analysis. For some cities with extensive sprawl or abutting urban areas, determining the limit to the city extent was problematic. Upstream points were chosen outside the most dense part of the city or near the boundary of the urban extent using the MODIS Urban Land cover 500 m dataset (Schneider et al., 2009). Fig. 1 shows the basin extents in relation to the urban areas and major rivers. We deliberately excluded the city from the basin for a number of reasons: 1) the natural infrastructure that we are interested in, is in the upstream, rural catchment, not in the city; 2) green infrastructure in the city is fairly small scale and primarily provides different services to those under investigation here and little opportunity for further investment given urban land prices and constraints; 3) WaterWorld is not an urban hydrological model so does not model urban drainage infrastructure. However, we acknowledge that the level of development in different basins will mean that the rural and peri-urban areas will have different levels of drainage via infrastructure. WaterWorld cannot model tidal flows, so for London specifically, an area upstream of the tidal reach of the Thames (Teddington Lock in the west of London) was used as the basin outlet. The level of development in different basins will mean that the rural and peri-urban areas will have different levels of drainage via infrastructure.

2.4. Natural-infrastructure metrics

Mulligan (2016) describes a range of new metrics for natural flood storage infrastructure based on analysis of remotely sensed data and hydrological modeling and delivered as part of WaterWorld. These include the floodplain storage capacity; water body storage capacity, wetland

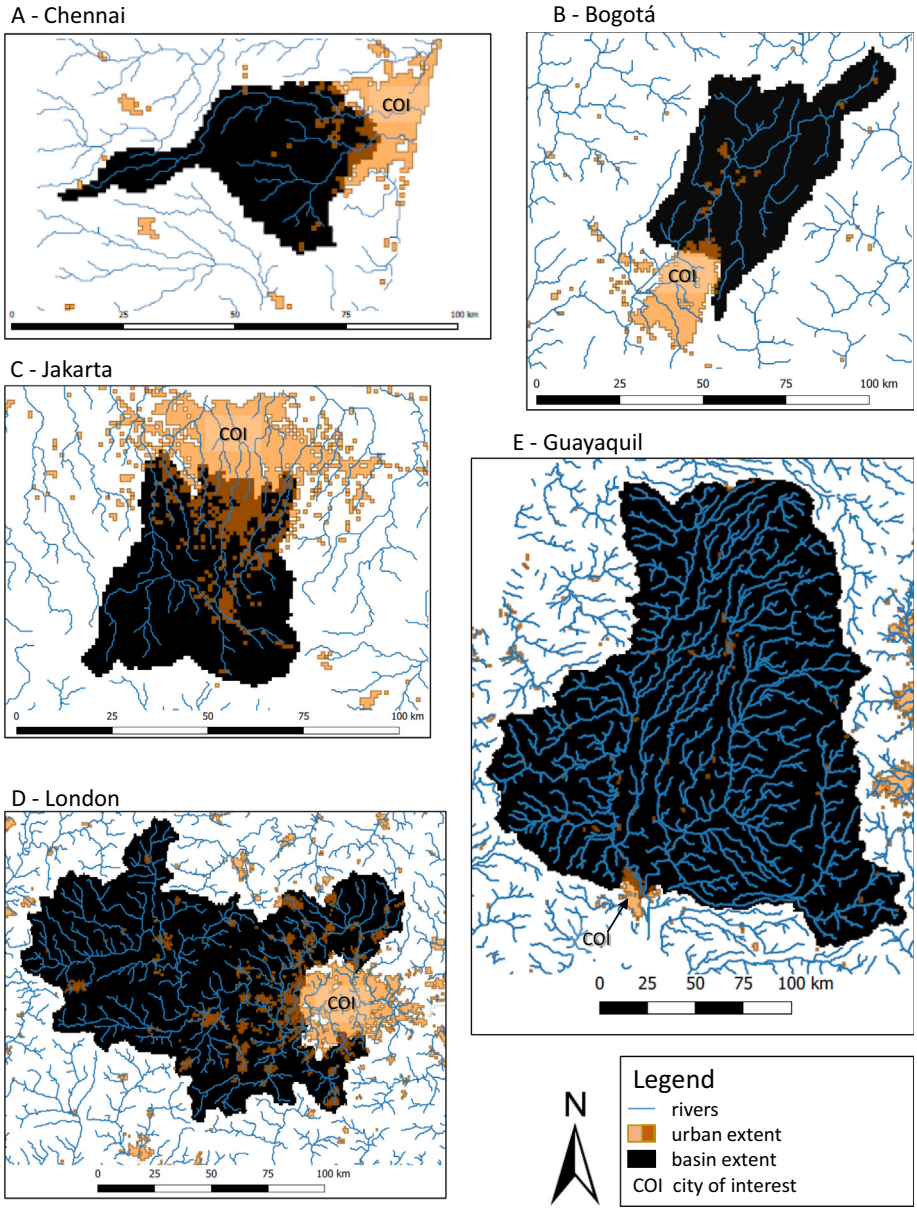


Fig. 1. Study areas showing the basin extents upstream of five cities, A) Chennai, B) Bogotá, C) Jakarta, D) London, E) Guayaquil.

storage capacity, canopy storage capacity, soil storage capacity, and the total storage capacity. Each can be calculated globally from a range of remote sensed data at 1 km spatial resolution on a per grid cell basis and can be accumulated down a surface flow network. They can be calculated for all areas or just for areas that are 'protected' according to the World Database of Protected Areas (WDPA) (IUCN and UNEP-WCMC, 2015) for example. In this way, flood-risk-relevant natural infrastructure can be mapped in terms of the areas supplying the associated ecosystem service (water storage), the accumulation of that service downstream and the volume of the service that is 'secured' within the boundaries of protected areas.

Total natural storage capacity includes floodplain, wetland, canopy, water bodies and soil components. Wetland, canopy and soil stores are considered together as "green" storage capacity since they are at least in part a function of land cover and use and thus can be managed through conservation interventions. Floodplain and water bodies are considered "blue" storage since they are a function of landscape properties such as topography, and the least susceptible to human modification or management. Although floodplains can be built on, their flood storage capacity remains and cannot easily be modified.

The ecosystem service value of natural flood management infrastructure depends upon the relationship between the supply of the potential service (the storage capacity in use) and the demand for the service (the potential service that is upstream of infrastructure or populations and thus realised). In this analysis we use the WaterWorld realised flood mitigation metric which is calculated as the ratio of runoff (downstream accumulated precipitation excess) to storage capacity (total volume of green and blue storage). Where this ratio is >1 there is, in an average hydrological year, more water flowing through a grid cell than the storage capacity to store it, and the excess water may thus overspill from the stores (which include rivers themselves as part of the water body layer) and represent a flood risk. Where the ratio is <1 there is a greater capacity to store surface water than there is runoff flowing through these stores annually, so flooding will be less likely. We calculate these service ratios separately for total storage capacity, green storage capacity and blue storage capacity in order to better understand which stores contribute most to mitigation of flood risk. Each metric is described fully in the WaterWorld V2 documentation (Mulligan, 2016) but a short summary is provided below.

2.5. Floodplain storage capacity

Floodplains are defined in WaterWorld using a combination of Strahler stream orders and elevation (details in Mulligan, 2016). The average height of water storage capacity on a floodplain can be set by the user but for this analysis the default of 0.5 m was used.

2.6. Water body storage capacity

Water body storage is calculated based on the full grid cell surface water frequency dataset of Mulligan (2013). The area of each water body is calculated and the volume of estimated based on the empirical relationship of Lehner et al. (2011). Seasonally dry grid cells (usually those around the edge of a water body) are considered to have lower storage capacity than those that are permanently wet and thus considered to be deeper.

2.7. Soil storage capacity

Soil storage capacity is a topographic metric based on a topographic index-scaled soil depth for all non-impervious surfaces. It thus represents porous soil storage capacity. Soil thickness is scaled between 0 and a user defined maximum accessible soil thickness (set to 2.0 m by default) linearly according to the calculated topographic wetness index (Beven and Kirkby, 1979). In addition to the topographic effect, vegetation is also considered to influence soil thickness with a user-specified thickness of soil added for each per-cent of tree cover (set by default to 1 mm, which gives 10 cm extra soil thickness at 100% tree cover). Finally, where water bodies, urban areas or roads exist, soil storage is considered inaccessible. For water bodies it is set to zero, for roads the fraction of the grid cell occupied by the road is considered inaccessible and for urban areas 90% of the soil storage is considered inaccessible (the remaining 10% representing green surfaces in the urban matrix).

2.8. Canopy storage capacity

Canopy storage capacity is calculated on the basis of the percentage tree cover in each grid cell and a closed canopy storage capacity per rainday set to 5 mm, the mid-point of the range proposed by Davies-Barnard et al. (2014), who present values for trees varying from 0.1 to 9.1 mm across arid, temperate and tropical regions. 5 mm is thus considered a representative average for a closed canopy. In order to account for interception losses, a rain per rain-day metric is calculated from the precipitation (Hijmans et al., 2005) and raindays layers (Cramer and Leemans, 2001). Where rain per rain-day is greater than the storage capacity of a grid cell the storage capacity is used, if less than the storage capacity, the available rain per rain day is used. This is thus a metric of the storage capacity available for a given rainfall event.

2.9. Wetland storage capacity

Wetland storage capacity is based on the part grid cell surface water frequency dataset of Mulligan (2013). The volume of storage per grid cell is calculated from the surface wetness frequency multiplied by a mean wetland depth set to 5.0 m by default. In this way surface wetness frequency is assumed to indicate the proportion of the grid cell available for water storage. This variable tends to capture water storage capacity at the edges of permanent water bodies and in seasonally drying wetlands.

2.10. Total storage capacity

Total storage capacity is by default comprised of floodplain storage capacity, wetland storage capacity, canopy storage capacity, soil storage capacity and waterbody storage capacity.

2.11. Accumulated storage and ratios of runoff to capacity

Storage capacity is only significant to downstream areas when there is sufficient rainfall to fill those stores. Where there is little or no rainfall, flood storage capacity will be of little relevance. The WaterWorld realised flood mitigation service is thus the ratio of runoff to water storage capacity. This assumes that if there is sufficient storage to store the total annual flow, that flood risk (outside of these stores) will be minimal since they will provide the buffering capacity to store the flows. This is simplistic in that it ignores the event basis of many floods and the role of antecedent filling of stores in creating risk. Nevertheless, for spatial comparisons of mitigation of flood risk, it is useful. Runoff in WaterWorld is the downstream accumulation of water balance (rainfall + fog + snowmelt minus actual evapotranspiration) derived from global datasets (Mulligan, 2013). The runoff is divided by the corresponding storage capacity and where the ratio is greater than one, the volume of water present is in excess of the capacity to store it either on a grid cell or downstream cumulated basis.

Fig. 2 illustrates this concept of natural storage being overtopped creating runoff that cumulates downstream. It shows a schematic of grid cells (1 ha × 1 ha or 1 km × 1 km land parcels used by the WaterWorld model) containing different storage types with different capacities of water volume that they can hold. If more water is input into the grid cell than the total capacity to store it, then the water will continue downstream. The ratio of downstream cumulated surface

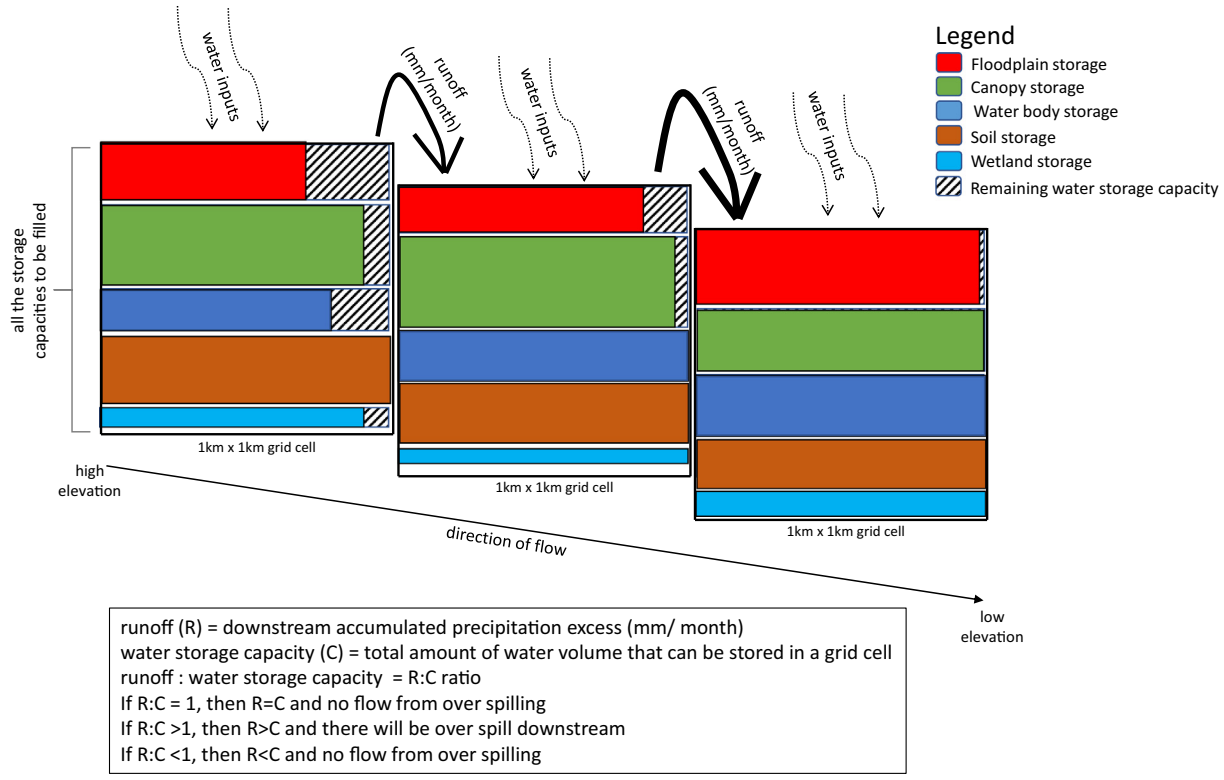


Fig. 2. Natural infrastructure provides different types and sizes of water storage capacity in the landscape. Runoff occurs when the downstream accumulated water balance is greater than all the stores. The relationship between runoff and water storage capacity can be expressed as a ratio with values above unity indicating greater flood risk and values at unity or below, indicating lower flood risk.

water (runoff) to surface water storage capacity is thus a measure of the extent to which the stores are full or over-full.

2.12. Calculating protected and urban storage

As green storage can be influenced and modified by land cover and land use change, it is more vulnerable than blue storage. Protecting upstream green storage is thus important for basins upstream of cities to maintain existing storage potential and possible flood buffering. Here we used WaterWorld's (Mulligan, 2013) calculation of green storage, the MODIS Urban Land cover 500 m dataset (Schneider et al., 2009) and a protected areas dataset (IUCN and UNEP-WCMC, 2015) to show and calculate where and how much blue storage lies in urban areas and how much green storage lies within protected areas. We calculated what percentage of the protected storage accumulates downstream by dividing the accumulated protected total storage by the accumulated total storage and multiplying by 100. We also used the same urban dataset to calculate how much of the blue storage upstream of the selected cities falls within urban areas, as these indicate urban areas that lie in floodplains.

3. Results

3.1. Storage capacity of natural infrastructure in upstream basins

Table 1 summarises key water (storage capacity, rainfall, water balance), landcover (tree cover) and urban metrics for each of the city upstream basins calculated from WaterWorld (except where indicated).

Although the Jakarta upstream basin and the Bogota upstream basin are similarly sized, Jakarta receives three times more rain and has a third larger water balance. The Guayaquil upstream basin is 4.7 times larger than the London upstream basin and receives nearly 20 times more rain (due to its tropical climate and location near the equator). Although the London upstream basin has only slightly more (1.1 times) people living in it than the Jakarta upstream basin, the Jakarta upstream basin has a much higher density of people at 2067 people/km^2, compared to London's 790 people/km^2.

Water storage capacity for individual natural storage components across all five basins show that canopy accounts for the greatest storage capacity, followed by soil, floodplains, water bodies and wetlands (Fig. 3a). However, these figures will be affected by basin size. The largest basins (Guayaquil and London) haver larger overall storages. Stores

Table 1
Comparison of area, water and urban metrics for each city upstream basin.

City upstream basin	Basin area (km^2)	Total water storage capacity (km^3)	Total rainfall (km^3/yr)	Total water balance (km^3/year)	Mean tree cover (%)	Urban area in upper basin (km^2)	Upstream basin population (number of people)	Upstream basin population density (people/km^2)	City population[a] (millions of people)
Chennai	1188.69	0.62	1903	253.8	6.6	94.48	1,518,610	1277.55	9.7
Jakarta	2340.65	0.96	2099	17,030.66	27.7	367.02	4,839,840	2067.73	10.1
Bogotá	2509.25	0.99	6920	5636.21	15.3	86.57	972,496	387.56	9.7
London	6939.35	6.53	98,768	81,507.03	16.4	549.71	5,488,530	790.93	8.6
Guayaquil	32,793.98	12.97	1,973,523	1,534,795.33	23.1	215.7	2,657,850	81.05	2.7

[a] UN (2018) for year 2015.

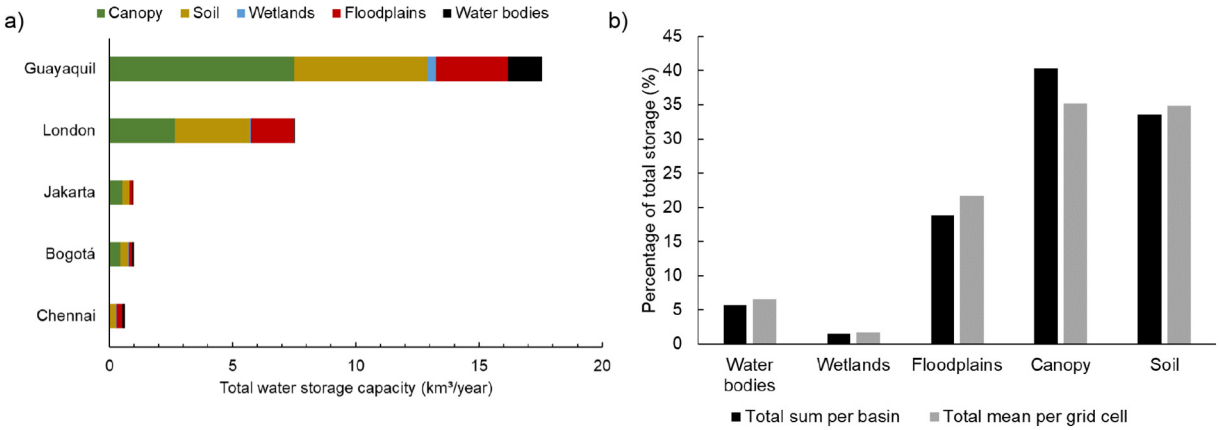


Fig. 3. Natural infrastructure storage capacities for five city upstream basins, a) showing the partition of storage type per city upstream basin, and b) showing the percentage of the total sum vs total mean (average per grid cell) storage that the storage components comprise for all basins.

that predominate in those basins will influence the overall pattern. To remove the effect of basin size, the total storages were divided by the number of grid cells in each basin to get a mean storage capacity per grid cell per storage component for each basin (Fig. 3b). This shows the same pattern but with different magnitudes; canopy is still the greatest storage across all the basins at 35.2% but is very closely followed by soil storage at 34.8%, a much smaller margin than when considering the sum storages.

Categorizing the catchment mean storages into green (canopy, soil and wetlands) and blue (floodplains and water bodies) storage capacity, shows that green storage capacity is greater than blue capacity in all cases, except for the Chennai city upstream basin (Fig. 4). Mean blue storage capacity is highest for Chennai (0.00023 km^3) and lowest for Jakarta (0.00005 km^3). However, of more interest is the relative proportion of green to blue, as green is more vulnerable to impacts of land use change or management than blue is.

For four of the five basins, green storage was at least two-thirds greater than blue storage. Jakarta has the highest proportion of green storage at 86.7% of the total water storage capacity. The exception is the Chennai city upstream basin, which has greater blue storage than green, at 53.4% blue compared to 47.6% green.

3.2. Geographic location and distribution of natural storage components

To investigate the spatial distribution of natural storages for each city upstream basin, the storage that was dominant in each grid cell is mapped by WaterWorld (Fig. 5). Even if one of the storage components is marginally greater for that grid cell, it will show as dominant. In other words, the greatest storage capacity does not have to be very large, just larger than the others. This is useful for indicating how, geographically, the most important storage types vary.

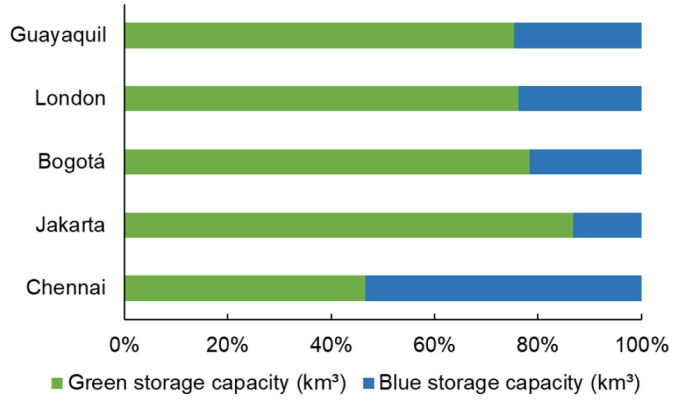


Fig. 4. Proportion of mean green to mean blue water storage capacity, ordered by increasing basin size. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Chennai is characterized by a lack of canopy storage at only 4.1% of the total storage and hardly any predominating except on the eastern edge closest to the city (Fig. 5A). Soil and floodplains make up most of the water storage, at 38.5% and 38.2% respectively and are distributed across the basin. Water body storage is at 15.3% and wetlands 3.9% of total water storage capacity.

Jakarta has an uneven distribution of soil and canopy storage predominating, with canopy (52.8%) greatest to the south of the city in the uplands and soil (33.4%) greatest towards the coast (Fig. 5B). Floodplain storage (13.2%) is also greatest to the north and west while wetlands (0.5%) are to the north and east. Waterbodies only account for 0.1% of total storage.

In the Bogotá upstream basin, the greatest storage comes from the canopy (45.7%) which is distributed throughout the basin, followed by soil storage (31.4%) (Fig. 5C). Soil storage is greatest along the boundaries of the basin and in the northern higher elevations. Floodplain storage makes up 14.5% of the total and is greatest to the west of the basin and the centre. Waterbodies account for 7.2% and wetlands 1.2%.

Most of the water storage in the London upstream basin occurs in the soil (40.4%) and canopy (35.3%). The canopy storage is greatest around the city and towards the south. Soil storage predominates in the north and west of the basin (Fig. 5D). Floodplain storage (23.6%) is evenly distributed throughout the basin. Water body (0.2%) and wetland storage (0.5%) is very limited.

The Guayaquil upstream basin shows canopy responsible for the most storage (42.7%) along the western edge and eastern edge of the basin (Fig. 5E). Soil (30.7%) and floodplain (16.6%) storage predominates in the middle of the basin. Wetland (2%) and waterbody (8%) storage dominates in the lower part of the basin.

3.3. Protected storage

The amount of green storage within protected areas, either national parks or other forms of designation was calculated. London has the greatest amount of green storage protected at 33%. This is mostly made up of three Areas of Outstanding Natural Beauty (AONB), the Chiltern Hills AONB, the North Wessex Downs AONB and the Cotswolds AONB. AONBs are areas designated for the purpose of conserving and enhancing their natural beauty where more consideration is needed by planning authorities for new development but doesn't mean that no new development occurs.

The next greatest green storage protection is the upper Bogotá basin with 12.5% and then Jakarta at 9.68%. Of concern is the Chennai city upstream basin, which has none of its green storage in protected areas.

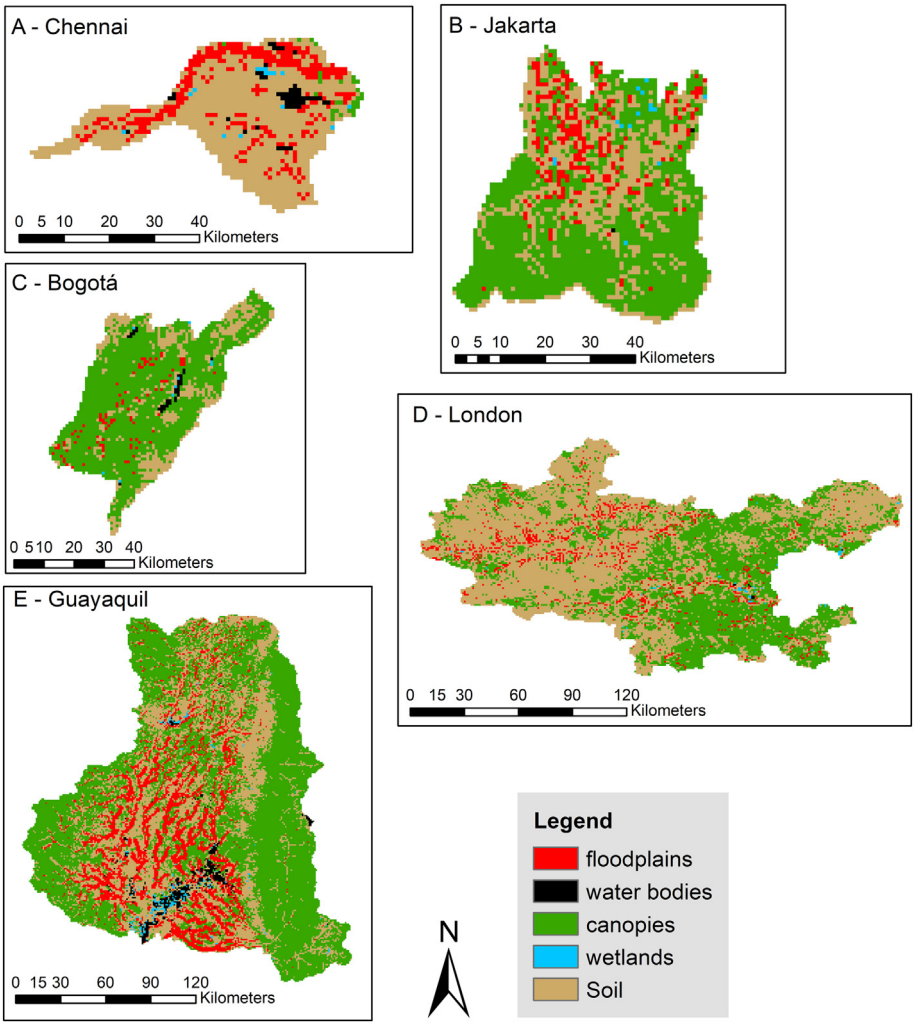


Fig. 5. Spatial patterns and geographic distributions of dominant NI storage type for upstream city hydrological basin.

This is perhaps not surprising since India as a country has only 4.89% of its land protected. The Guayaquil upstream basin, which has just over three times more green storage than blue storage, has only 0.85% of this green storage protected. This is potentially concerning considering the very large size of the upstream basin and the fact that the Guayaquil city upstream basin is the least urbanised of all the watersheds. Most of the land use in this basin is agricultural. Ecuador's protected areas tend to be in the far eastern part of the country (Amazon), in the Andes mountains or along the coast.

We used the corresponding WaterWorld metrics to examine the flow and spatial configuration of protection by i) comparing the greatest accumulated protected storage, and ii) what percentage of total storage volume is protected as it accumulates downstream (Fig. 6). The greatest accumulated protected storage tells us what type of storage the protected storage comes from as it accumulates downstream. For instance, in Bogotá, Jakarta and Guayaquil, it is the protected storage that originates from canopy upstream that is greatest and dominates as the storage accumulates downstream (Fig. 6a). In the London upstream basin it is soil storage, with canopy storage dominating further downstream. So even though the most important functional storage may be the floodplains, the protected storage is of canopy or soil storage y. Besides a few places in the London upper basin, none of the basins show floodplain storage as the dominant storage protected. This has implications both for the volume of storage and for flood risk to human infrastructure placed within this storage (i.e. on floodplains).

The percentage of total storage volume that is protected shows, for all basins, a decay of the fraction protected as the storage accumulates downstream towards the city (Fig. 6b). Even though most of the flood risk may be realised in the downstream more urbanised reaches, very little of the accumulated storage to these areas is protected with most of the protected storage occurring in the remote, most upstream parts of the basin.

3.4. Urban water storage

Of the five city upstream basins, Jakarta, is the most urbanised at 15.7% (Table 3). London and Chennai have similar levels of urbanisation at 7.92% and 7.95% respectively, just over half that of Jakarta. The percentage of blue storage volume that lies in urban areas was determined as these indicate urban areas that lie in floodplains (Table 2). Although <1% of the upper Guayaquil basin is urbanised, 6% of the blue storage volume in the basin overlies urban areas. The urbanised part of the Chennai upstream basin was almost all coincident with blue storage.

3.5. Spatial distributions of accumulated flood risk NI service

The WaterWorld surface water storage to capacity ratios were extracted for each city basin, to show the spatial distribution of potential flood risk. Values >1 indicate likelihood to overspill on an annual basis since annual runoff is greater than available flood storage and, as is

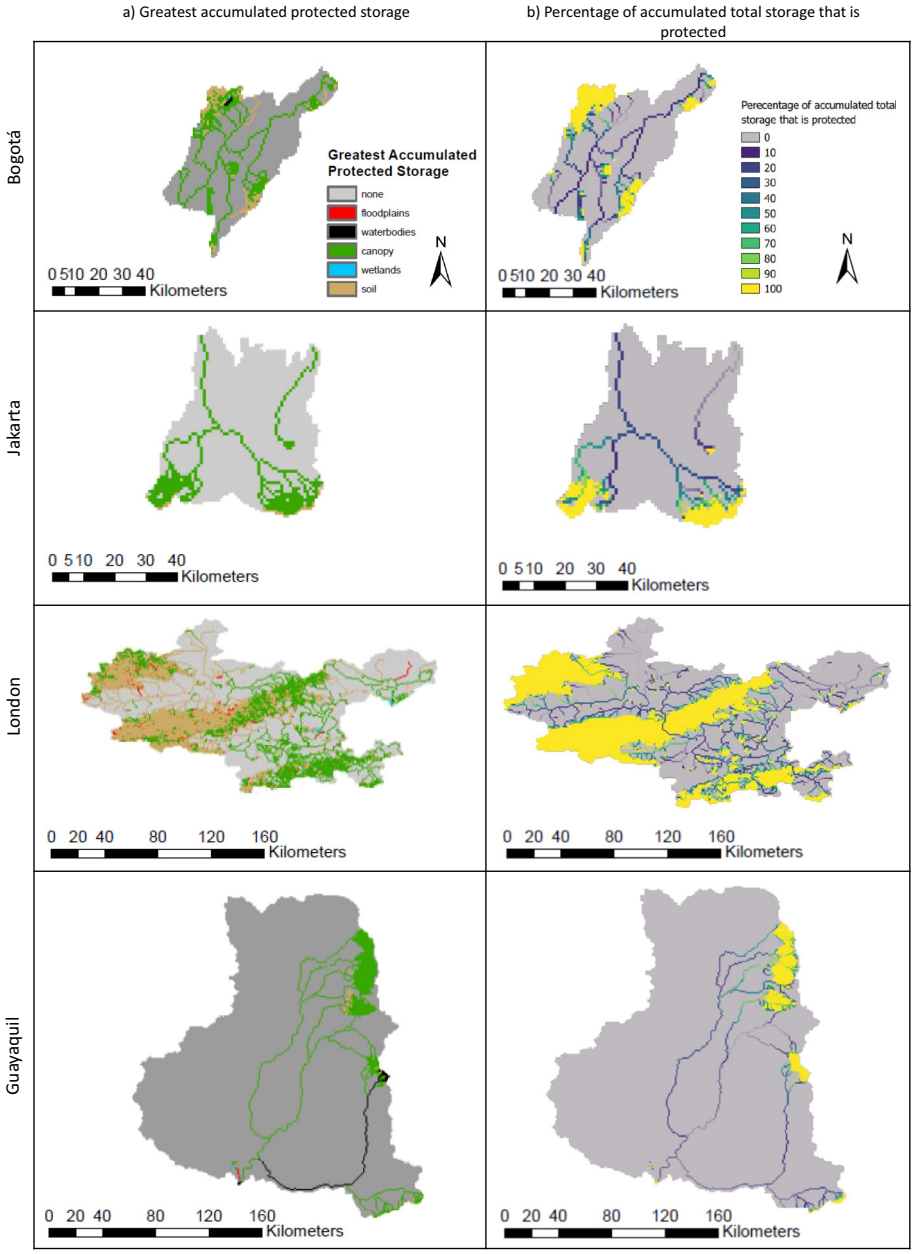


Fig. 6. a) The greatest accumulated protected storage showing the dominant type of storage the protected storage comes from as it accumulates downstream, and b) the percentage of the total storage volume that is protected, shown for four of the five city basins. Chennai was excluded as none of its storage is protected.

common, if this runoff were to occur in temporal clumps rather than evenly over the year, the storage may be overcome.

Ratio values <1, are unlikely to overspill on an annual timeframe (Fig. 7). In these areas the storage types are under-utilised and have extra capacity to cope with increased water inputs.

Table 2
Percentage of city upstream basin catchment, and blue storage volume, that is urban. i) Calculated by dividing the urban area in the upper basin by the total area of the upper basin, and ii) by dividing the urban blue storage by the total blue storage for the upstream basin.

	Chennai	Jakarta	Bogotá	London	Guayaquil
i) % of upper catchment that is urban	7.95	15.68	3.45	7.92	0.66
ii) % blue storage volume in urban area	7.65	0	0	0.21	6.28

The upper basin of Chennai shows a patchwork of cells with potential to flood (Fig. 7A), mostly of low value; 48% have values between 1 and 6. These tend to coincide with cells that have greatest storage in the soil category. Another 48% of cells have a value <1, indicating low potential to flood on an annual basis. The area most downstream, and thus in the urbanised area of west Chennai, has the highest values, up to a maximum of 23.

The Bogotá upstream basin shows that most of it has potential to flood on an annual basis. High value cells are located on the eastern edge and north-west of the basin in the high mountain areas, as well as in the downstream urban area closest to Bogotá and the town of Chia (Fig. 7B).

Almost every cell in the upper Jakarta basin has a value >1, indicating potential to flood on an annual basis (Fig. 7C). The Jakarta basin shows a wide spread of values with 96% of the values between 2.2 and 21, with a mean of 7.05. Areas of relative high value occur in the uplands adjacent to rivers with either soil or canopy supplying the greatest storage. The

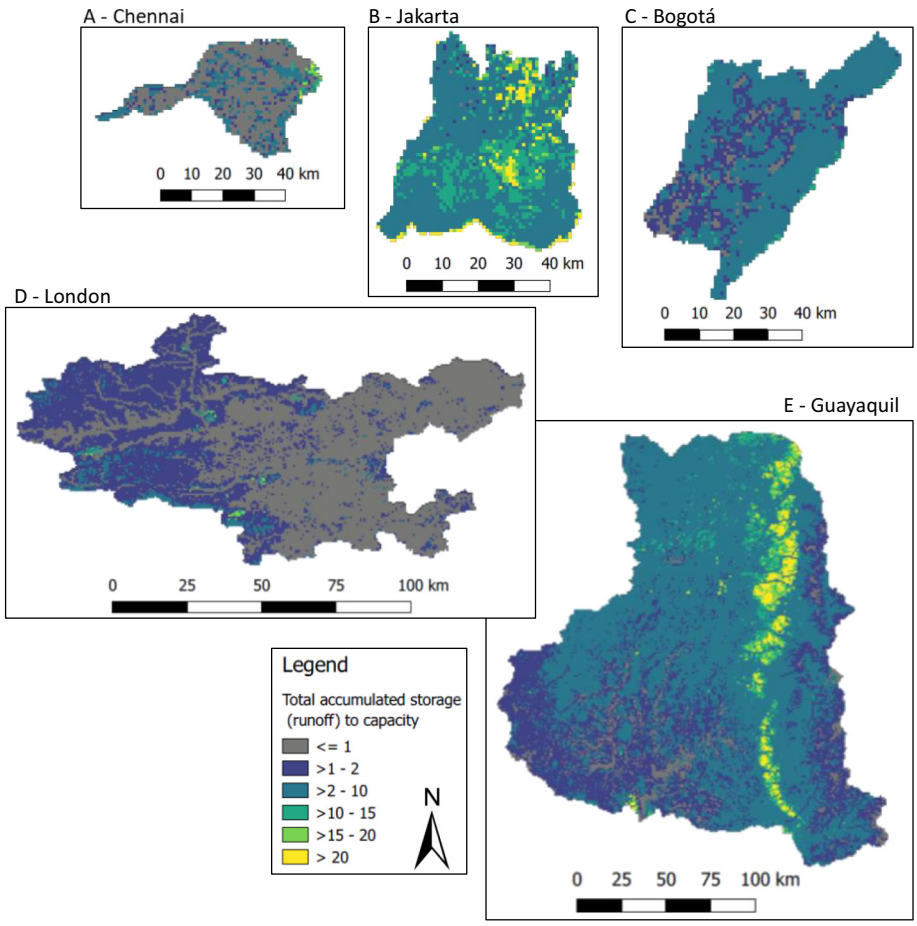


Fig. 7. Spatial distribution of ratios of accumulated runoff to capacity for each of the upstream city watersheds (A - Chennai, B - Jakarta, C - Bogotá, D - London, and E - Guayaquil).

areas with the highest values are at the southernmost boundary of the basin, which is at the top of the watershed on the slopes of the volcanoes, and in the urban areas of Bogor and Depok.

Large areas of the London upper basin do not show ratios >1, indicating that they have capacity to store the accumulated downstream precipitation (Fig. 7D). The areas that do show potential to flood appear to be in W-E horizontal bands, adjacent to areas of high floodplain storage. 96% of the grid cells have relatively low ratios of between 1.2 and 2.2. Areas showing the highest ratios (and thus most potential to flood) coincide with urban areas such as Reading, Swindon, Basingstoke, Oxford, Maidenhead, Slough, Luton, Hemel Hempstead, Welwyn Garden City, and areas immediately west of London, such as Hounslow and Heathrow Airport. This reflects the fact that they have low tree and soil storage (being largely covered by concrete). Of course, the greater threat to flooding in London is from sea level rise and tidal surge combining with high flows on the Thames.

In the Guayaquil upstream basin, 95% of cells have values between 1.7 and 14, with a mean of 4.4 (Fig. 7E). In the lower part of the basin are areas with values <1, showing capacity to store the water. These appear to be areas of water body storage. Extreme high values occur on the slopes of the Andes Mountains in the western part of the basin. High values also occur in the urban area of Quevedo and in the northern parts of Guayaquil at the bottom of the basin. Of all the cities, Guayaquil has the most extreme high values with max values up to 54. This is probably due to the high rainfall that occurs in the Andes Mountains.

3.6. Which storage component is providing the realised mitigation?

Separating the accumulated storage to capacity ratios into accumulated green and blue storage to capacity ratios is useful for telling us which storage type is providing the realised flood mitigation, i.e. flood mitigation where runoff is high enough for it to be necessary (Fig. 8). The Chennai upstream basin shows a widespread mix of green and blue values over 1, mixed with widespread areas of values under 1 (Fig. 8A). It appears that both green and blue are contributing fairly equally to flood mitigation throughout the basin.

In the Jakarta upstream basin it is green storage that is providing most of the flood mitigation but blue doing the work along the rivers, with hardly any areas below 1 (Fig. 8B). In the Bogotá upstream basin, it is the green storage that is providing the flood mitigation, with thinly localised areas of blue providing storage along some rivers, adjacent to areas below 1 (Fig. 8C). The London upstream basin is quite different to the others as it shows a west-east divide, with green storage dominating in the west half of the basin and the east half mostly being below 1, so not overspilling. Realised blue storage is found evenly on both sides along the river networks (Fig. 8D). The Guayaquil upstream basin shows a fairly even mix of green and blue storage providing the flood mitigation, with green dominating on the eastern hillslopes and blue dominating towards the centre and west but distributed from north to south through the valley (Fig. 8E).

Comparing annual cumulated runoff to storage capacity as potential flood risk ratios shows differences in the spatial distribution and overall pattern of green and blue mitigating storage, and areas of high and low flood risk. The patterns are summarised in Table 3; highlighting the dominance of either green or blue storage type, as 'heavy' or 'green-blue hybrid' if relatively spatially dispersed, and the spread of low-risk values as either 'dispersed' or 'concentrated', based on visual observation of Fig. 8. Each pattern-type may suggest a different strategy for improving or enhancing flood risk mitigation through natural infrastructure storage.

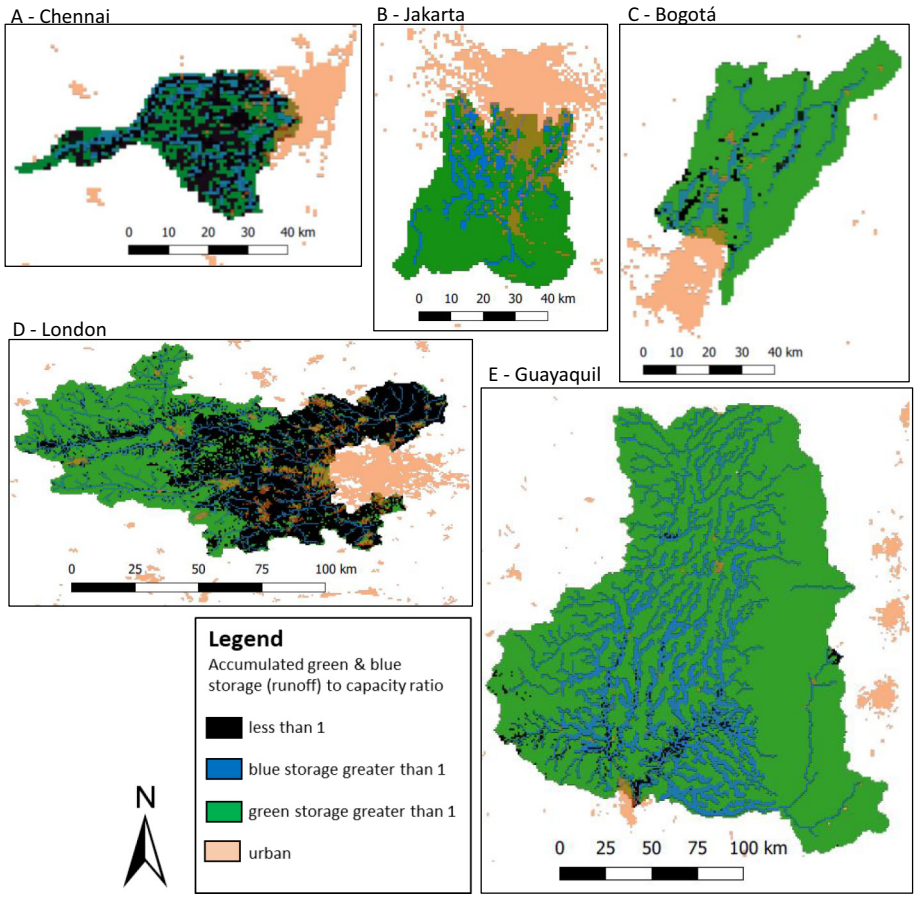


Fig. 8. Spatial distribution of the accumulated storage (runoff) to capacity ratios >1 (indicating flow) and <1 (no flow) for both green and blue/blue infrastructure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

It is worth noting that these ratios and associated patterns are based on average annual values and provide a broad picture; at a finer temporal resolution individual events may cause flooding that show different patterns and trends that are more to do with the size and distribution of the event than the patterns of available storage.

4. Discussion

4.1. Characterisation of the different types and magnitudes of natural flood storage

Landscapes vary in their ability to store water with the variability largely due to differences in topography, soil depth and condition, number of water bodies including rivers and lakes, and also land cover and land use, affecting canopy cover and soil characteristics (as seen in Fig. 5). The ability to quantify the storage capacity and evaluate the distribution of these natural infrastructure components by city upstream basin should enable us to characterise the city upstream basin's potential to store upstream precipitation excess and thus flood risk.

Table 3
Summary of the city upstream basins' flood risk patterns.

Upstream basin	Natural storage and potential flood risk pattern
Chennai	Green-blue hybrid; low-risk dispersed
Jakarta	Green heavy; low-risk dispersed
Bogotá	Green heavy; low-risk dispersed
London	Green heavy; low-risk concentrated
Guayaquil	Green-blue hybrid; low-risk concentrated

In this paper we propose that categorizing natural flood storage as either 'green' or 'blue' based on ability to be influenced by human activity, and determining the size of the relative contribution of green and blue storage to total storage, indicates the level of vulnerability to modification of the upstream water storage and flood buffer. If the water storage is skewed in favour of green storage (canopy, soil, wetlands), which is vulnerable to human modification, then it can be altered (lost or enhanced) due to land conversion or reclamation, which may influence downstream exposure to flood risk.

Indeed, our analysis revealed a strong reliance on green storage. For three of the basins (Bogotá, London and Guayaquil) there is three times more green storage than blue. Jakarta had 6.5 times more green than blue storage. This strong skew towards green storage may be surprising to those who consider blue storage and grey infrastructure (reservoirs) the most significant for flood mitigation. Our results highlight the value and importance of green storage in these systems emphasising the need to appropriately value and preserve them. These findings agree with those from other studies. Nedkov and Burkhard (2012) also found that land cover classes with higher vegetation cover (i.e. forests) have higher flood regulation capacities due to their higher ability to "catch" part of the incoming water from precipitation. Stürck et al. (2014) found that regions with a high capacity to provide flood regulation are mainly characterized by large patches of natural vegetation or extensive agriculture. Fu et al. (2013) found that the flood mitigation function for forests, grasslands and other terrestrial ecosystems was significantly higher than that for lakes, reservoirs, marshes and other wetland ecosystems.

Contrary to the other basins, Chennai had more blue than green storage. The volume of canopy storage appears to be what drives this pattern, reflecting the lack of tree cover in the basin. For the green-heavy basins, between 35 and 54% of their storage was in the canopy while

Chennai only has 4% of its storage in canopy storage. The strong influence of canopy storage for some basins is most likely due to its wide coverage across the landscape, and that this store empties to the atmosphere after rainfall events so can be refilled without emptying downstream to the rivers. It is likely that historically Chennai's canopy cover, and thus green storage, was greater but has declined due to land use change. A temporal analysis may be of interest to see how the green and blue storage has changed over time.

Soil (part of green storage) was also a large part of the overall storage, accounting for 33.6% of the total storage on average across the basins. Unlike canopies, when soil empties it drains largely to throughflow and baseflow (thus generating runoff). Stürck et al. (2014) concluded that the main factor limiting flood regulation supply on a continental scale is low water holding capacity of the soil.

Water bodies and wetlands are commonly associated with water storage but are rather intermittent in landscapes and so have a relatively small overall storage capacity among our basins, at 5.7% and 1.6% of the total storage, respectively. This has also been observed in application of these WaterWorld metrics around the world. Many wetlands tend to be fairly small, and it may be the case that they were not picked up by the resolution (1 km) of the MODIS imagery. However, the size of wetlands has been shown to be important in their capacity to provide flood mitigation. If wetlands are too small, functions such as storage of floodwater, no longer exist. It has been assessed that 3–7% of the area of a watershed in temperate zones should be maintained as wetlands to provide both adequate flood control and water quality improvement functions (Depietri et al., 2012; Mitsch and Gosselink, 2000). Although it is difficult to create new waterbodies, other than through building dams, the creation of new wetland storage may be an important tactic to increase overall flood storage to specific sites downstream.

For Chennai, the relatively large volume of blue storage in the system indicates a possible opportunity to increase flood storage by increasing the amount of green storage, particularly through soil conservation measures, but also through wetland creation and restoration. Any strategy aimed at mitigating flood must also ensure that dry season flows are maintained and water resources are not compromised.

4.2. Determining how much is 'secured' in protected areas or 'at risk' in urban areas

Due to the vulnerability of green storage to modification it is important to downstream users that upstream green storage is protected. Our analysis showed that very little (0–32%) of the green storage in the five city upstream basins is protected. The storage that is protected tends to be remote and in high elevation areas resulting in significant distance between sites of service provision and of potential benefit. Also, the level of protection may not be adequate, such as the AONB's in the London basin, to deter the kinds of land modification that could affect storage.

Criteria for choosing where to designate a protected area (PA) has historically been based on aesthetic and socio-economic concerns (Leader-Williams et al., 1990; Pressey, 1994), and more recently by levels of species-richness or degrees of 'naturalness' (Dudley, 2008). Most PAs tend to over-represent high elevation areas and other regions with low agricultural potential (Oldfield et al., 2004) reflecting also the role of low land prices. PA location is rarely based on its utility for providing flood regulation services.

We propose that provincial and city authorities liaise with relevant organizations, and in open consultation with all relevant stakeholders, to secure more of their upland green storage from land use change and development by designating these areas as protected, or placed under stewardship schemes, that are focused on natural flood management. Many of the service-providing areas are agricultural and affording protection will require engagement with farmers. Policy and stakeholder analysis in each catchment should be explored in further policy-science or governance research. However, it is not just the green storage that needs protection. Our analysis showed that barely any floodplain storage was protected. Floodplains are extremely important for providing a flood buffer but also tend to be built upon, increasing the exposure to flood risk. Where significant flood storage occurs on floodplains within the urban fabric, for this storage to be utilised, exposed assets (buildings and infrastructure) are flooded.

4.3. Targeting areas for protection, restoration or enhancement of flood mitigation interventions

Our analysis and the method described could assist in determining the amount and locations of the green storage to be protected, restored or enhanced. We propose to prioritise areas for intervention upstream of where:

1) Accumulated green storage to capacity ratio is >1 (but not so much >1 that intervention to bring the ratio to 1 would not be feasible). The >1 to 2 ratio classes shown in Fig. 7 may be a good starting point to target initial interventions.
2) Accumulated protected storage at cities is low (e.g. such as demonstrated in Fig. 6) and thus storage is vulnerable.
3) Areas are urban or heavily populated and thus have low land prices.
4) Areas with the potential for one of a variety of interventions, including soil management, afforestation, wetland restoration etc.

Decisions for each region will require use of detailed land-cover/land-use maps and property value information; this study has made the first step but has primarily demonstrated the use of accessible and freely available global metrics that can be applied consistently across basins for preliminary assessments.

NFM interventions generally aim to achieve three things: 1) reduce rapid runoff generation and retain water in the landscape through management of infiltration, 2) reduce river and floodplain conveyance, and 3) increase water storage. Practices to achieve reduction of runoff and increased infiltration include land-use changes, changes in arable land-use practices, changes in livestock land practices, changes in tillage practices, field drainage (to increase storage), creation of buffer strips and buffer zones, machinery management (such as low-ground pressures and avoiding wet conditions), urban land-use changes (such as permeable paving) and afforestation (Dadson et al., 2017; Lane, 2017). Practices to reduce river and floodplain conveyance are focused on reducing hillslope-channel coupling (the connections between the stream channel and the hillslope and between the channel and the upstream reaches) e.g. by blocking drains; management of riparian conveyance, by increasing river and floodplain roughness, and realignment and restoration of river channels (Dadson et al., 2017; Lane, 2017). Water storage can be increased i) upstream, such as ponds, bunds and ditches; wetlands and washlands, impounded storage; and ii) in the floodplain, such as through floodplain restoration (Dadson et al., 2017; Lane, 2017).

However, the impact of NFM interventions on flooding is increasingly being shown to depend on i) the scale of the measure, ii) the size of the catchment on which the measure is being implemented, iii) the location within the catchment, and iv) the connectivity of the channel network (Iacob et al., 2014; Dadson et al., 2017). For example, Dadson et al. (2017) found in their review that there is clear evidence that appropriately chosen land-use and land-cover interventions can reduce local peak water flows after moderate rainfall events and in small catchments. However, the evidence does not suggest these interventions will have a major effect on nearby downstream flood risk for the most extreme events or in large catchments. Our study basins are in large catchments, but the flood risk maps we present show the likelihood to overspill on an annual basis. If additional storage can be created to cope with the annual runoff so that it does not overspill, then there is also a greater chance of dealing with flooding during extreme rainfall events.

4.4. Impacts of land use and population change on the capacity of natural flood management infrastructure

This study has particular relevance in highlighting the role and lack of protection of green infrastructure, given the vulnerabilities of such areas to land use changes associated with nearby urbanisation. The urbanisation of the countryside, called peri-urbanisation, results from the migration of urban populations to rural areas for a better quality of life. Peri-urban areas are frequently subject to sprawl of urban and agricultural infrastructure associated with growing urban populations, and such sprawl will inevitably impact on areas of green storage infrastructure unless steps are taken to protect these areas and/or mitigate impacts. Key land use changes associated with sprawl include removal of vegetation (canopy storage), compaction or destruction of soils (soil storage) and drainage of wetlands. Likewise, the drive for greater productivity in farming has led to agricultural intensification which includes landscape changes such as the loss of hedgerows and an increase in field size, the installation of land drains connecting hilltop to river channel, and channelised rivers with no riparian zone (Wheater and Evans, 2009). In this way, changes to land use associated with increasing urbanisation and agricultural intensification, are likely to significantly negatively impact water storage capacity, flood regulation and other ecosystem services, and the results presented here indicate that key areas of concern around major cities can be highlighted for further consideration and potential conservation and restoration actions.

4.5. Significance of natural infrastructure flood risk metrics

We have applied simple but robust and globally applicable metrics based on remote sensed data to enhance understanding of flood risk and the role of natural flood management infrastructure across a range of cities. These metrics can be applied for any basin or country as part of the WaterWorld tool (Mulligan, 2013; Mulligan, 2016). They have the advantage of not requiring complex data gathering or processing so can be applied rapidly to new study areas in a way that is globally consistent and therefore comparable. They consider both the potential service (as the storage volume), the realised service (the storage volume in relation to the volume of storage required to store the annual runoff), the sites of service consumption (urban areas for this paper) and other characteristics of the service providing areas (e.g. protected areas for this paper). As simple globally applicable metrics, they do not incorporate grey flood mitigation infrastructure such as levees and flood control schemes (other than large dams). Nor do these metrics focus on flood events (since future rainfall magnitudes and distributions are essentially unpredictable). Rather the WaterWorld metrics focus on the extent to which the annual runoff is less than or greater than the flood storage capacity, in recognition that if there is sufficient flood storage capacity to hold the annual runoff then, all else being equal, flooding will be less common. Stores that drain to the land component of the hydrological cycle are not considered to have refill capacity within the year given that any drainage is to land stores downstream and thus represents flood risk; the only store that refills is the canopy storage that empties to the atmosphere and thus does not contribute to flood risk. Though we calculate a full water balance including evapotranspiration by agriculture, water extraction for urban domestic use is not factored in as this is not a consumptive use (water is returned through drains to the land system so is still available to cause flooding downstream).

5. Conclusion

We have demonstrated the application of WaterWorld's Natural Infrastructure flood risk metrics in the upstream basins of five cities that have differing basin characteristics and climatology. By mapping the magnitude and types of 'natural' storages in these basins, we have shown that most city upstream basins have a strong reliance on green natural storage which is driven primarily by canopy cover but also soil storage. This skew towards green storage means that major sources of landscape level water storage are susceptible to modification or removal, leaving those cities vulnerable to an increase in flood risk.

Indeed, when relating the storage to protected areas we discovered a widespread lack of protection for this valuable green natural storage. Some city upstream basins, such as Chennai and Guayaquil, have almost no protection of green storage areas. For those basins with some level of protection, these areas were often in remote high-elevation areas at considerable distance to the beneficiaries of the service.

The use of WaterWorld's accumulated annual runoff to storage capacity ratios to determine areas of potential annual flood risk revealed distinct patterns as to which storage was contributing to the flood mitigation and where it was located. These patterns could indicate that disparate city basins may be categorised into different 'storage/risk' types with associated strategies for intervention. Hence, such tools that allow rapid initial assessments of the contribution of natural flood infrastructure to mitigating flood risk in urban areas, across multiple cities at national, regional and even global scales, allows a diverse range of stakeholders, from city planners and protected area managers, to national governments and civil society organizations, to assess optimal locations for further, more detailed analysis, planning and investment in green flood storage.

Overall, we have shown that the method of comparing storage capacity to runoff volumes as ratios could be a useful way to determine potential flood hazard using globally accessible data inputs. This analysis was done using the default parameter values for the natural storage metrics across all five basins. However, practitioners working in specific locations could use their own parameter values, or even their own storage maps in the WaterWorld platform, to obtain more locally specific results. In particular, site specific information on soil types and depths could greatly improve the storage estimates.

The methods outlined here allow for the identification of priority areas for conservation of flood relevant natural infrastructure under current conditions and scenarios of land use and climate change.

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Chapter 4

The impact of climate change on hydrology and flood risk mitigation services in selected upstream city watersheds

4.1 Chapter summary

Climate change will result in some areas of the world getting wetter and others getting drier. Some basins (or parts of basins) upstream of cities are already at or over capacity in terms of natural water storage, and any additional input of precipitation above baseline (as a result of climate change) may increase flood risk if not mitigated. In this chapter, flood risk is determined by the Storage to Total Capacity ratio, described fully in Chapter 3, and is referred to as the 'flood risk ratio' or FRR in this chapter. Flood risk ratios above one are considered high-risk. This chapter, i) shows where, and by how much, unmitigated flood risk will be higher, lower or the same under the various climate scenarios, ii) determines if there are any geographic patterns to increases in flood risk in the study basins, and iii) determines which climate scenarios pose the greatest threat in terms of increasing flood risk. The climate scenarios referred to in this chapter are three Representative Change Pathways (RCPs) for two time periods (totalling six scenarios) conducted using multi-model ensembles.

To determine change in flood risk, I used the *WaterWorld Policy Support System* (described in Chapter 2, section 2.6) to run climate change scenarios and compare scenario variables of water balance (such as rainfall, evapotranspiration and fog) to baseline values for the whole basin annually, and seasonally. I then compared the change in flood risk ratios for the whole basin as well as at spatially distributed river points in the basin. Instances where flood risk ratios increase under a climate change scenario were mapped to the associated Natural Infrastructure (NI) storage. I evaluated the geographic patterns of flood risk ratio increases.

I found the following:

- The smallest study basins (Nairobi and Chennai) showed the largest increases in water balance and flood risk ratios, at the basin scale, indicating a possible effect of basin size on flood risk. However, the inverse was not true.

- At the river point scale, the Nairobi, Chennai, Bogotá and Guayaquil watersheds, show an increase in flood risk ratios at all the river points for all RCPs. In the London and the Jakarta upstream basins, almost all the points show a decrease compared to baseline.
- For the river sampling points, there is no significant relationship between distance to city boundary and mean pcd of FRR due to climate change for four out of six of the basins: Nairobi, Jakarta, Bogotá and London. However, there is a significant correlation for Chennai and Guayaquil but in opposite directions.
- An association between the number of climate scenarios agreeing on a >10% increase in flood risk and increasing slope and tree cover was found in the Jakarta and Bogotá basins.
- Elevation was a predictor of flood risk increase in the Jakarta basin.
- There is an association between where more than three scenarios project increases in flood risk to occur, and the NI storage type that predominates in those locations, i.e., either soil or canopy.
- The basins which will need additional mitigation for some, or all scenarios (based on close-to-the-city sampling points) are Nairobi, followed by Guayaquil, then Chennai and last, Bogotá. The London and Jakarta basins are the best able to mitigate the flood risk related impacts of climate change, if all else remains equal.
- The ‘worst-case’ scenario, RCP 8.5 2070s, did not always produce the greatest increases in flood risk ratio.

Overall, this study has successfully shown where flood risk ratios are projected to increase under climate change scenarios in the study basins, highlighting where NI is likely to be overwhelmed, and thus where additional flood storage, natural or grey or hybrid, may be useful.

4.2 Introduction

This chapter focuses on modelling the change in flood mitigation service provision to six cities under different scenarios of climate change (Objective 2 of the thesis). The aim of this chapter is to determine how six scenarios of climate change (three radiative forcing scenarios based on emissions trajectories, for two time periods) will alter variables of water balance and flood risk in the six case study basins: Nairobi, Chennai, Bogotá, Jakarta, London, and Guayaquil. Flood risk is determined by the Storage to Total Capacity ratio, described fully in Chapter 3, and is referred to as the 'flood risk ratio' or FRR in this chapter. Flood risk ratios above one are considered high-risk. If flood risk is projected to be higher than the baseline, then more mitigation (grey or green) will be required in those basins (or else assets will have to adapt). These areas also have other attributes which we target in Chapter 5.

Specifically, my research questions are:

i) show where, and by how much, unmitigated flood risk (as defined in Chapter 3) will be higher, lower or the same under the various scenarios;

ii) determine if there are any geographic patterns to increases in flood risk in the study basins; and

iii) determine which climate scenarios pose the greatest threat in terms of increasing flood risk.

I present background context on climate change modelling in Chapter 2, and projections from the literature for my study regions in **Appendix D**.

4.3 Methods

4.3.1 Model parameters used for running climate scenarios

The policy support platform, *WaterWorld* (Mulligan, 2013), was used to conduct the climate modelling runs and, subsequently, to measure the change in flood risk ratios.

To ensure consistency across the study, I used the same basin extents (ZOI: zone of interest) identified in Chapter 3. After running a baseline simulation in *WaterWorld* v2, I used the '*Policy exercises*' feature to run various climate scenarios. I set up the runs to use CMIP5 (rather than the alternative option of AR4); the scenarios used were RCP 4.5, 6.0 or

8.5 (*WaterWorld* refers to them as RCP 45, 60 and 85). RCP 2.6 was excluded due to its improbability of being an achievable target by global society. The downscaler used was WorldClim[49] (description below). For the GCMs (General Circulation Models, the '*mean of all models*' or '*mean plus 1 SD*' or '*mean minus 1 SD*' (see below) was selected. Finally, the 2041-2060 or 2061-2080 time periods are available. A screenshot of the model setup is shown in Figure 4.1.

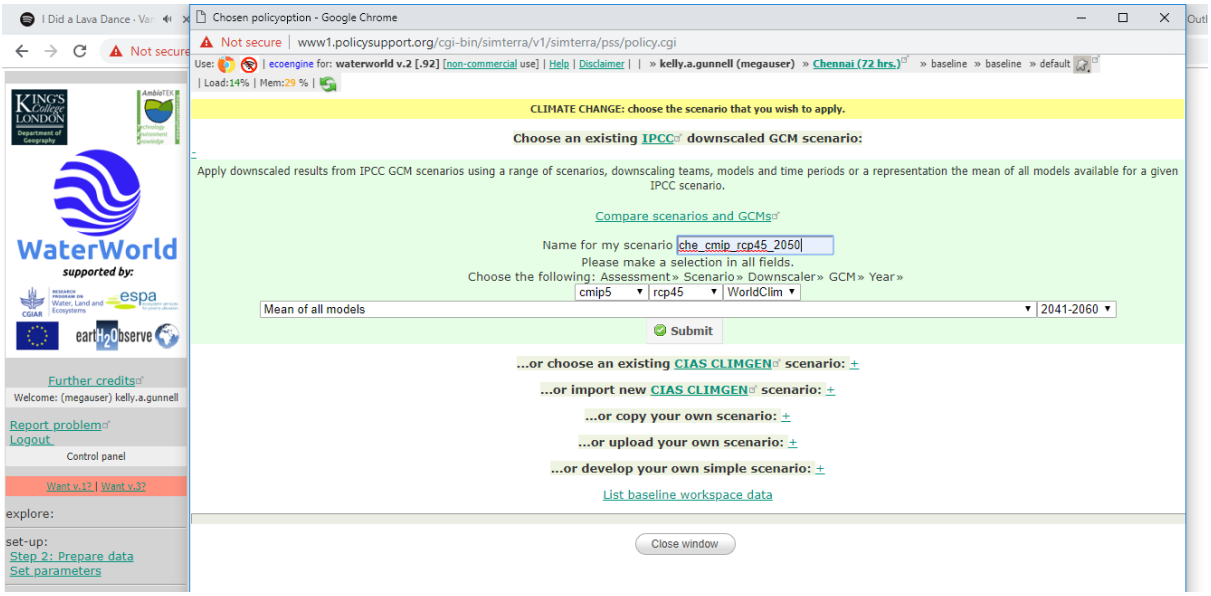


Figure 4.1 Screenshot showing model setup for climate scenarios in WaterWorld

WaterWorld, via WorldClim, provides 19 GCMs (for RCP45; Table 2.11, Chapter 2) to choose from as well as the option to run the Mean of All, Mean of All minus one SD (standard deviation) [between the GCMs, at a pixel level] or Mean of All plus one SD [between the GCMs, at a pixel level]. Except for where stated otherwise, I used the 'Mean of all models' option (see below).

WorldClim: baseline and downscaling of future climate data

The baseline (near current conditions) climate data and future climate data (downscaled) used in the *WaterWorld* platform are from WorldClim. WorldClim is a set of global climate layers (gridded climate data in GeoTiff format) that can be used for mapping and spatial modelling. It contains climate data for current, historical and future conditions. The 'current conditions' dataset of WorldClim v1.4 (Hijmans et al., 2005) used in these analyses contains gridded data for the period 1950-2000 (the baseline) for average monthly minimum, mean, and maximum temperature, as well as other bioclimatic variables. The 'future' climate data has temperature and precipitation projections by the IPCC Fifth Assessment Report using

[49] https://worldclim.org

several GCMs for four RCPs. The datasets on future projections refer to the middle century (2041–2060) and the end of the century (2061-2080). The midpoint years, '2050s' and '2070s', will be used as reference in the rest of the chapter. The down-scaling approach used for WorldClim future data is described on its website[50].

Multi-GCM (ensemble) means

There are hundreds of GCMs currently available, although only 28 GCMs are used in CMIP5, and they differ in structural identity, modelling variability and uncertainties. Some models perform better than others for certain regions or variables (Hayhoe et al., 2017), producing another source of uncertainty. Over-reliance on a single GCM is discouraged (Wilby & Harris, 2006). To reduce some of these uncertainties, models are usually combined into a multi-model ensemble for which the average of the multiple climate projections for a given climate variable is taken. This is called the ensemble mean, or in WaterWorld, the *Mean of all Models*. It has been empirically shown in a number of studies that the ensemble average can produce better observations than even the best individual model, and for a variety of applications not only limited to weather and climate predictions (Palomino-Lemus et al., 2018; Tebaldi & Knutti, 2007; Wallach et al., 2016). A benefit of using multi-model means is that they represent the range and distribution of the most plausible projected outcomes, but a disadvantage is the averaging out of extremes. A further note on this approach is the implicit and invalid assumption that each climate model is independent from the others and of equal ability (Hayhoe et al., 2017).

GCM uncertainty

To further account for uncertainties and bias, I captured the standard deviation (SD) +1 and SD -1 for all the variables under all scenarios. The standard deviation is a measure of the amount of variation or dispersion of a set of values relative to its mean. Assuming that the data are normally distributed, 1 SD should capture 68% of the values. **These results are presented in Figure D1 in Appendix D.**

Descriptions of climate change modelling terms and methods, such as GCMs, CMIP and RCPs, are explained in Chapter 2.

4.3.2 Comparing change in hydrological variables under climate scenarios

The climate scenarios were run for the whole basin and compared to the baseline in three ways: i) ***Annually***: taking the mean of all models for one time step on an annual scale, ii)

[50] https://worldclim.org/data/downscaling.html

taking the ***standard deviation mean +1*** and ***standard deviation mean -1***, and iii) ***Seasonally***: The model runs were repeated to write to every time step and then the monthly means were collated into four seasons: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA) and September, October, November (SON). The seasonal differences were calculated for water balance and rainfall only. **The results for standard deviation and seasonal change in hydrological variables are reported in Appendix D.**

Both the baseline and scenario total sum and mean estimates for each of the following hydrological variables were captured for each upstream basin: water balance, rainfall, total fog inputs, evapotranspiration and runoff (see Table 4.1 for definitions). All these variables were considered, and not only runoff, as they help explain why and how runoff changes. This has implications for land management, for example.

Table 4.1 Definitions, determinations and units for the relevant hydrological variables calculated and used in WaterWorld.

Hydrological	Definition or how determined	Units
Water balance	The sum of rainfall, fog and snowmelt, minus actual evapotranspiration.	mm/year
Rainfall	The total annual wind-driven rainfall, calculated according to the impact of wind speed on falling rain.	mm/year
Total fog inputs	The impacted (wind driven) and the sedimented (deposited under low wind speeds) fog inputs	mm/year
Evapotranspiration	Actual evapo-transpiration as determined by available energy and vegetation cover and properties.	mm/year
Runoff (total annual runoff)	Calculated as water balance cumulated downstream. Negative water balance occurs where (AET>precipitation) in a cell and is supported by runoff from upstream.	m^3/year

To capture the scale and direction of change from the baseline condition to the scenario condition, the *percent change difference* (pcd) was calculated as follows:

pcd = ((new value-old value)/old value)*100 *eqn(1)*

where the *new value* is the scenario sum for the ZOI and the *old value* is the baseline sum for the ZOI, calculated annually. The result is a percentage: either positive, indicating an

increase, or negative, indicating a decrease, compared to the baseline value. In addition, the absolute (not percent change) difference between the scenario means and the baseline means was calculated (mm/year). Both the absolute magnitude and percent change is important to capture because in some areas the percent change may be small but in absolute numbers is large compared to the other basins (for example Guayaquil) or the opposite, the percent change is very large but the absolute values are small (for example Nairobi). In a flooding context, relative change is important: if a river can cope with 5000 mm rainfall, it can cope with 5050 mm, but a river that normally has 20mm rainfall may flood with the extra 50 mm.

4.3.3 Comparing change in flood risk under climate scenarios

Flood risk ratios for each basin were captured from *WaterWorld* as Storage to Total Capacity ratio, either accumulated or non-accumulated (as detailed in Chapter 3). For this chapter, the change in flood risk ratios due to different climate scenarios was calculated, first for the whole basin and then second, for individual points along the river network.

Point locations were chosen first, by where the rivers enter the main urban area as defined by the urban layer in WW (Schneider et al., 2009), then by their position before entering the HDC (High Density Center) or LDC (Low Density Center) urban areas[51] (identified by overlaying a river network on these layers in GIS), and finally (especially for the large basins) by distributing the points along the upstream network in the ZOI to get an even distribution, covering main tributaries and/or before urban areas (where flooding is a potential hazard). **See Figures D1.1 and Figure D.2 in Appendix D for the point locations.** For each point, the change in flood risk ratios (defined in Chapter 3) based on the three RCPs and two time periods were calculated as percent change difference (pcd) from baseline.

4.3.4 Mapping change in flood risk ratios

Flood risk ratios were calculated for each climate scenario for each basin. Two ratios are available to use:

i) Water storage: total capacity ratio, and ii) Water storage: total capacity ratio (downstream accumulated). The difference between them is that the first is grid cell water balance over storage capacity in the grid cell, i.e., local storage and local capacity. The second is

[51] From the Global Human Settlements Model grid (GHS-SMOD) 2015 (Pesaresi et al., 2016). HDC areas have a density of at least 1,500 inhabitant/km2 or density of built-up greater than 50%, and a minimum of 50,000 inhabitants. LDC areas have a density of at least 300 inhabitants/km2 and a min population of 5,000 inhabitants.

accumulated water balance (runoff) over accumulated storage capacity. The first is good for looking at grid-cell by grid-cell contributions. The second is more relevant to understanding upstream-downstream relationships and landscape scale flood risk mitigation. For this section, I use the second ratio, "Water storage to accumulated total storage capacity", which I refer to as the *flood risk ratio* or FRR.

To calculate the scenario mean, I created a raster stack of the scenario results for each basin and calculated the mean. To calculate the mean (of the scenarios') difference from baseline, I took the scenario mean and subtracted it from the baseline result. In order to determine the mean difference from high-risk (>1) baseline values, I removed all values <=1 from the baseline, then subtracted the scenario mean.

Since the flood risk ratios might increase by very small amounts, it may not be useful to show all the grid cells where the scenarios have increased in flood risk but where they have increased by a minimum value or percentage. I therefore used a lower threshold value of 10% to remove the effect of lots of small increases. To do this, I created a function in R:
*x>(y*0.1)*

where x is the difference map (scenario - baseline) and y is the baseline. This was applied to all the scenario difference maps resulting in maps of 0s and 1s. The 1s indicate cells where the scenario increase was greater than 10% of the baseline value. These binary maps were then added together to show how many of the six scenarios have an increase of greater than 10% of the baseline value. Hence, if a grid cell shows "1" then only one climate scenario shows an increase in that cell, and if a cell shows "6", then all six scenarios show an increase of more than 10% compared to baseline.

Two aspects of change that are of interest are where i) climate scenarios show high-risk ratios increasing, and where ii) low risk ratios in the baseline become high-risk in the scenario. To determine i) "high-risk increasing", all low-risk cell values (<=1) were recoded to NA in both the baseline and scenario maps so that only the high-risk (>1) values remained. I took the difference between the scenario and baseline to create a difference map, and then chose those values that were >0 to indicate the values that had increased from the baseline in the scenario. These maps were then added together to create a combined map with values ranging from "1" to "6", with "1" indicating only one climate scenario shows an

increase in that cell, and if a cell shows “6”, then all six scenarios show an increase in that grid cell, if “5”, then five scenarios, etc.

To determine ii) “low risk becoming high-risk”, I made a binary map where all the grid cells in the baseline that were low risk (<=1) became “1’s” and everything else 0s. For the scenario maps, I created a binary map where the high-risk values (>1) became “1s” and everything else “0s”. I then multiplied the new binary “low-risk” baseline map by the new binary “high-risk” scenario map, so that if the result was a “1” it indicates where a low-risk grid cell value became a high-risk grid cell value, and if a “0” then not. These maps were then added together to create a combined map with values ranging from “1” to “6”, with “1” indicating only one climate scenario shows a risk increase in that cell, and if a cell shows “6”, then all six scenarios show an increase in that grid cell, and so forth.

4.3.5 Mapping the NI storage type where flood risk ratios increase under climate scenarios

Knowing the NI water storage type in the areas where the flood risk ratios increased under climate scenarios may help determine if there is an overall pattern to increases in flood risk or may help to target specific NI storage types or locations with more effective mitigation. In the output maps described, a threshold of more than three scenarios showing an increase was used as a mask of the Local Greatest Storage Map (defined in Chapter 3). Three was chosen as a medium value, as one would only show an extreme scenario and six (all the scenarios) may be too limiting a threshold. The output maps show the NI Storage type where more than three climate scenarios showed i) >10% increase, ii) high-risk increasing, and iii) low risk becoming high-risk.

4.4 Results

4.4.1 Comparing change in hydrological variables – Annual

Changes in overall water balance, rainfall, fog inputs, evapotranspiration and runoff were compared to baseline conditions on an annual timescale. Figure 4.3 shows the difference from the baseline mean in real units (mm/year). Figure 4.4 shows the percent change difference (pcd) from baseline.

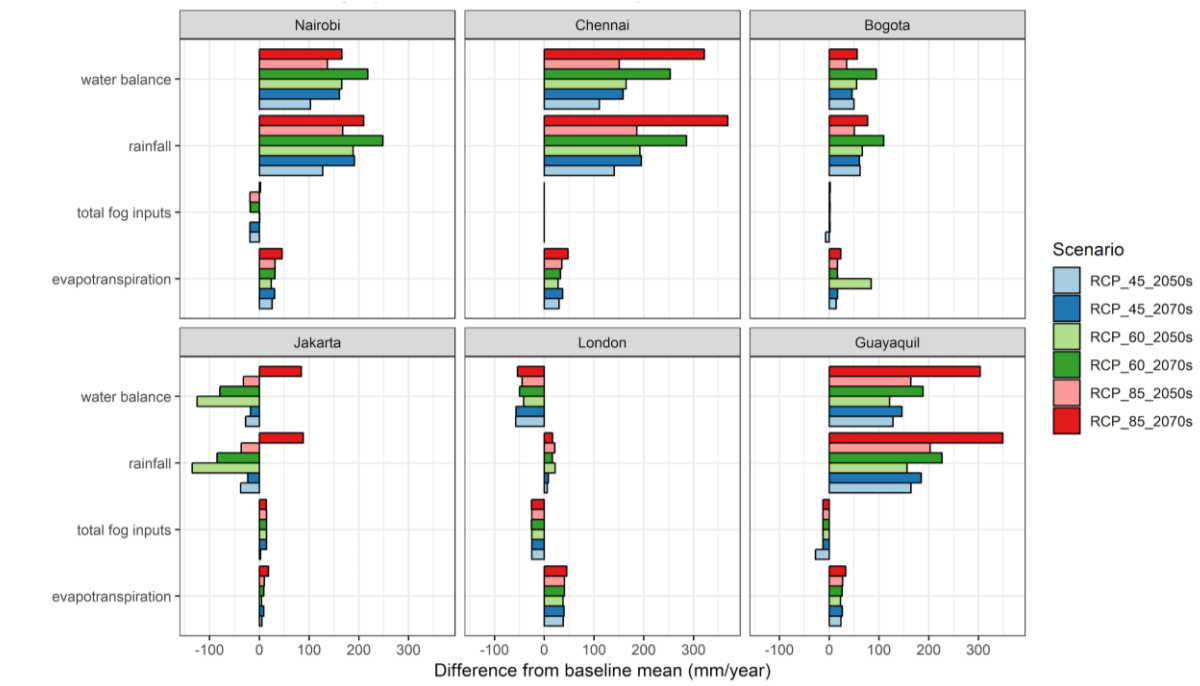


Figure 4.2 Difference from baseline mean (mm/year) for four variables of water balance for the six upstream city basins calculated annually. Runoff is excluded as it does not fit on the same axis.

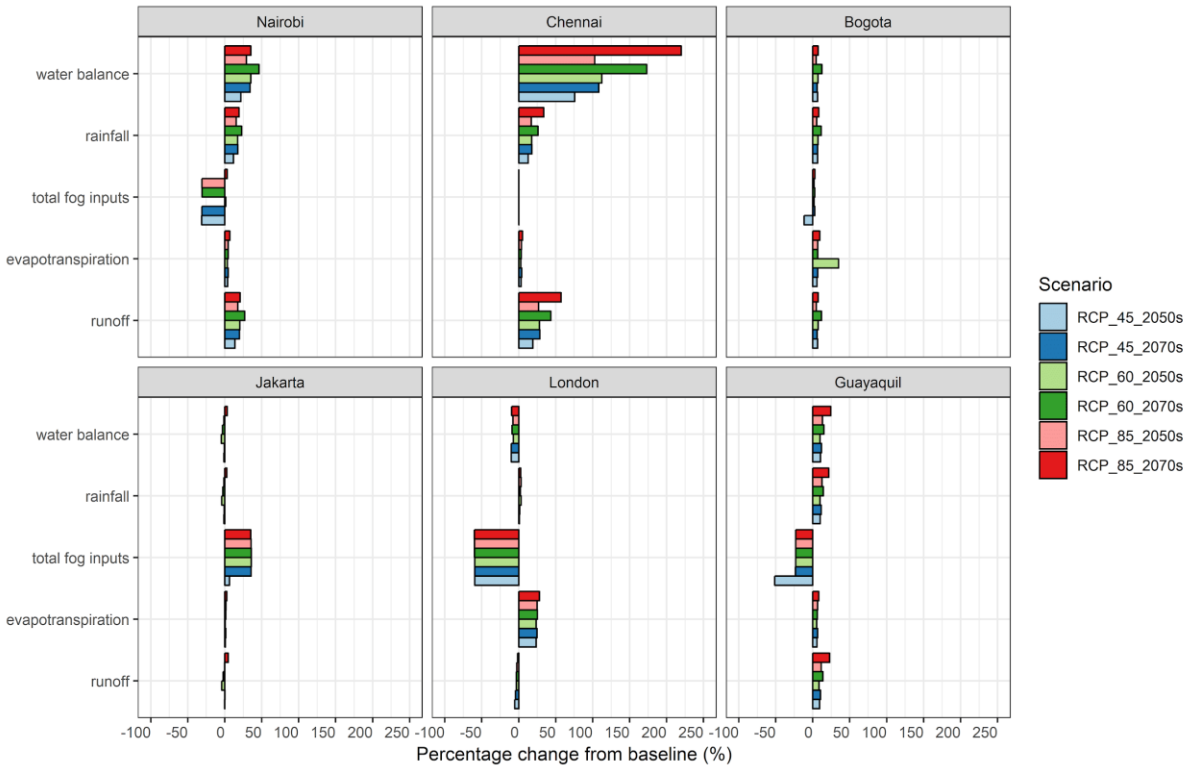


Figure 4.3 Percent change difference (%) from baseline conditions for five variables of water balance in six upstream city basins calculated annually.

City comparison

The Chennai basin shows the largest percent change difference from baseline, with an increase of +75% to just under +225% in water balance under the RCPs (Fig. 4.3). Nairobi had the next largest increase, with +25% to +50% increase in water balance from baseline. Water balance increases by smaller percentages for Bogotá (+6 to +12%) and Guayaquil (+10% to +24%; Fig.4.5). However, the Guayaquil basin has one of the largest absolute increases in mean water balance and rainfall, after Chennai, of +121 to +303 mm/year for water balance and +156 to +348 mm/year for rainfall (Fig 4.2).

In contrast, water balance decreases for the Jakarta and London upstream basins. In the Jakarta upstream basin, water balance decreases by between -4.7% and -0.67%, with an increase of 3.18% under RCP 8.5 for the 2070s (Fig. 4.2). In the London upstream basin, water balance decreases even though rainfall increases. Water balance decreases by between -7% to -10% under all the RCPs, and rainfall increases by between +0.88% and +3.19% (Fig 4.3). The increase in mean rainfall is between +5.97 mm/year and +21 mm/year which is quite small and offset by the increase in evapotranspiration and decline in total fog inputs (Fig 4.2).

Standard deviation

The percent change difference (pcd) in mean +1 standard deviation (SD) and mean -1 SD was calculated for the same variables. The results mostly show mean +1 with positive pcds, indicating variables increasing compared to the baseline. Mean -1 SD showed negative pcds, indicating variables decreasing compared to the baseline. **The figures illustrating these results are in Appendix D (Fig. C1).**

4.4.2 Compare change in hydrological variables - Seasonal

The seasonal effects of the various climate change scenarios were analysed for four seasons: DJF, MAM, JJA, and SON, for i) rainfall and ii) water balance. **The figures illustrating these results are in the Appendix D** (Fig. D2 and D3 for changes in seasonal rainfall and D4 and D5 for seasonal water balance). The main finding is that there is seasonal variation in the increase/decreases of rainfall and water balance compared to baseline within the basins. For most basins, even if the annual trend is for an increase in rainfall compared to baseline, there is usually at least one three-month period where rainfall decreases compared to baseline (the exception being Chennai where rainfall increases in all seasons). Another finding is that increases in rainfall compared to baseline do not necessarily track to increases in water balance for the same time period.

4.4.3 Change in flood risk ratios

The change in FRR due to different climate scenarios was calculated, first for the whole basin and then second, for individual points along the river network.

Whole basin

The change in FRR as a result of climate scenarios was applied to the whole upstream basin for each city. Figure 4.6 shows the results for non-accumulated FRR (as not possible to accumulate basin sums).

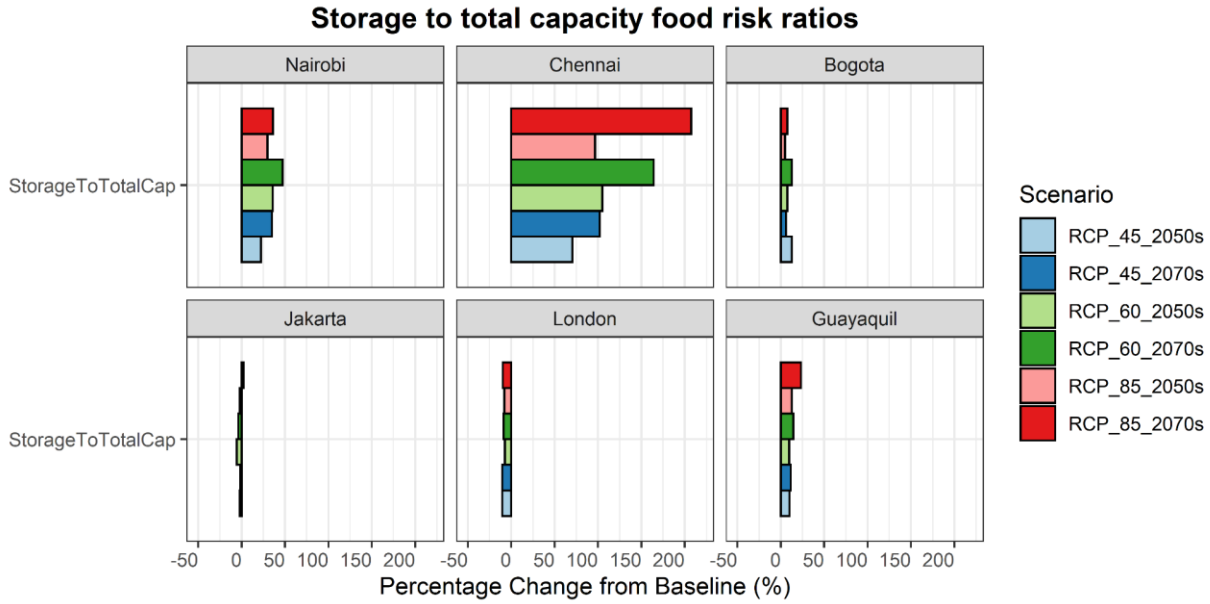


Figure 4.6 Impact of climate scenarios on annual Storage to Total Capacity ratios across RCPs 4.5, 6.0 and 8.5 for the six upstream city basins, as measured by percent change difference (pcd) from baseline.

At the basin scale, Chennai shows the greatest increase in FRR, from +66% to +207% increase across the RCPs (Fig. 4.6). Nairobi follows with a +21 to +47% increase in FRR across RCPs. The Guayaquil basin shows a smaller increase from +9 to +27%, as does Bogotá with a +5.5 to +12.5% increase in FRR across RCPs. Both the Jakarta basin and the London basin show a decrease in annual flood risk ratios. Jakarta's flood risk ratios decrease by -1.95 to -5.7% for RCPs 4.5 and 6.0, and increase by 2.5% for RCP 8.5 for the 2070s. London's flood risk ratios decrease by -7.4 to -10.2% across all the RCPs (Fig. 4.6).

River sample points

To provide a sense of the spatial variability of the climate impacts on flood risk ratio at that point, the changes in ratio for individual points along the river network in each basin were determined:

Nairobi sampling points

Figure 4.7 shows the change in FRR at the river points in the Nairobi basin. All the river points showed an increase in FRR (Fig. 4.7). The range across all points is from +8.07 to + 264.5% (mean = 57.29, median = 30.93).

For all points, the scenario RCP 6.0 for the 2070s showed the greatest change (Fig. 4.7.c).

The points' mean pcd, distance to the city-basin boundary and calculation of Spearman's rank coefficient are summarised in Table D2 in Appendix C and summarised in Table 4.2.

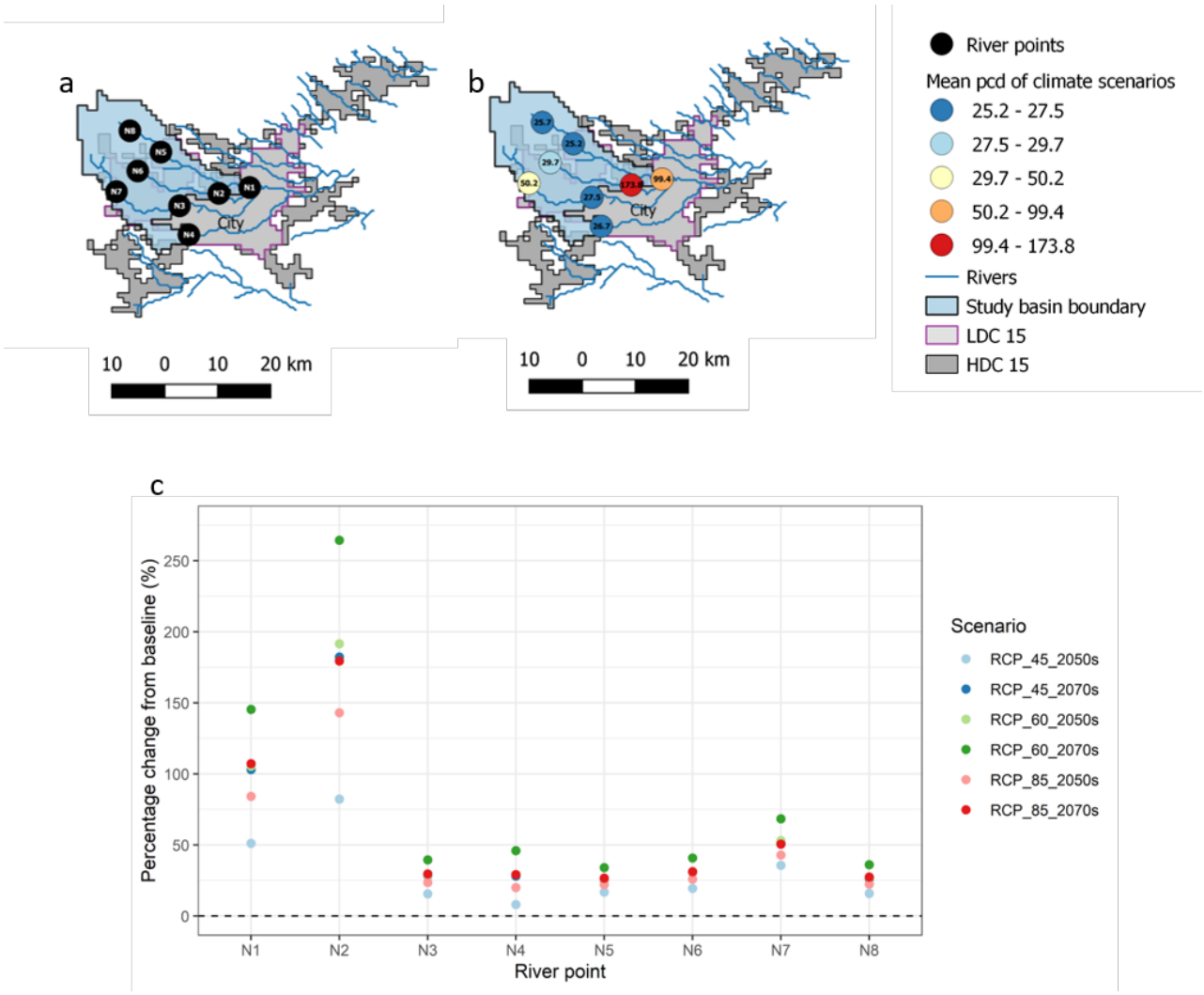


Figure 4.7 Percent change difference (pcd) from baseline for flood risk ratios for eight river points in the basin upstream of Nairobi under climate scenarios: a) shows the location and ID of the river point, b) shows the mean pcd for the river point with graduated scale (natural breaks), and c) the pcd for each scenario at each point (dashed line represents baseline).

Chennai sampling points

In the Chennai upstream basin, all the river points showed an increase in flood risk ratios (Fig. 4.8). The range across all points is from +20.83 to +148.28% (mean = 62.56%, median = 53.8%). The greatest increase in pcd is for river point C7 (range = +51.72 to +148.28%; mean = +88.51%) followed by point C6 (range = +48.28% to +141.38%; mean = +84.48%). Points C7 and C8 are the most distant points from the city boundary (Fig. 4.8.a). RCP 8.5 for the 2070s had the greatest impact for all points, and RCP 4.5 for 2050s had the least impact (Fig. 4.8c).

The points' mean pcd, distance to the city-basin boundary and calculation of Spearman's rank coefficient are summarised in Table D3 in Appendix D and summarised in Table 4.2.

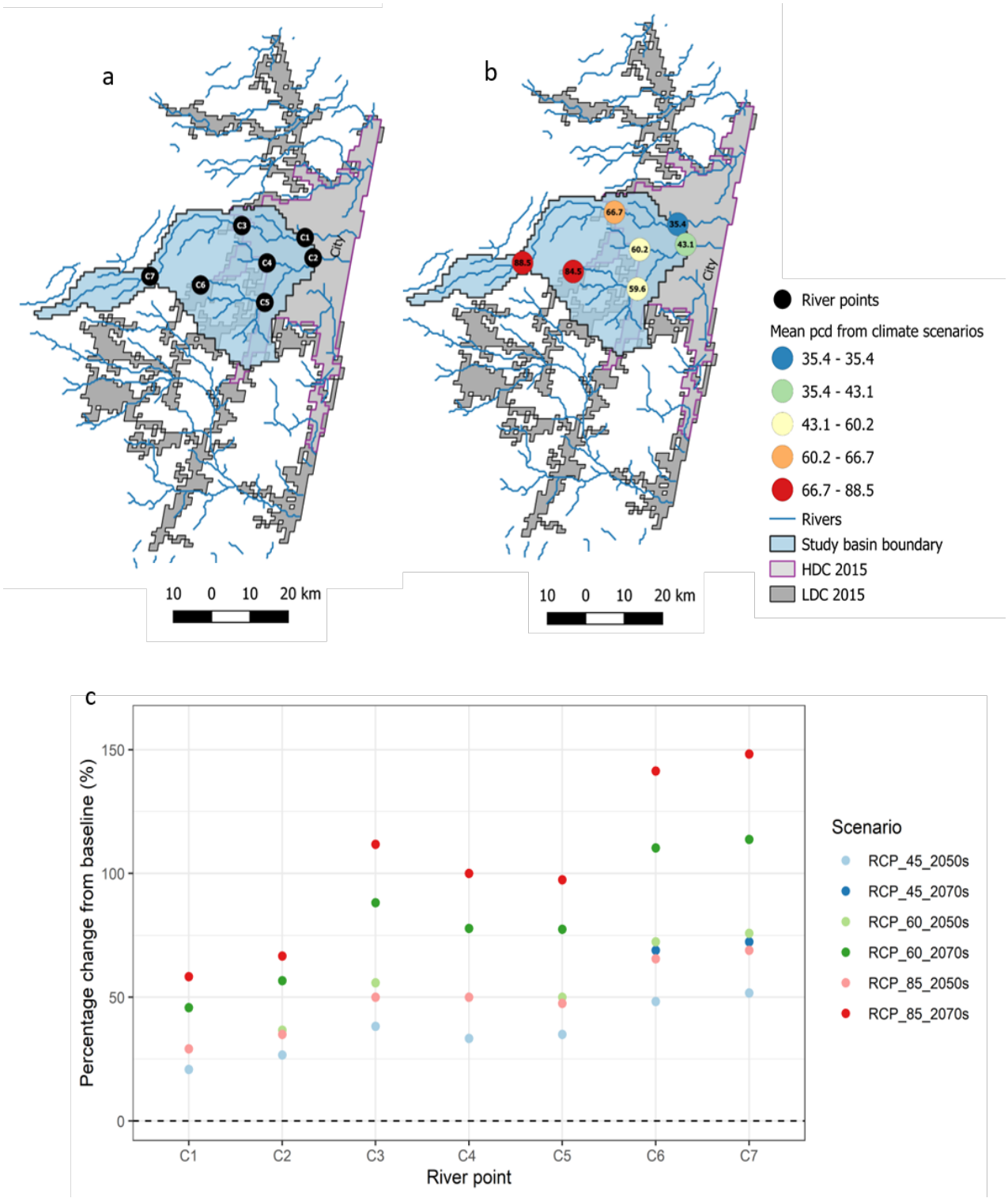


Figure 4.8 Percent change difference (pcd) from baseline for flood risk ratios for seven river points in the basin upstream of Chennai under climate scenarios: a) shows the location and ID of the river point, b) shows the mean pcd for the river point with graduated scale (natural breaks), and c) the pcd for each scenario at each point (dashed line represents baseline).

Jakarta sampling points

In the Jakarta upstream basin, all the river points showed both an increase and a decrease in flood risk ratios depending on the RCP scenario (Fig. 4.9). The range is from -7.67 to +7.49% (mean = -2.071, median = -2.440). The greatest increase in pcd is for river point J13 (range = -0.44 to +7.49%; mean = +3.06%). Point J13 is in the upstream, south-east part of the basin at a transition into the HDC urban area (Fig. 4.9.a).

For 11 of the 16 points, the ratios were above the baseline only under RCP 8.5.

RCP 8.5 for the 2070s had the greatest impact in terms of increasing FRR for all points. RCP 4.5 for the 2050s had the least impact in terms of decreasing FRR.

The points' mean pcd, distance to the city-basin boundary and calculation of Spearman's rank coefficient are summarised in Table D4 in Appendix D and summarised in Table 4.2.

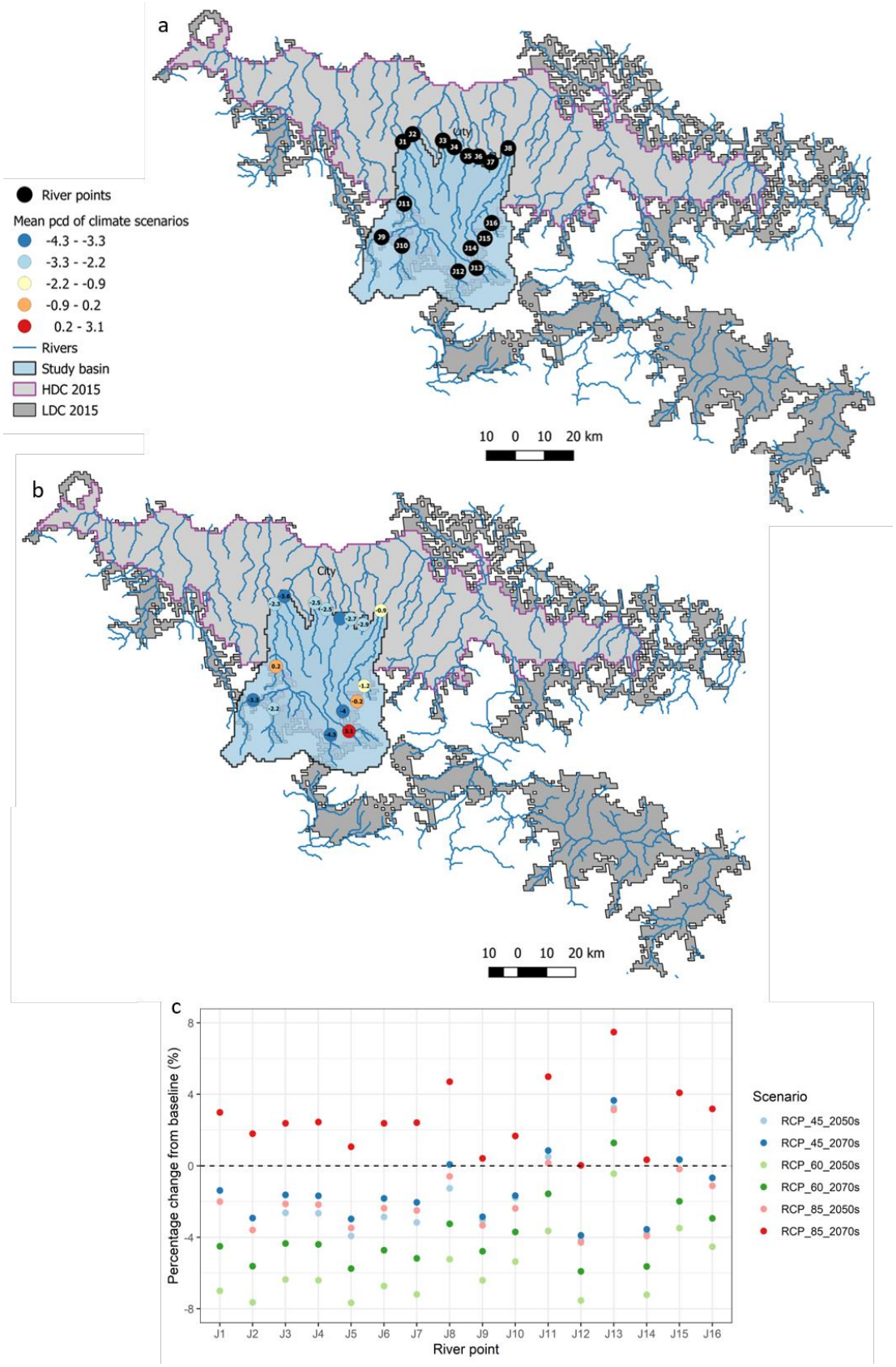


Figure 4.9 Percent change difference (pcd) from baseline for flood risk ratios for 16 river points in the basin upstream of Jakarta under climate scenarios: a) shows the location and ID of the river point, b) shows the mean pcd for the river point with graduated scale (natural breaks), and c) the pcd for each scenario at each point (dashed line represents baseline).

Bogotá sampling points

In the Bogotá upstream basin, all the river points showed an increase in flood risk ratio (Fig. 4.10). The range is from +3.03% to +33.33 % (mean = +13.93%, median = +8.33%). Table 4.5 shows the mean at each point and the distance of the point to the city-basin boundary sorted by shortest distance. The greatest increase in pcd is for river point B3 (range = +22.22% to +33.33%; mean = +27.5%). Point B3 is the most upstream point at the transition into the LDC urban area (Fig. 4.10.a).

RCP 6.0 for the 2070s had the greatest impact (for increasing FRR) for all points and RCP 4.5 for 2050s had the least impact.

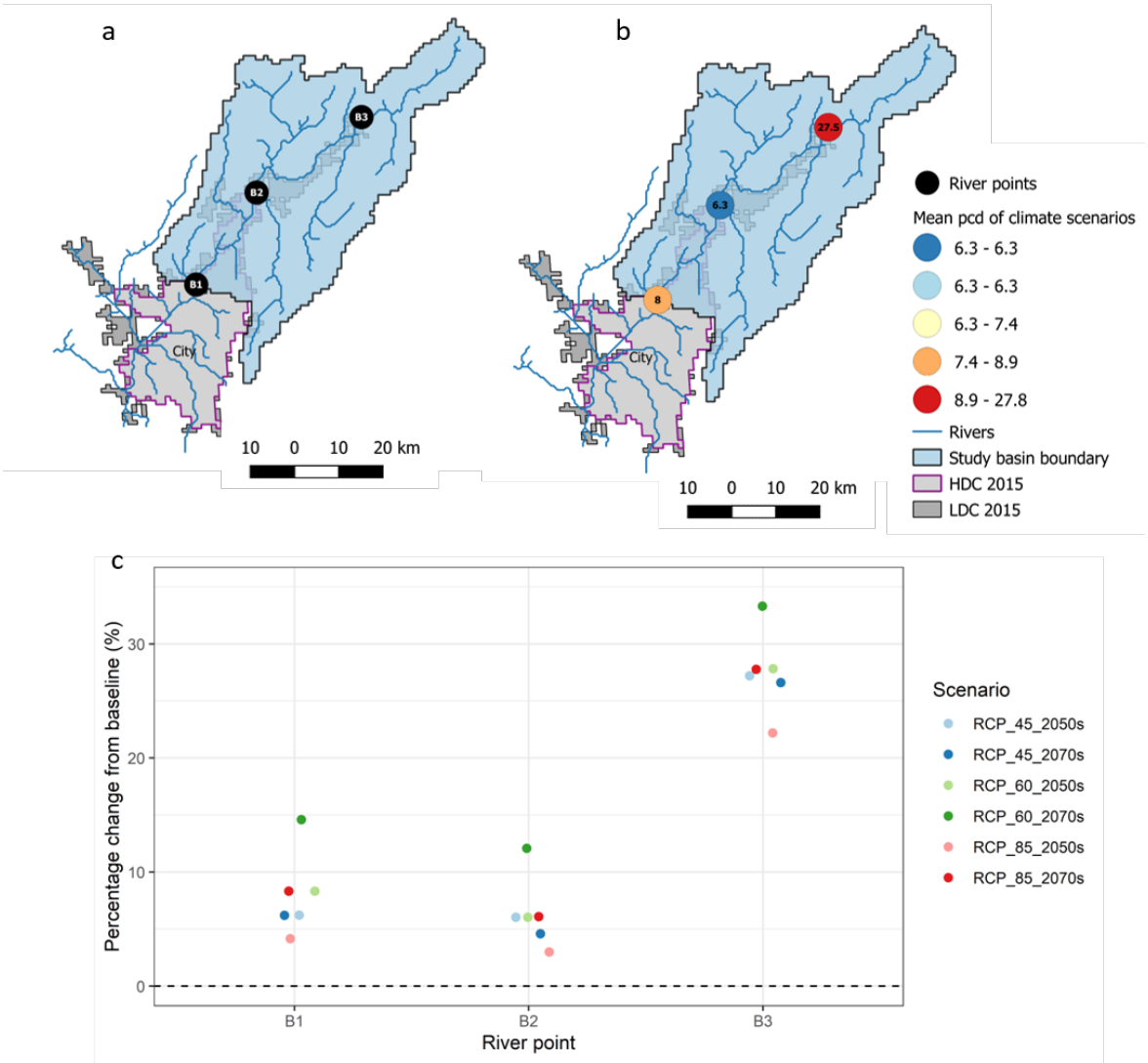


Figure 4.10 Percent change difference (pcd) from baseline for flood risk ratios for 3 river points in the basin upstream of Bogotá under climate scenarios: a) shows the location and ID of the river point, b) shows the mean pcd for the river point with graduated scale (natural breaks), and c) the pcd for each scenario at each point (points are jittered to avoid overplotting; dashed line represents baseline).

The points' mean pcd, distance to the city-basin boundary and calculation of Spearman's rank coefficient are summarised Table D5 in Appendix D and summarised in Table 4.2.

London sampling points

In the London upstream basin, all points showed a decrease except for Point L4 under scenario RCP 60 2050s (Fig. 4.11). The range is from -14.98% to +0.49% (mean = -7.79%). River point L6 had the lowest Storage to Total Capacity ratios (mean = -13.42%), followed by point 11 (mean = -12.58%). Point L4 is on the William Girling Reservoir, by the River Lea at the boundary of the study basin. Point L6 is on the River Colne on the study basin boundary (Fig 4.11.a).

The points' mean pcd, distance to the city-basin boundary and calculation of Spearman's rank coefficient are summarised in Table D6 in Appendix D.

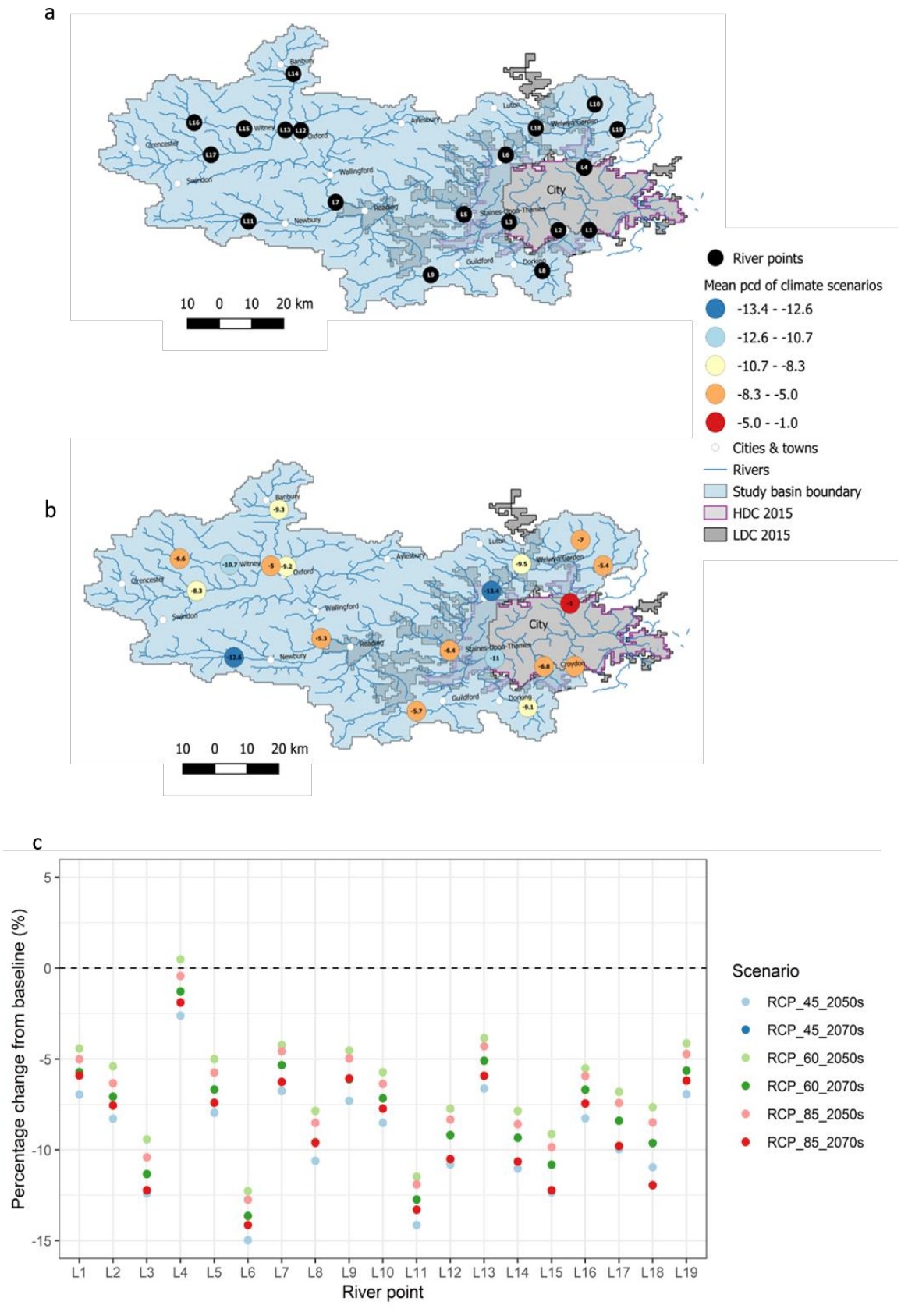


Figure 4.11 Percent change difference (pcd) from baseline for flood risk ratios for 19 river points in the basin upstream of London under climate scenarios: a) shows the location and ID of the river point, b) shows the mean pcd for the river point with graduated scale (natural breaks), and c) the pcd for each scenario at each point (dashed line represents baseline).

Guayaquil sampling points

In the Guayaquil upstream basin, all the points showed an increase in flood risk ratios (Fig. 4.12). The range is from +2.72% to +111.89% (mean = +24.78%, median = +17.23%). River point G1 had the highest pcd increase (mean = +70.3%), followed by river point G6 (mean = +66.4%). Point G1 is at the most downstream point at the boundary of the study basin, in the HDC urban area. Point G6 is on the Rio Daule just before the river enters the town of Daule (Fig. 4.12.a).

The points' mean pcd, distance to the city-basin boundary and calculation of Spearman's rank coefficient are summarised in Table D7 in Appendix D and summarised in Table 4.2.

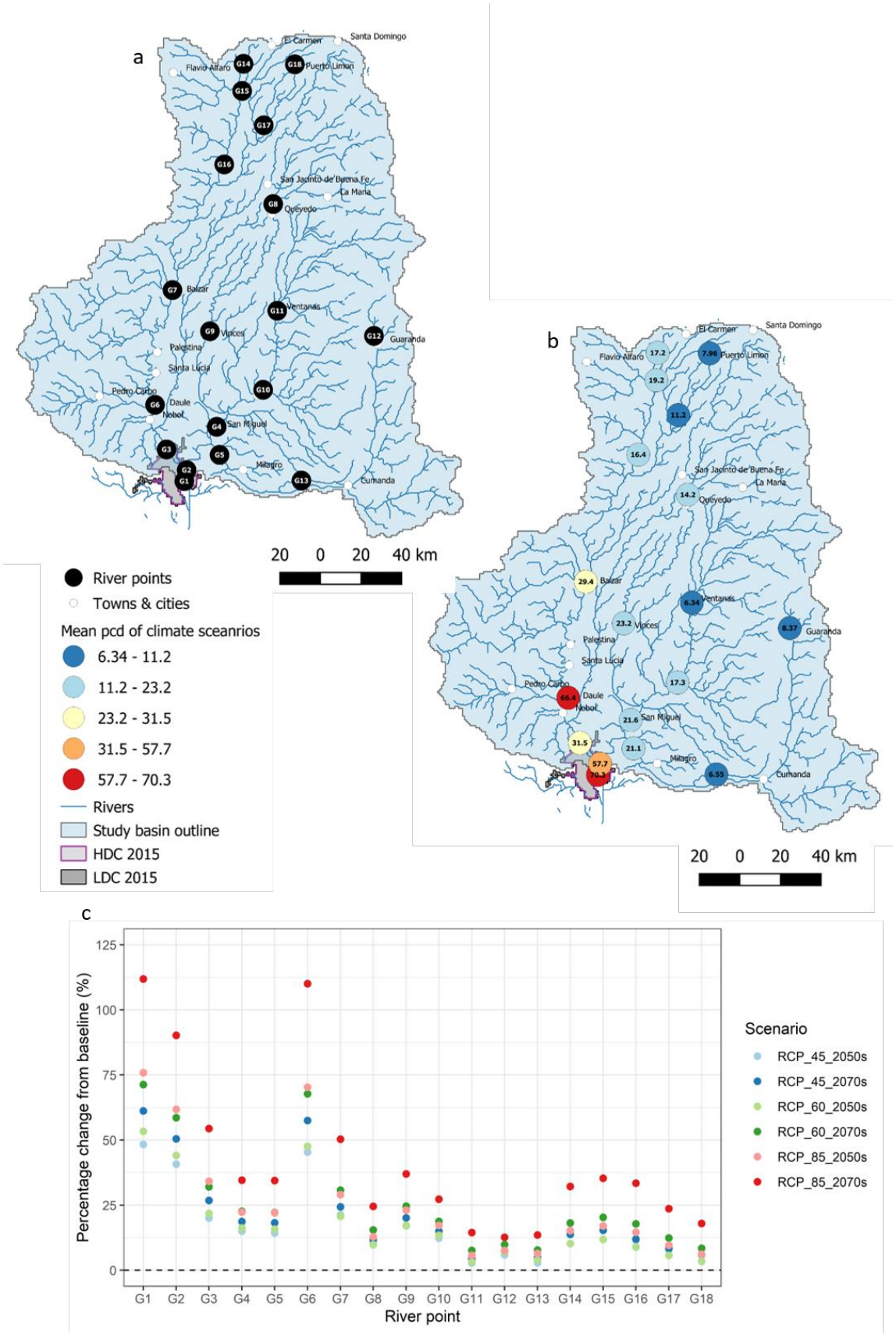


Figure 4.12 Percent change difference (pcd) from baseline for flood risk ratios for 18 river points in the basin upstream of Guayaquil under climate scenarios: a) shows the location and ID of the river point, b) shows the mean pcd for the river point with graduated scale (natural breaks), and c) the pcd for each scenario at each point (dashed line represents baseline).

Test of correlation of distance to city boundary and mean pcd of flood risk ratio

To test if there is a relationship between the distance between the river sampling point and the city boundary and the mean pcd of the flood risk ratio (FRR) due to climate scenarios, I proposed the following null hypothesis (H_o) and hypotheses (H_1 and H_2):

H_o: There is no significant relationship between the distance of the river sampling point and the mean pcd in FRR due to climate scenarios.

H_1: The mean pcd increases as distance to city boundary decreases.

H_2: The mean pcd increases as distance to city boundary increases.

Spearman's rank correlation coefficient was used to discover the strength of the link between the two sets of data and either prove or disprove the hypotheses. **The data tables for each basin are in Appendix D (Table D2 to D7)** and the results summarised below in Table 4.2. The results show that there is no significant relationship between distance to city boundary and mean pcd of FRR due to climate change for four out of six of the basins: Nairobi, Jakarta, Bogotá and London. However, there is a significant correlation for Chennai and Guayaquil but in opposite directions. In Chennai, mean pcd increases as distance to city increases (H_2 accepted; very strong positive correlation). In Guayaquil, mean pcd increases as distance to city decreases (H_1 accepted; moderate negative correlation).

Table 4.2 Summary of the Spearman rank coefficients (Rs), correlation meaning, significance level and decision to accept or reject the hypothesis of a relationship between distance to city boundary and mean pcd for FRR for each river basin. A significance level greater than 5% means that the result was likely a product of chance, and the hypothesis must be rejected. Significance levels are determined by a graph that compares the Rs against the degrees of freedom.

Basin	Rs	Correlation	Significance	Accept/reject hypothesis
Nairobi	-0.55	moderate negative correlation	>5%	Reject
Chennai	0.96	**very strong positive correlation**	**1%**	**Accept**
Jakarta	-0.04	very weak negative correlation	>5%	Reject
Bogotá	0.50	moderate positive correlation	>5%	Reject
London	-0.26	weak negative correlation	>5%	Reject
Guayaquil	-0.69	**moderate negative correlation**	**~5%**	**Accept**

Performance of RCPs at point locations

To determine the effects of the different RCPs, the pcd from the baseline for flood risk ratios of each upstream basin was first grouped by RCP in a dot plot (Fig. 4.13), and second by RCP only in a box plot (Fig. 4.14).

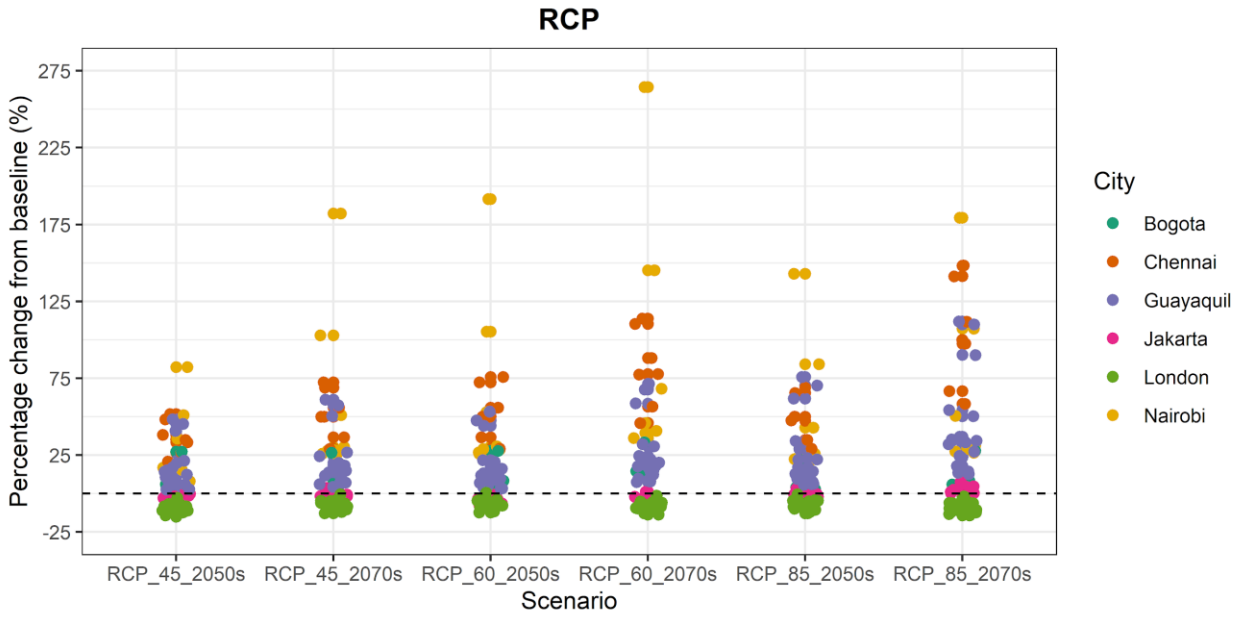


Figure 4.13 Percent change difference (pcd) from baseline to scenario of Storage to Capacity ratios of river point grouped by RCP (points jittered). Colours represent the city upstream basin. Dashed line represents 0 pcd, i.e., where no change has occurred relative to baseline.

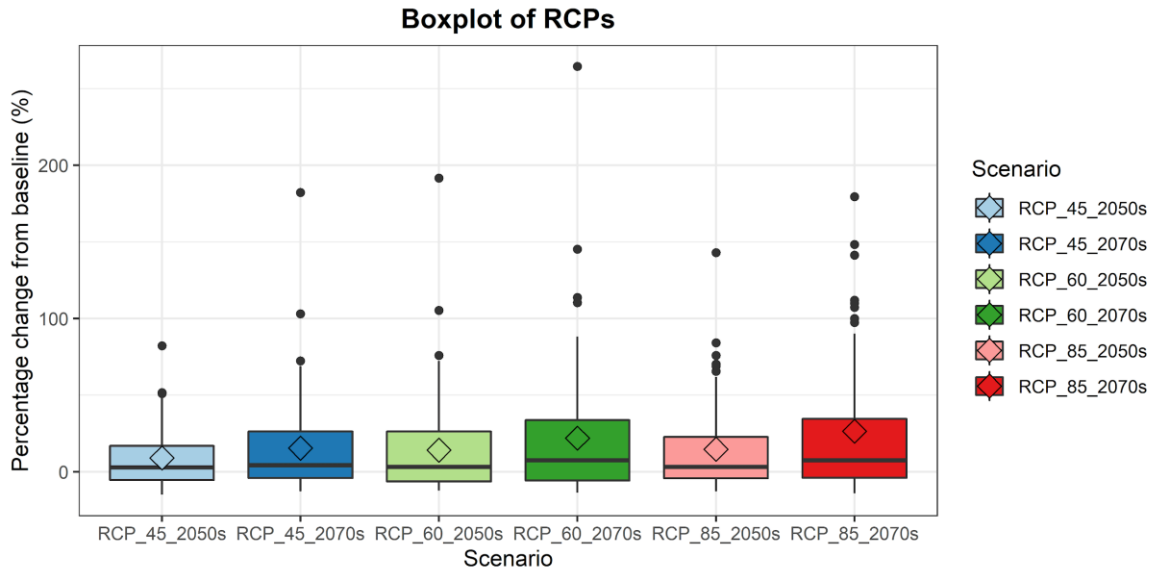


Figure 4.14 Boxplot of the performance of the RCP scenarios for all the river points in all the basins: Line is the median. Diamond indicates mean. Dots indicate outliers. RCP_45_2050s denotes RCP 4.5 for the 2050s time slice, and so forth.

In Figure 4.13 we can see that a river point in the Nairobi basin (yellow dots) is showing the largest increase in flood risk ratios across all the RCPs, followed by points in Chennai (orange dots), then Guayaquil (purple dots). The London basin (green dots) has the most negative values of all scenarios. To determine how the different RCPs performed, the pcd values for FRRs, of each upstream basin, were grouped by RCP in a boxplot (Fig. 4.14) and the mean, max and min values for each RCP is summarised in Table 4.3. From the boxplots we can see that there are a number of outliers indicating that the data has a skewed distribution and as such, the median may provide a more accurate assessment than the mean (Fig. 4.13). RCP 8.5 2070s and RCP 6.0 2070s are very similar and have the largest values. They have similar means, with RCP 8.5 only slightly larger, and similar medians, with RCP 6.0 slightly larger (Fig. 4.13). RCP 4.5 2070s has very similar (slightly bigger) values to RCP 6.0 2050s. Interestingly, RCP 8.5 2050s has a smaller mean, median and max value than RCP 4.5 2070s. RCP 4.5 2050s produced the smallest changes in flood risk ratio across the points (Table 4.3).

Table 4.3 Mean, max and min percent change difference (pcd) for each scenario. Scenarios for the 2050s highlighted grey. The most extreme value per column is in bold.

Scenario	Mean	Median	Max	Min
RCP 4.5 2050s	9.0	2.88	82.2	**-15**
RCP 4.5 2070s	15.4	4.35	182.0	-12.8
RCP 6.0 2050s	14.1	3.19	192.0	-12.3
RCP 6.0 2070s	21.9	**7.61**	**264.5**	-13.6
RCP 8.5 2050s	14.7	3.13	143.0	-12.8
RCP 8.5 2070s	**26.5**	7.49	179.0	-14.2

Overall, across all RCPs, all basins and all points, the percent change difference from baseline to scenario for FRR, ranged from -15 pcd to +264.5 pcd, with a mean of +16.9 pcd and a median of +4.13 pcd (Table 4.3). RCP 8.5 for the 2070s had the highest mean pcd for the flood risk ratios at +26.5 pcd followed by RCP 6.0 for the 2070s at +21.9 pcd and RCP 4.5 for the 2070s at +15.4 pcd (Table 4.3). For the 2050s the highest mean pcd is for RCP 8.5 at +14.7 pcd, closely followed by RCP 6.0 at +14.1 pcd and finally RCP 4.5 at +9 pcd. The highest point value was for RCP 6.0 2070s.

Within RCPs, the scenarios for the 2070s had a higher mean than for the scenarios for the 2050s. However, between RCPs, the mean for the next level up RCP for the 2050s time period is less than the prior RCPs 2070s mean. For example, RCP 6.0 2050s has a lower mean than RCP 4.5 2070s mean, and RCP 8.5 2050s has a lower mean than RCP 6.0 2070s. There is not much difference in the means and medians between RCP 6.0 and RCP 8.5.

4.4.4 Mapping change in flood risk ratios and NI storage types

Mapping where the flood risk ratios increase compared to baseline and then combining for all the climate scenarios gives an indication of the spatially distributed change. Figures 4.15 to 4.20 are panel plots for each upstream basin showing the cumulative change in flood risk ratios under the six climate scenarios and then the NI water storage types masked where more than three scenarios show the respective change.

Nairobi upstream basin:

Figure 4.15 shows panel plots of FRR change under climate scenarios for the Nairobi basin. **Table D8 in Appendix D summarises the changes in cell values observed from Figure 4.15.**

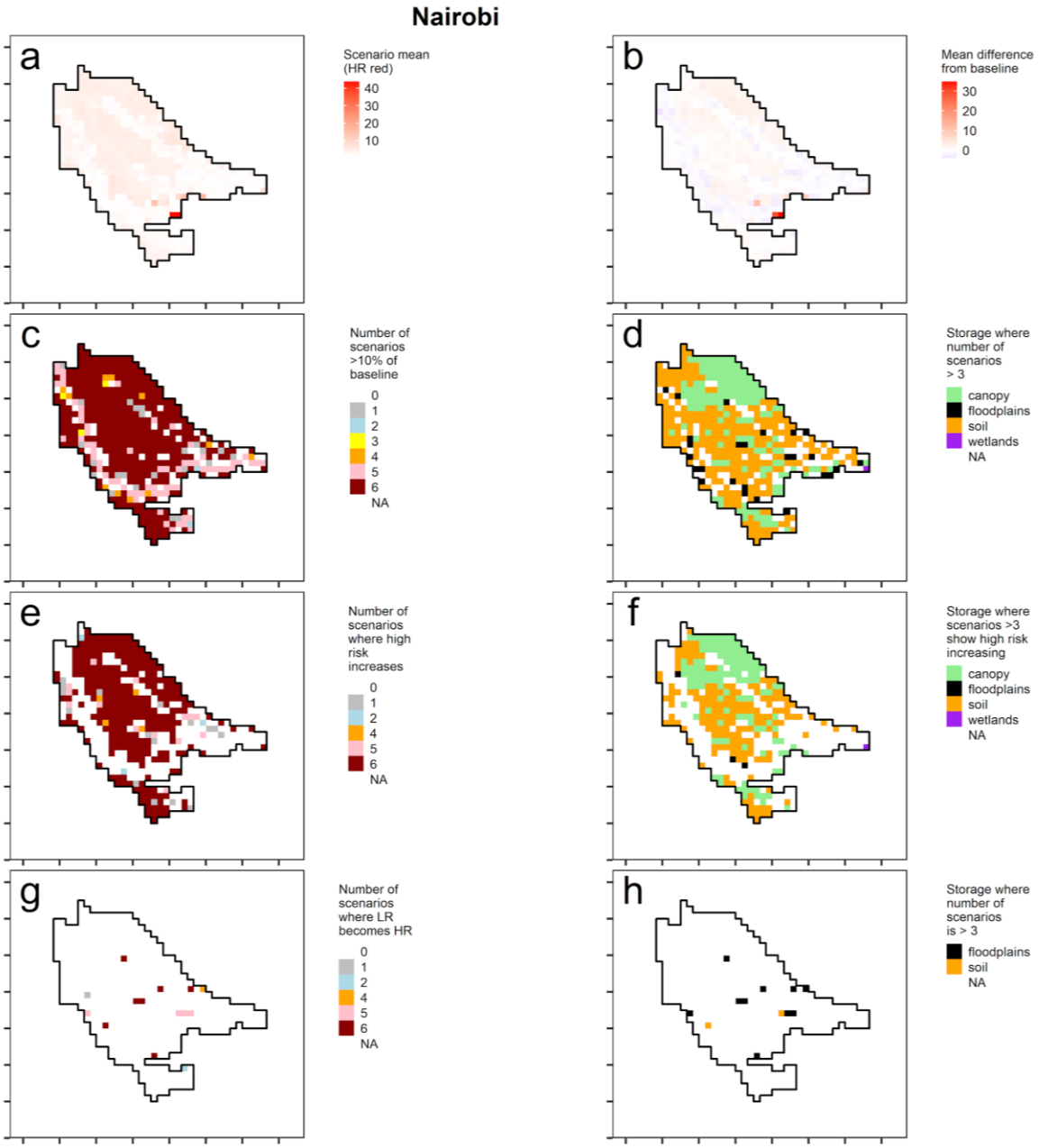


Figure 4.15 Nairobi upstream basin showing a) the climate scenarios' mean FRR values (%), b) the climate scenarios' mean difference from baseline (+/-%), c) the number of scenarios showing an increase of more than 10% of baseline values, d) the NI storage types where more than three scenarios in "c" showed an increase of more than 10% of baseline values, e) the number of scenarios where high-risk in the baseline increased in the scenario (high-risk increasing), f) the NI storage types where more than three scenarios in "e" show high-risk increasing from baseline, g) the number of scenarios where low risk values in the baseline become high-risk in the scenario, h) the storage types where more than three scenarios in "g" show low risk becoming high-risk.

Chennai upstream basin:

Figure 4.16 shows panel plots of FRR change under climate scenarios for the Chennai basin. In the Chennai basin (Fig. 4.16), there are a number of grid cells that are blank (NA). This is where ratios were not calculated because water balance is negative (i.e., there is no

runoff generated by those cells). **Table D9 in Appendix D summarises the changes in cell values observed from Figure 4.16.**

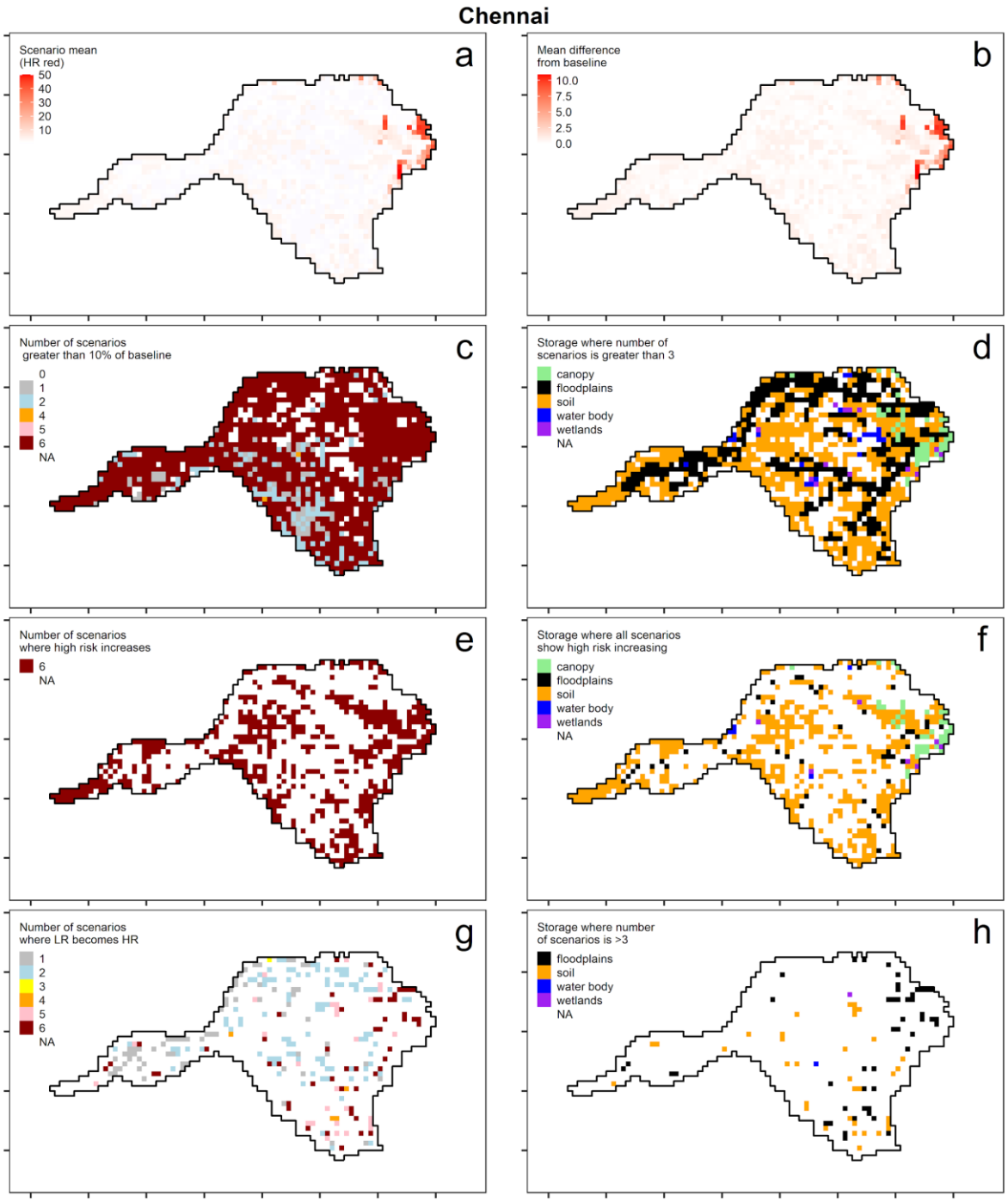


Figure 4.16 Chennai upstream basin showing a) the climate scenarios mean values, b) the climate scenarios mean difference from baseline, c) the number of scenarios showing an increase of more than 10% of baseline values, d) the NI storage types where more than three scenarios in "c" showed an increase of more than 10% of baseline values, e) the number of scenarios where high-risk in the baseline increased in the scenario (high-risk increasing), f) the NI storage types where more than three scenarios in "e" show high-risk increasing from baseline, g) the number of scenarios where low risk values in the baseline become high-risk in the scenario, h) the storage types where more than three scenarios in "g" show low risk becoming high-risk.

Jakarta upstream basin:

Figure 4.17 shows panel plots of FRR change under climate scenarios for the Jakarta basin. **Table D10 in Appendix D summarises the changes in cell values observed from Figure 4.17.**

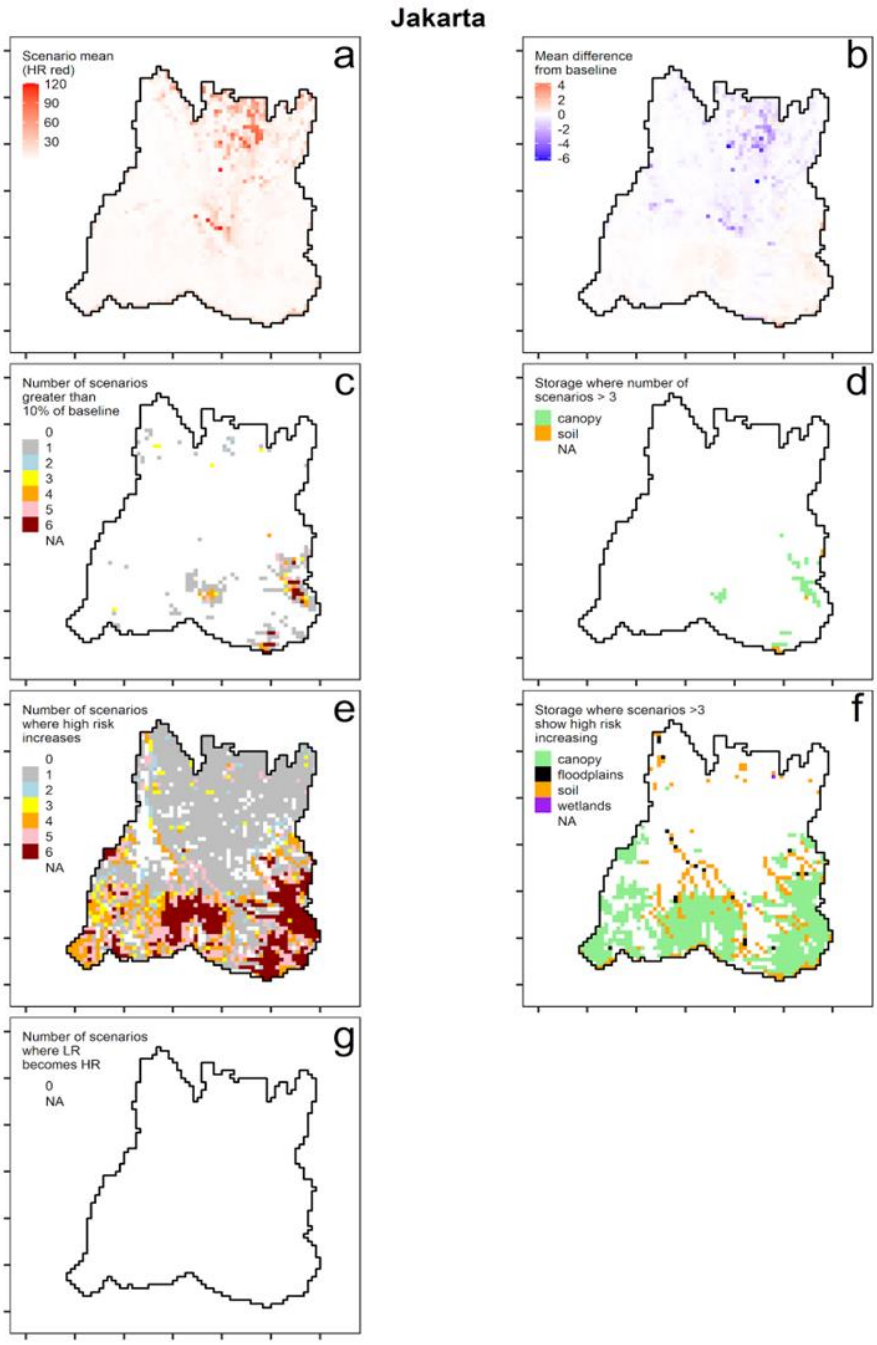


Figure 4.17 Jakarta upstream basin showing a) the climate scenarios mean values, b) the climate scenarios mean difference from baseline, c) the number of scenarios showing an increase of more than 10% of baseline values, d) the NI storage types where more than three scenarios in "c" showed an increase of more than 10% of baseline values, e) the number of scenarios where high-risk in the baseline increased in the scenario (high-risk increasing), f) the NI storage types where more than three scenarios in "e" show high-risk increasing from baseline, g) the number of scenarios where low risk values in the baseline become high-risk in the scenario.

In the Jakarta basin, the grid cells where flood risk increased under the most number of climate scenarios were located in the southern area, which are the high mountain regions of the basin (Fig. 4.17a). The grid cells with an increase in flood risk under all six scenarios mapped to NI storage of mostly canopy, with a small number of scattered soil cells and one floodplain cell (Fig. 4. 17b).

To investigate the relationship between elevation and slope with the increase in flood risk ratios, I overlaid the map of increases of more than 10% onto a DEM and calculated zonal statistics (statistics on cell values of a raster within the zones defined by another dataset) for elevation, slope and percentage of tree cover using the 'Cover of tree-covered ground' dataset (Copernicus, 2015; Table 4.4). Spearman rank corelation coefficient calculations **(Appendix D; Table D8)** reveal that there are strong positive correlations between these variables and the number of climate scenarios, with elevation and the number of scenarios having a perfect positive, and significant, correlation. Slope has a strong positive correlation with number of scenarios (showing an increase of >10%) but is not significant. Tree cover has a strong positive correlation with number of scenarios and is significant.

To summarise, there is an effect whereas the elevation increases, slope becomes steeper, and tree cover increases, the number of scenarios showing an increase in FRR of greater than 10% of baseline value, increases. The class (zone) of six scenarios is coincident with the highest elevation, steepest slope and highest tree coverage.

Table 4.4. Mean values of elevation, slope and tree cover per class (number of climate scenarios showing an increase greater than 10% of baseline) in the upstream Jakarta basin.

No of climate scenarios	Elevation (m)	Slope (degrees)	Tree cover (%)
0	359	2.49	40.5
1	736	5.80	62.0
2	602	5.50	53.6
3	583	5.03	50.1
4	769	7.27	77.1
5	808	7.18	80.9
6	1080	8.64	90.8

Bogotá upstream basin:

Figure 4.18 shows panel plots of FRR change under climate scenarios for the Bogotá basin. **Table D11 in Appendix D summarises the changes in cell values observed from Figure 4.18.**

To investigate the relationship of elevation, slope and tree cover with the increase in flood risk ratios, I overlaid the map onto a DEM and calculated zonal statistics for elevation, slope and tree cover (Table 4.5). Spearman rank corelation coefficient calculations (Appendix C; Table C9) reveal that there are positive correlations between these variables and the number of climate scenarios, but the strength and significance varies. For the relationship between elevation and the number of scenarios, there is a weak positive, and non-significant, correlation. Slope has a strong positive correlation with number of scenarios (showing an increase of >10%) but is not significant. Tree cover has a very strong positive correlation with number of scenarios and is significant. To s summarise, in the Bogotá basin, steepness of slope and percentage of tree cover increase as the number of climate scenarios, showing an increase >10% of FRR baseline values, increases.

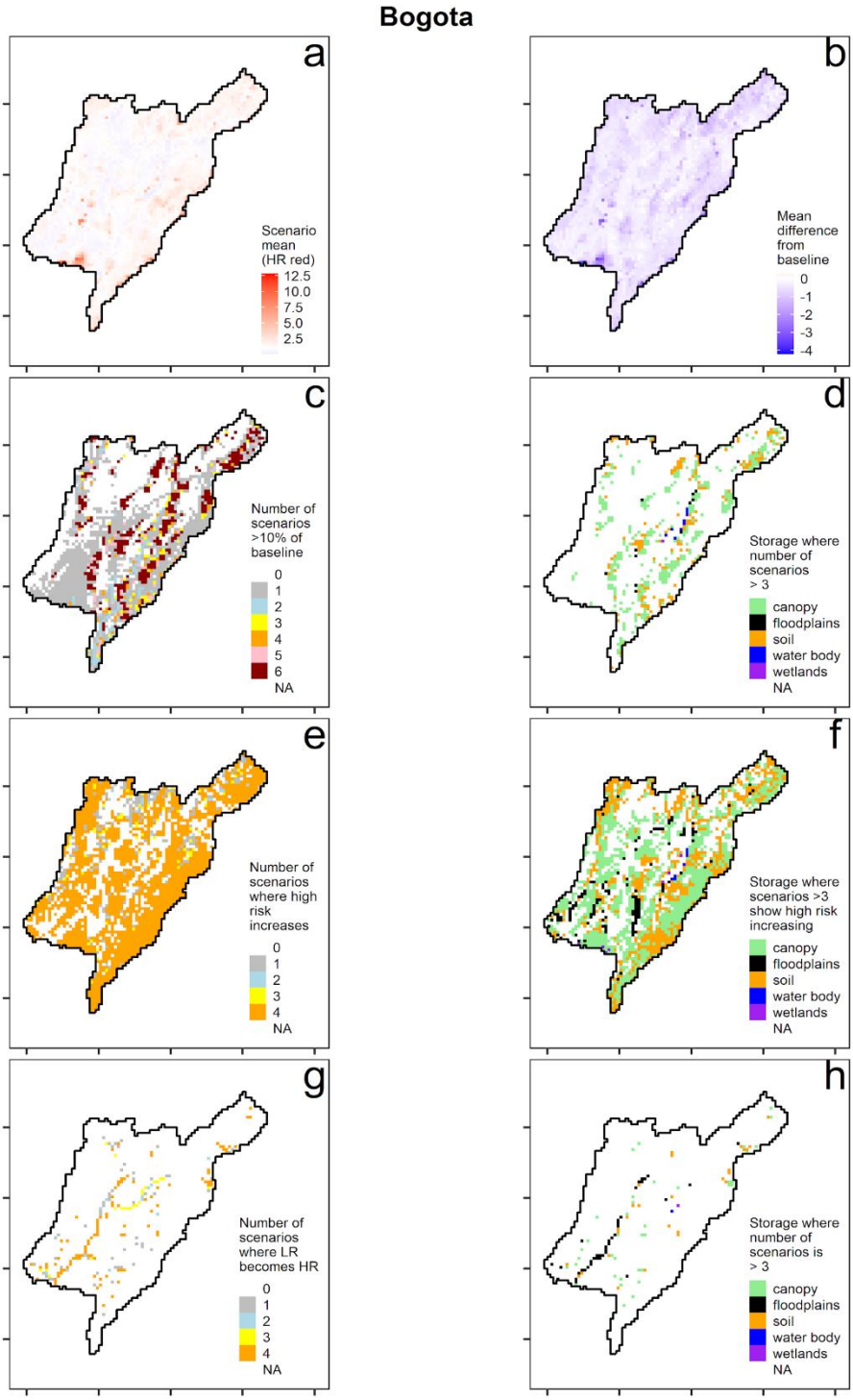


Figure 4.18 Bogotá upstream basin showing a) the climate scenarios' mean FRR values, b) the climate scenarios mean difference in FRR from the baseline, c) the number of scenarios showing an increase of more than 10% in FRR of baseline values, d) the NI storage types where more than three scenarios in "c" showed an increase of more than 10% of baseline values, e) the number of scenarios where high-risk in the baseline increased in the scenario (high-risk increasing), f) the NI storage types where more than three scenarios in "e" show high-risk increasing from baseline, g) the number of scenarios where low risk values in the baseline become high-risk in the scenario, h) the storage types where more than three scenarios in "g" show low risk becoming high-risk.

Table 4.5. Mean values of elevation and slope per class (number of climate scenarios showing an increase greater than 10% of baseline) for the Bogotá upstream basin.

No. of climate scenarios	Elevation (m)	Slope (degrees)	Tree Cover (%)
0	2849	4.80	25.6
1	2779	3.45	24.4
2	2887	3.48	27.0
3	2922	4.49	28.0
4	2939	4.93	30.2
5	2942	5.14	30.4
6	2818	5.78	31.4

London upstream basin:

Figure 4.19 shows panel plots of FRR change under climate scenarios for the London basin. **Table D12 in Appendix D summarises the changes in cell values observed from Figure 4.19.**

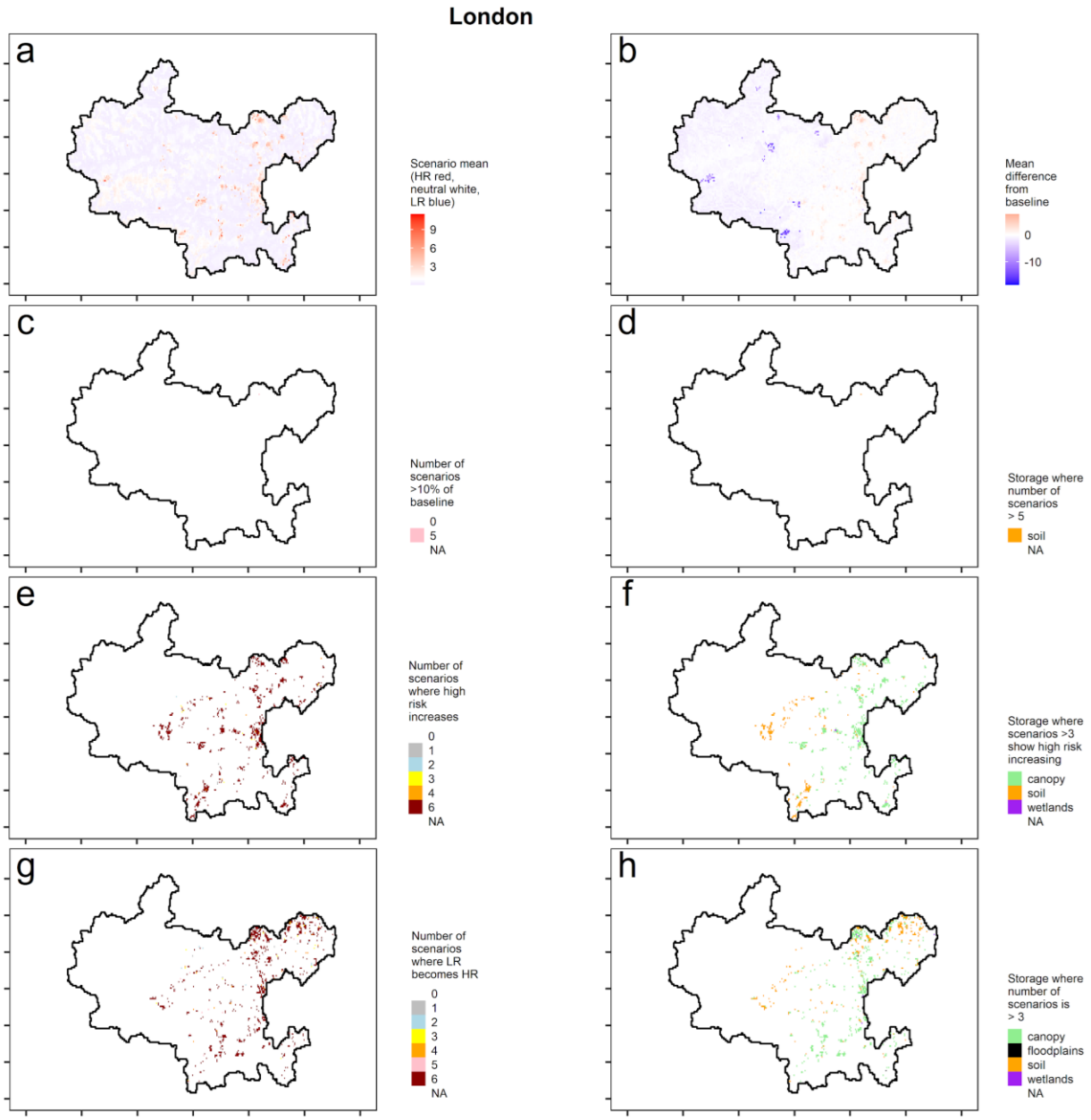


Figure 4.19 London upstream basin showing a) the mean of all climate scenarios, b) the climate scenarios' mean difference from baseline, c) the number of scenarios showing an increase of more than 10% of baseline values, d) the NI storage types where more than three scenarios in "c" showed an increase of more than 10% of baseline values, e) the number of scenarios where high-risk in the baseline increased in the scenario (high-risk increasing), f) the NI storage types where more than three scenarios in "e" show high-risk increasing from baseline, g) the number of scenarios where low risk values in the baseline become high-risk in the scenario, h) the storage types where more than three scenarios in "g" show low risk becoming high-risk.

Guayaquil upstream basin:

Figure 4.20 shows panel plots of FRR change under climate scenarios for the Guayaquil basin. **Table D13 in Appendix D summarises the changes in cell values observed from Figure 4.20.**

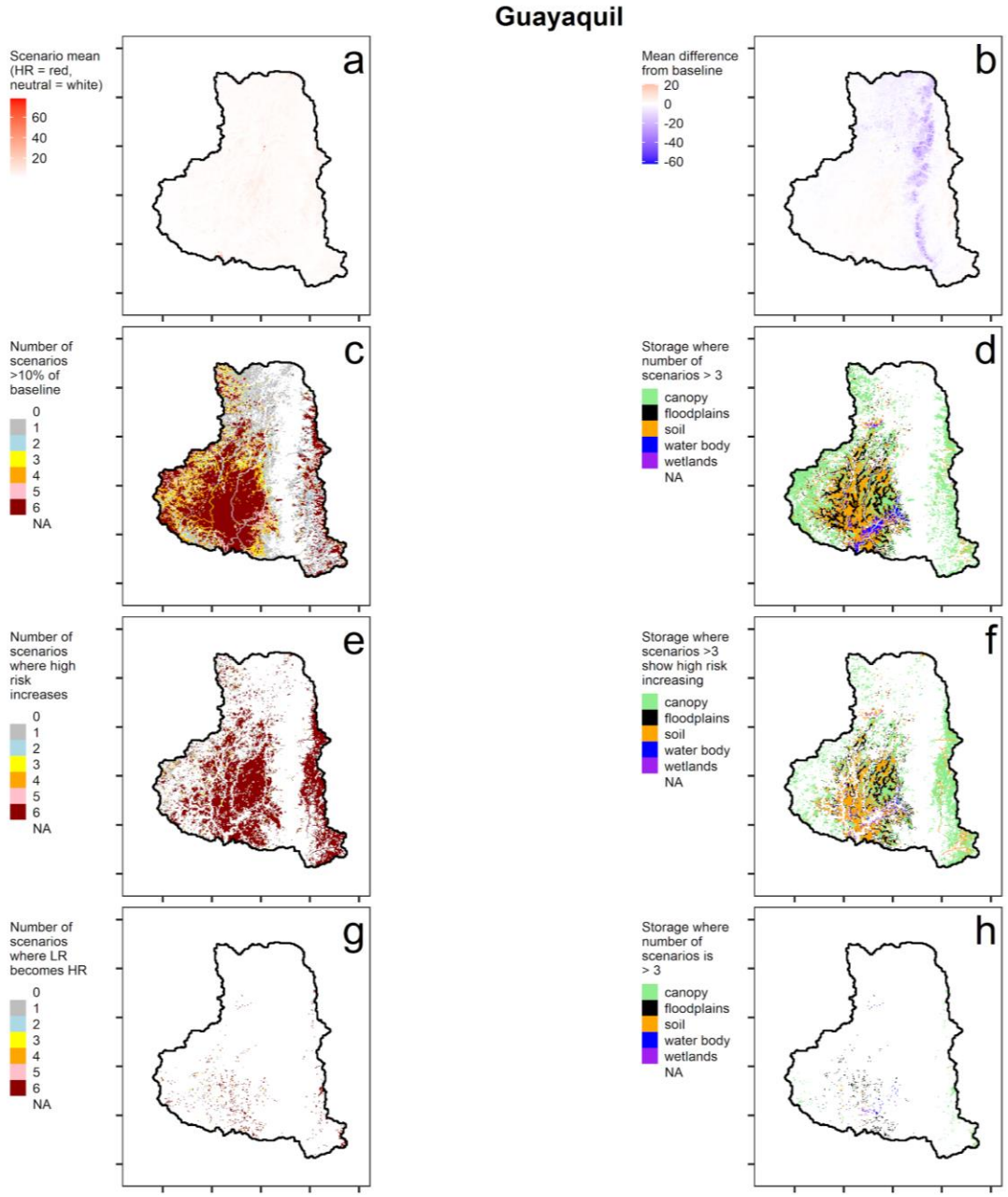


Figure 4.20 Guayaquil upstream basin showing, a) the mean of climate scenarios, b) the climate scenarios mean difference in FRR from baseline, c) the number of scenarios showing an increase of more than 10% in FRR of baseline values, d) the NI storage types where more than three scenarios in "c" showed an increase of more than 10% of baseline values, e) the number of scenarios where high-risk in the baseline increased in the scenario (high-risk increasing), f) the NI storage types where more than three scenarios in "e" show high-risk increasing from baseline, g) the number of scenarios where low risk values in the baseline become high-risk in the scenario, h) the storage types where more than three scenarios in "g" show low risk becoming high-risk.

To investigate the relationship of elevation, degree of slope and tree cover with the increase in flood risk ratios, I overlaid the map onto a DEM and calculated zonal statistics for

elevation and slope (Table 4.6). Spearman rank corelation coefficient calculations **(Appendix D; Table D10)** reveal that there are negative correlations between these variables and the number of climate scenarios, but the strength and significance varies. For the relationship between elevation and the number of scenarios, there is a weak negative, and non-significant, correlation. Slope has a moderate negative correlation with number of scenarios (showing an increase of >10%) but is not significant. Tree cover has a very strong negative, significant correlation with number of scenarios. To summarise, in the Guayaquil basin, percentage of tree cover decreases as the number of climate scenarios (showing an increase >10% of FRR baseline values) increases. There is no significant correlation between elevation and slope on the number of climate scenarios showing an increase in flood risk ratio greater than 10%, contrary to what can be seen on the Google Earth images (Fig. 4.21). However, this is probably due to the large difference in elevational range in the same part of the bounding watershed; a large area to the west is lowland but the east part of the watershed is very high upland.

Table 4.6. Mean values of elevation, slope and tree cover per class (number of climate scenarios showing an increase greater than 10% of baseline) for the Guayaquil upstream basin.

No. of climate scenarios	Elevation (m)	Slope (degrees)	Tree cover (%)
0	908	5.88	53.9
1	595	2.76	41.5
2	1183	4.21	36.3
3	294	1.52	36.1
4	247	1.25	32.4
5	762	2.68	34.0
6	633	2.34	23.4

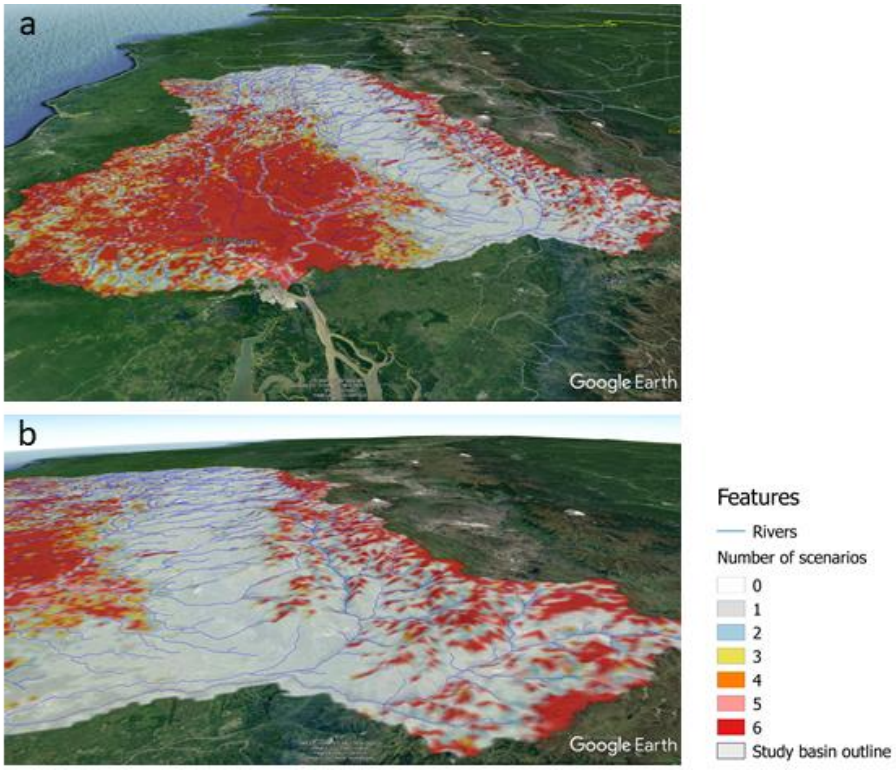


Figure 4.21 Google Earth image of the Guayaquil upstream basin showing the number of scenarios greater than 10 percent of baseline. a) shows a zoomed-out view of the whole basin, and b) shows a zoomed in 3D view to show the mountains and foothills.

4.5 Discussion

Climate change will result in some areas of the world getting wetter and others getting drier. Some basins (or regions of basins) upstream of cities are already at or over their "natural" floodwater storage capacity on an annual basis (Chapter 3), and any additional input of precipitation above baseline (as a result of climate change) may increase flood risk if not mitigated. In this chapter, I evaluated the impact of climate change on flood risk ratios in case study basins, to i) show which basins (or locations within basins) will have increased flood risk under different climate scenarios, ii) determine if there were geographic patterns to the projected increases, including differences and similarities between the city upstream basins, and iii) examine the role of the RCPs in influencing the increase in flood risk.

This section is structured firstly, by discussing the annual change of hydrological variables at the basin sum scale, then changes in flood risk at both distributed points and spatially distributed basin scale. This is followed by discussions on the influence of geographic patterns on the change in flood risk, such as basin size, elevation and slope, distance to the

city boundary and the role of the NI storage type. Lastly, the strengths, assumptions and limitations of the study are discussed.

4.5.1 Change in hydrological variables at the annual scale

Overall, it has been difficult to compare results of this study with those reported by others because other studies use different regions, periods, seasons, GCMs, and scenarios compared to this one, making a direct comparison impossible. Descriptions from other studies are included in Appendix C. Based on the climate modelling of three RCP scenarios (4.5, 6.0 and 8.5) for two time slices, the 2050s and 2070s, this study found that the upstream basins of the following cities are projected to have increased rainfall and water balance on an annual scale compared to baseline conditions: Nairobi, Chennai, Bogotá and Guayaquil. The increases projected for Nairobi and Chennai are in agreement with the IPCC predictions showing increases in average precipitation for east Africa and the Indian peninsula (Figure 1.1 in Chapter 1) and other studies (described in Appendix C). The IPCC predictions for South America are more variable, with the southern part of South America showing an increase and the North-Eastern region of South America showing a decrease. However, there is a small section of North-Western South America, possibly coincident with Ecuador and Colombia, which is projected to have increases in average precipitation (Figure 1.1 in Chapter 1), as found in this study.

The upstream basins of London and Jakarta are projected to have decreased rainfall and water balance on an annual scale compared to baseline conditions. This is in agreement with previous studies (see Appendix C8). However, it does not agree with the World Bank's Climate Knowledge Portal[52] figures (Table C1 in Appendix C) but these are averaged results for the entire country and only for RCP 8.5.

4.5.2 Areas of increased flood risk under climate scenarios

Points

Projected flood risk ratios for the watersheds and distributed points along the river network were calculated (using the Storage to Total Capacity metric described in detail in Chapter 3) for RCP 4.5, 6.0 and 8.5 scenarios for two time slices, 2050s and 2070s, and compared to the baseline values.

[52] https://climateknowledgeportal.worldbank.org/

The trend for the river points follows that for the basin values for both hydrological variables and flood risk ratios. For the Nairobi, Chennai, Bogotá and Guayaquil watersheds, all the river points for all RCPs show an increase in flood risk ratios. In the London and the Jakarta upstream basins, almost all the points show a decrease compared to baseline. The exception being under scenario RCP 8.5 2070s, which is positive across all points in the Jakarta basin. A rationale for choosing distributed points along the river network is to identify locations where flood risk is projected to increase by a large degree. Locations upstream of these points could be targeted, to determine if particular interventions to increase water storage, are effective in lowering the FRR and to what extent.

Spatial distribution of flood risk

The spatially distributed maps of change in flood risk ratios under climate scenarios illustrate the geographic pattern to the projected increases/decreases. There were different patterns in the *central tendency*, which looked at whether the mean FRR of the scenarios increased or decreased, and the *certainty*, which looked at how many of the scenarios showed a particular change.

Central tendency

In the Nairobi basin, the areas of no change and decrease in FRR appear to follow the river lines in a north-south direction. No FRR increases along rivers makes sense, as these are non-built-up spaces that function to carry water, i.e., have large capacity.

In the Chennai basin, the pattern of increases was highest to the east, closest to the entry into the urban area, and was scattered throughout the rest of the basin. This is at odds with the river sampling data which showed the points farthest from the city having the highest changes in pcd.

In the Jakarta upstream basin, the mean FRR for all the scenarios is high, but most of the basin showed no change in mean FRR compared to baseline. Even though the highest mean scenario values are in the lower coastal reaches, these actually decline in value compared to the baseline. The increases occur in the upper mountain regions, specifically the south-east part of the basin. This is probably due to a combination of rainfall increases in those mountain areas (orographic effects) and the lack of storage capacity on steep mountain slopes.

In the Bogotá basin, most of the area did not have any change in mean FRR compared to the baseline, and the remainder declined compared to baseline. This is puzzling since the hydrological variables and FRRs do increase slightly for Bogotá at the basin sum scale, and the majority of cells showed an increase in FRR compared to baseline for the combined climate scenarios.

In the London basin, most of the basin had no change in mean FRR compared to baseline and the rest showed a decrease, with only a very small percentage showing an increase. However, there does appear to be geographic segregation with the decreases mostly occurring in the western, upstream part of the basin, and the increases occurring in the eastern downstream part of the basin. This may be a result of the eastern area being closer to the city of London and thus more built-up, i.e., has less storage capacity.

In the Guayaquil upstream basin, around 20% of cells show a mean increase in flood risk ratio. The areas with the highest increases are located in the river plain area in the south-west of the basin, immediately above the city of Guayaquil. Interestingly, the area that shows a mean decrease in flood risk ratios compared to baseline is a north-south band that is coincident with the foothills and lowlands of the Andes Mountains. A possible explanation for this is that this area experiences rainfall decreases under future climate. To explore this, I generated a baseline rainfall map of the basin from *WaterWorld* (Fig. 4.22). Here we can see an area of relatively lower rainfall (blue in the image) on the eastern edge of the basin, coinciding with the western slopes of the Andes. This 'low-rainfall' area is potentially a result of a rain shadow effect that causes uneven precipitation on one side of a range versus the other(Sklenář & Laegaard, 2003). However, it is the area west of these slopes that is showing rainfall decreases under climate scenarios. In the baseline, this area is a very high rainfall accumulation area (red, orange and yellow in the image; Fig. 4.22). The slight decreases in rainfall under climate scenarios, could indicate an extension of the rain-shadow effect.

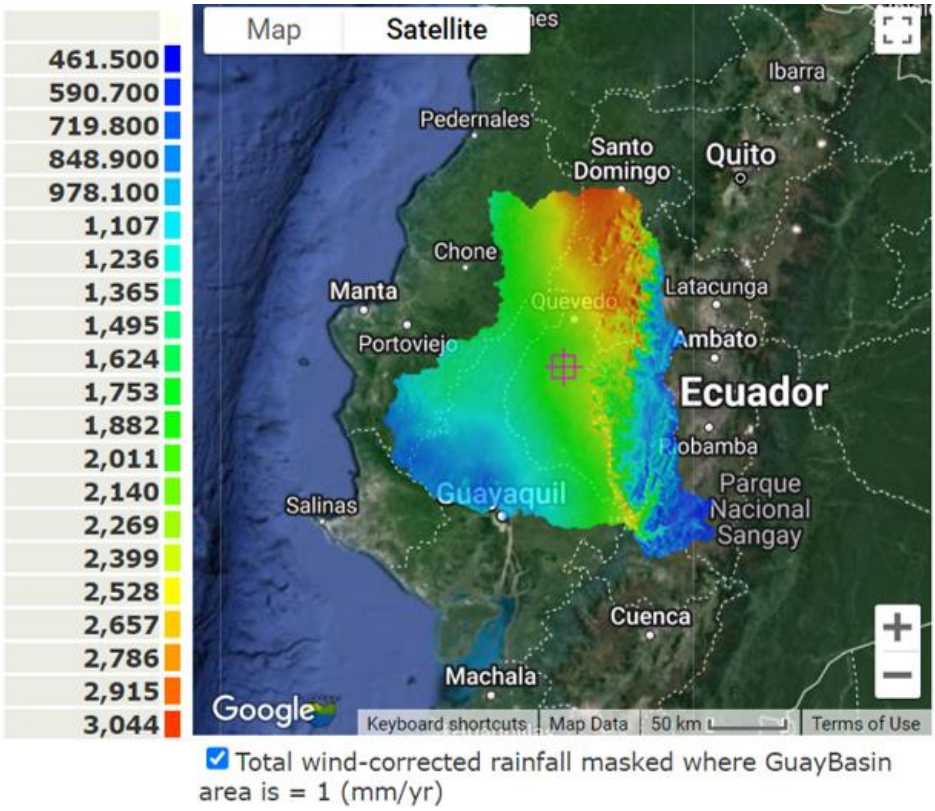


Figure 4.22 Total wind-driven rainfall map (baseline) of the Guayaquil basin generated in WaterWorld.

Certainty

When I looked at how many of the scenarios showed a particular change to represent *certainty* of that change, the pattern occasionally differed from the scenario means. The patterns examined in this case are increases in FRR >10% of the baseline mean.

For instance, in the Bogotá upstream basin, most of the basin did not have any change in mean FRR compared to baseline (Figure 4.18b) and the remainder declined compared to baseline (Fig. 4.18b). However, looking at the number of scenarios showing a >10% increase in FRR, nearly 60% of the basin shows an increase for between one and six scenarios (Fig. 4.18c). This must mean that although there are scenarios showing increases greater than 10% of the baseline FRR, there are more scenarios showing a decrease, or that the decreases are larger than the increases.

4.5.3 Geographic patterns of increase in flood risk under climate scenarios

Between the basins, geographic patterns such as, i) the role of basin size, ii) the role of elevation, slope and percentage tree cover, iii) distance to the city-basin boundary, and iv) the role of natural infrastructure (NI) water storage on flood risk increase were evaluated.

The role of basin size in flood risk increase

The basins showing the largest positive percentage change in rainfall, water balance and flood risk ratios were Chennai and Nairobi, which also happen to be the two smallest of the study basins. The Nairobi upstream basin is 443.3 km^2 and Chennai upstream basin is 1,188.7 km^2 (compared to the largest basins in this study: 6,939.4 km^2 for the London upstream basin and 32,794 km^2 for the Guayaquil upstream basin). This suggests that basin size could be a factor determining flood risk. Hydrological studies on the role of catchment size have found that runoff generation and water fluxes tend to become more attenuated, or dampened, with increased size of the catchment (Wood et al 1988, McGlynn et al 2004). In terms of the relationship between flood frequency and catchment size, the likelihood of an extreme rainfall event occurring over large portions of a catchment is inversely related to catchment size (Smith, Sampson & Bates 2014), probably because the spatial variability of rainfall increases with catchment size (Arnaud et al. 2002). Larger basins have more opportunity to mitigate increases in rainfall by distributing and dissipating flows over a large area and making use of unused storage compared to small basins. The small basins experience a big change in precipitation because they are small in area and average increases are large; conversely, the bigger the area, the smaller the average change. Small basins may also have limited ability to increase NI storage.

In this case, small basin size does seem to show a relationship to increased flood risk, but the opposite was not necessarily true for large basins. For example, Guayaquil, the largest basin in this study, is also projected to have large increases in flood risk ratios.

The role of distance to city in flood risk increase

I am most interested in flooding that occurs close to cities, as that is where the most 'assets at risk' are concentrated. Examining the scenario means shows that for all city upstream basins, except Guayaquil and possibly London, the highest values of FRR are at the most downstream part of the study basins (panel plots 'a' in Figures 4.15. 4.16, 4.17, 4.18, 4.19, 4.20). However, in terms of *change* between the scenario mean and the baseline, these same areas tended to decrease in mean flood risk values compared to the baseline (panel plots 'b' in Figs. 4.15. 4.16, 4.17, 4.18, 4.19, 4.20). An exception was the Chennai basin, which showed high scenario means *and* increases in mean flood risk values at 'close to city' areas. The opposite was true for the Jakarta basin, where the areas of greatest increasing change were in the upland areas. Change between scenario and baseline is only an indication of change in runoff (precipitation, evapotranspiration) and interaction with topography. The scenarios are not capturing any change in storage capacity, so increases or

decreases in FRR close to cities will be a result of changes to precipitation patterns near cities. This is unlikely to be a factor picked up by climate modelling.

Since most flooding is river flooding, change in flood risk was captured at points along the river networks for the case-study basins. However, it must be noted that these points cannot be considered a true rural-urban gradient, as the points are on multiple rivers or river tributaries (except for Bogotá) and some of the most distant points are often still in fairly urbanised areas or on transition points from rural to low-density or low-density to high density (as defined by the GHSL 2015 dataset by Pesaresi et al., 2016). I found no significant relationship between distance to city boundary and mean pcd of FRR due to climate change for four out of six of the basins: Nairobi, Jakarta, Bogotá and London. However, there is a significant correlation for Chennai and Guayaquil but in opposite directions. In Chennai, mean pcd increases as distance to city increases, i.e., the more rural points will experience greater increases in flood risk. This is opposite to what the basin maps indicate. In Guayaquil, mean pcd increases as distance to city decreases, i.e., the more urban points, closest to the city will experience the greatest increases in flood risk.

The role of NI storage type on flood risk increase

An association between NI storage type and increase in flood risk ratio might indicate that certain NI storage types are more susceptible to reaching or breaching capacity than others. The prevalent NI storage type in areas where flood risk ratios increased (>10% relative to baseline) is summarised in Table 4.7 below. Based on these results, canopy and soil NI water storage have the strongest association with increases in flood risk ratios. This may be a result of soil and canopy NI storage being the most prevalent and widely distributed of the storage types (as found in Chapter 3); although water body and floodplain NI storage may have greater water storage capacity on a per grid cell basis, they are rather rare in comparison at a spatial scale. The London basin only had one grid cell that had increased FRR (over 10%) and so has a primary, and no secondary NI storage type.

Table 4.7 Summary of the primary and secondary NI storage types in the upstream city basins where flood risk ratios increased (>10% relative to baseline).

	NI storage type	
	Primary	**Secondary**
Nairobi	Soil	Canopy
Chennai	Soil	Floodplain
Bogotá	Canopy	Soil
Jakarta	Canopy	Soil
London	Soil	-
Guayaquil	Canopy	Soil

4.5.4 Which basins might need extra mitigation beyond the current?

Knowing how climate change may influence future precipitation and thus flood risk is useful if we can use it to determine if the current NI infrastructure is sufficient and resilient, or not, to those projected changes. It is reasonable to assume that if the area above a city is already high-risk then the NI, or other built infrastructure, must be working well if the city is not continually flooding. In these cities, the NI is sufficient. However, if existing flood risk is low and increases, then the NI could be overwhelmed. To get an idea of the existing versus projected ability of the city NI to cope, I collated the values for the sampling points that occur on the city-basin boundaries (multiple points represent different river entry points into the city) for the different scenarios. I then compared the scenario value to the change from baseline (*percentage change difference (pcd; eqn 1)*) and indexed the pcd scores from *'very low decrease*' to '*extremely high increase*' (Table 4.8). I then used those scores to create a heatmap illustrating the score range for each city basin (Figure 4.23).

Table 4.8 An index of percent change difference (pcd) values categorised from 'very low' to extremely high'.

Percent change difference (pcd)	Index score
-20- -11	Very low decrease
-10- -0	Low decrease
+ 0-10	Very low increase
+11-30	Low increase
+31-40	Med-low increase
+41-60	Medium increase
+61-70	Med-high increase
+71-90	High increase
+91-100	Very high increase
100+	Extremely high increase

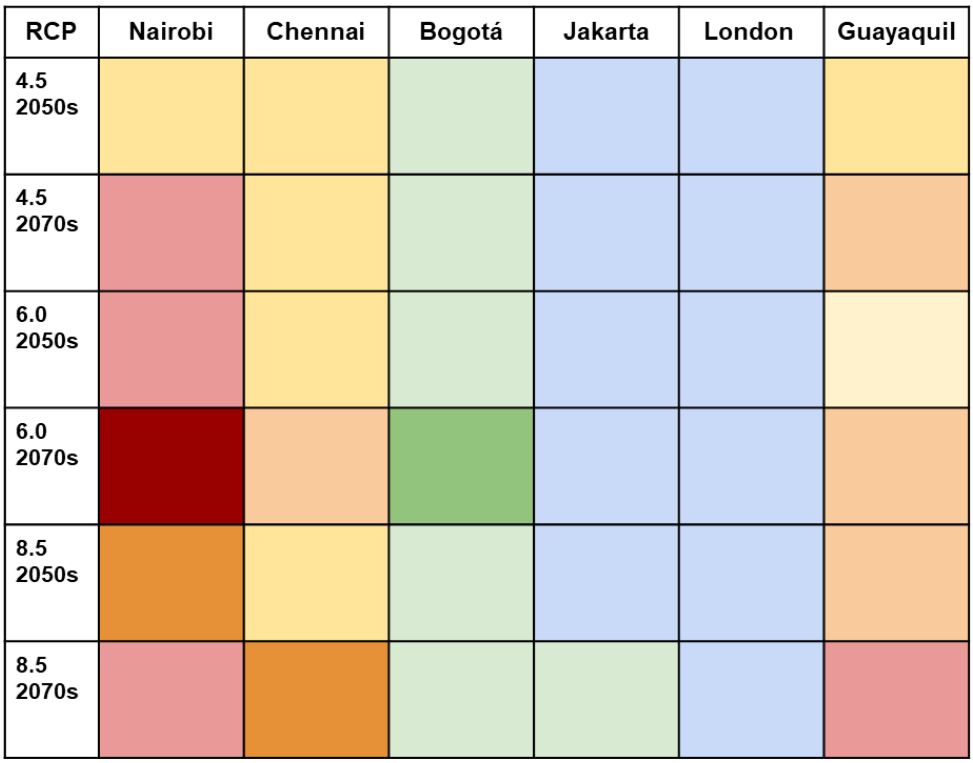


Figure 4.23 A heatmap of the city basins' pcd index score based on the closest-to-city sampling points.

Figure 4.23 provides a sense of the scale of the increases or decreases in future flood risk for each city basin. Without validation and calibration, we cannot determine how these different levels of changes in future flood risk will be realised on the ground. However, the simple indexing of the pcds gives an indication of which basins will need additional mitigation for none, some or all scenarios. The Nairobi basin has the largest increases, followed by Guayaquil, then Chennai and last, Bogotá. The London and Jakarta basins have mostly '*low decreases*' so are the best able to mitigate the flood risk related impacts of climate change, if all else remains equal.

4.5.5 The role of the climate scenarios (RCPs)

The scenarios used in this study range from medium stabilisation scenarios (RCP 4.5 / 6.0) to the very high, 'worst-case' scenario with RCP 8.5 (van Vuuren et al., 2011;Hausfather, 2019). Based on this, we would expect that the most extreme values for flood risk ratios would be for RCP 8.5 for the 2070s (as the later time period provides more time for changes to accumulate). However, this was only true for points in half of the basins studied: Chennai, Jakarta and Guayaquil. For the upstream basins of Nairobi and Bogotá, it was scenario RCP 6.0 for the 2070s which caused the greatest increases in flood risk ratio, and in the London upstream basin, it was scenario RCP 6.0 for the 2050s which caused the greatest increases in flood risk ratio (although minor). Interestingly, when all the results are cumulated, it is RCP 8.5 for the 2050s that produced the second lowest increases in flood risk ratios, even being slightly lower than RCP 4.5 2070s. RCP 4.5 for the 2050s produced the lowest increases in flood risk ratios which is what we would expect.

Unfortunately, I have not been able to find any literature that discusses why we would see more extreme rainfall values for RCP 6.0 than RCP 8.5. These discrepancies could be a result of the GCMs used or excluded in the different RCPs in WorldClim (Table 2.11, Chapter 2). RCP 4.5 uses 19 GCMs, RCP 6.0 uses 12 and RCP 8.5 uses 17 GCMs. The more extreme values seen for RCP 6.0 might therefore mean that one or some of the missing five GCMs have a moderating influence in the Nairobi, Bogotá and London regions. These missing GCMs are: CNRM-CM5 (Centre National de Recherches Météorologiques), INMCM4 (Institute for Numerical Mathematics), HadGEM-CC (Met Office Hadley Centre), ACCESS1-0 CSIRO (Commonwealth Scientific Industrial and Research Organisation, Australia) and BOM (Bureau of Meteorology, Australia), and CESM1-CAM5-1-FV2 (Centre National de Recherches Météorologiques). The one GCM that RCP 4.5 and 6.0 both use that RCP 8.5 does not, is GFDL-ESM2G (Geophysical Fluid Dynamics Laboratory).

Additionally, it is worth highlighting that the RCP scenarios are considered worst case or not, on the basis of radiative forcing (caused by global GHG emissions). There will be a direct translation of this forcing to global temperature but forcing may not align with global rainfall. Moreover, the study sites are a very small sample of the globe, so it is not too surprising that the global worst-case scenario does not produce the locally worst-case rainfall in these small areas.

4.5.6 Assumptions and limitations

The literature is inconsistent

Comparing this work to other published studies that utilise climate change models and scenarios has been difficult because the literature is inconsistent. Climate change studies tend to focus on large areas so results will be reported for regions of continents, like northern or north-west South America, or whole countries or best case, sub-regionally, such as southern Colombia. It is rare to find studies focused at the basin scale. Also, studies tend to use only one GCM, or if they do use an ensemble, the older studies will use AR4 rather than CMIP5 ensembles. If they do use an ensemble from CMIP5, then they may only report for one or two RCP scenarios. This study is comprehensive for studying climate change in a number of geographically disparate locations at the basin scale, using an ensemble of models from CMIP5, for three RCP scenarios. However, this means that we cannot directly compare the results to other published studies.

The problem of percentages

Throughout this work, percentages, specifically the percentage change difference (pcd), has been used as a measure of the change between the baseline values and the scenario values. The alternative, using absolute change, would tell us the amount of change but not the relative significance of that change. The advantage of using percentage as a change measure is that it can provide an indication of whether a change is large or small relative to the original value.

The disadvantage of using percentage as a measure is that it may not always communicate well. For instance, in basins with typically low flows a change from 0.01 to 0.02 is a small change in terms of absolute magnitude but is an increase of 100% (pcd). Whereas in wet environments or basins with high flows, a change from 35 to 50 is high in absolute magnitude but in relative terms is low/moderate at 42.9% (pcd). Rivers in wet environments can more easily cope with larger flows so the relative change measure is a good indicator in that respect but proves challenging when interpreting comparisons between basins.

Comparing between basins

When studying different entities using the same metrics and parameters, it is natural to look for commonalities between them. However, the six study basins examined here are geographically disparate with different size basins, different climate, different landscape/vegetation types and topographies. The one similarity is that, except for the London basin, they all occur in the tropical latitudes. Choosing vastly different study basins was deliberate, but it does mean that finding commonalities between them can be challenging and thus, the conclusion that they have different responses is not surprising. Yet, it was never the purpose of this work to find commonalities between the basins, rather to explore the impacts for each basin and attempt to interpret the cause of the differences. This has the added benefit of demonstrating the versatility of the methods used.

Scenario agreement

Agreement amongst climate models, known as 'model agreement', is a commonly used metric in climate science and it is usually represented as the number of models agreeing on the sign of change. Its interpretation is that if multiple models (based on different but plausible assumptions, simplifications and parameterizations) agree on a result, we have higher confidence than if the result is based on a single model, or if models disagree on the result (Tebaldi et al., 2011). An interesting and useful outcome of this work has been the maps showing not only where flood risk is projected to increase on average, but the number of scenarios which 'agree' on that increase. As with 'model agreement', the level of agreement among scenarios can be considered a proxy for the plausibility or confidence we have that the changes might occur under those scenarios of climate change.

Land use change in the future

Both land use change and climate change will impact hydrology and flood risk. However, future land use change was deliberately not accounted for in this work because if I had modelled land use change and climate change together, I could not have separated out the impact of climate change. The objective of the work is to understand areas at risk of climate change induced flood risk and design NFM solutions that mitigate that risk through land management (Chapter 5).

4.6 Summary & Conclusions

This study is comprehensive for examining the impact of climate change on hydrological variables and flood risk ratios in six geographically disparate locations, at the basin scale, using an ensemble of models from CMIP5, for three RCP scenarios.

Below, I address the aims set at the beginning of the study, based on the findings:

- *show where, and by how much, unmitigated flood risk (as defined in Chapter 3) will be higher, lower or the same under the various scenarios*: The climate modelling revealed that hydrological variables (such as water balance, rainfall, and runoff) and flood risk ratios will increase for the whole basin, on an annual scale, for the upstream watersheds of Chennai, Nairobi, Guayaquil, and Bogotá. Whereas the upstream watersheds of London and Jakarta are projected to decrease for the same hydrological variables and flood risk ratios, under scenarios of climate change. The seasonality of these changes was also examined (presented in the Appendix). A pcd index score, based on close-to-the-city sampling points for each scenario, indicates that the Nairobi then Guayaquil, Chennai and last, Bogotá basins will need additional mitigation to cope with the increase in climate-related flood risk. The London and Jakarta basins are the best able to cope with the flood risk related impacts of climate change, if all else remains equal.

- *determine if there are any geographic patterns to increases in flood risk in the study basins:* Changes in flood risk ratios were examined in detail via spatially distributed maps and via river sampling points. This provided a means to determine if there were any geographic patterns to increases in flood risk in the study basins. The smallest study basins showed the largest increases in water balance and flood risk ratios, indicating a possible effect of basin size on flood risk. However, the inverse was not true. Large basins, such as the Guayaquil basin, also showed large increases in flood risk. An association between the number of scenarios agreeing on a >10% increase in flood risk and increasing elevation, slope and tree cover was found in the Jakarta basin. In the Bogotá basin, there was a very strong positive correlation between percentage of tree cover and the number of scenarios agreeing on a >10% increase in flood risk. The opposite was found in the Guayaquil basin. Percentage tree cover declined (very strong negative correlation) as the number of scenarios (agreeing on a >10% increase in flood risk) increased. There was no clear evidence of a distance to city relationship and increases in flood risk ratio, for most basins. Although scenario means were the highest closest to the basin-city boundary for many of the study areas, the greatest increases in flood risk ratio were not in these locations. For the river sampling points there is no significant relationship between distance to city boundary and mean pcd of FRR due to climate change for four out of six of the basins: Nairobi, Jakarta, Bogotá and London. However, there is a significant correlation for Chennai and Guayaquil but in opposite directions. In Chennai, mean pcd increases as distance to city increases. In Guayaquil, mean pcd increases as distance to city decreases. There does appear to be an association

between where more than three scenarios project increases in flood risk to occur and the NI storage type that predominates in those locations. For half the basins (Nairobi, Chennai and London), it is the soil NI storage type associated with the increases in flood risk ratios. For the other basins (Bogotá, Jakarta and Guayaquil) it is canopy NI storage that is associated with the greatest number of scenarios showing an increase in flood risk ratios (>10%). This is probably a result of soil and canopy NI storage being the most prevalent and widely distributed of the NI storage types.

- *determine which climate scenarios pose the greatest threat in terms of increasing flood risk:* A surprising result of this study has been that the 'worst-case' scenario, RCP 8.5 2070s, has not always produced the greatest changes in flood risk ratio. In the Nairobi and Bogotá basins, the biggest extremes are projected to occur under RCP 6.0 for the 2070s, and in the London basin, RCP 6.0 for the 2050s. Also, RCP 4.5 for the 2070s had greater values than RCP 8.5 for the 2050s. A potential reason for these unexpected patterns may be due to the lack of some GCMs in the RCP 6.0 ensemble, compared to the other RCPs. It also points to the fact that the 'worst-case scenario' in terms of increased global temperatures does not equate to the 'worst-case' scenario in terms of precipitation and flood risk, at least at the scales examined here.

Overall, this study has successfully shown where flood risk ratios are projected to increase or decrease under climate change scenarios in six study basins. This will provide an important basis to determine locations to target mitigation and/or adaptation actions aimed at increasing water storage, either via grey or natural infrastructure, or both. However, it is important to recognise that there may be other reasons why these basins flood in the future, such as land use change, urbanisation, sea level rise etc, and this study has purposefully only looked at the influence of climate change on hydrological variables in order that impacts of climate change can inform mitigation measures to be applied in Chapter 5.

Chapter 5

Forestation scenarios to reduce current and future flood risk in watersheds upstream of two cities

5.1 Chapter summary

This chapter explores how increasing green water storage capacity in the form of canopy cover, via afforestation and/or reforestation (hereafter referred to as 'forestation' as in Chapter 2), can mitigate current and future flood risk. Specifically, I examine the influence of forestation extent and forestation spatial targeting on flood risk ratios within two of the catchments. Two types of forestation scenarios were used in two basins: Bogotá and Guayaquil. The first approach used general forestation scenarios to explore the effect of different extents of forest coverage, outside of protected areas. The second approach used a spatially restricted '*Restoration*' scenario that selects areas of recent deforestation and avoids urban, water and other natural land, plus incorporated a mask to avoid biodiverse land and target low-value land. Change in flood risk because of these scenarios was evaluated for *current risk,* by comparing the results to the baseline, and evaluated for *future risk,* by comparing the results with the changes from the climate scenarios, established in Chapter 4.

I found that:

- The greater the increase in forest cover extent, the greater the flood risk reduction but the magnitude of change is basin dependent;
- There is a non-linear relationship between forestation extent and flood risk reduction i.e., greater rate of flood risk reduction at lower forestation extents;
- Even 100% forest cover will not neutralise flood risk;
- Reforestation of even very small extents of the basins, via spatial targeting, can contribute to mitigating flood risk at the basin scale but the reduction at the river point scale is marginal, dependent on where upstream has been forested and how far upstream these areas are located;
- Focusing only on reforesting areas of recent deforestation is not sufficient, if the aim is to eliminate the negative impacts of flooding;

- However, it is still possible to lessen the impact of increased flood risk from both current and future flood risk by using this approach;
- In terms of cost to benefit, targeting slopes has the greater efficiency, and should be the preferred strategy for small-scale forestation NbS programmes;
- However, to reduce flood risk as a result of climate change, planting along lowlands and rivers in the Bogotá basin, and in mountains and alongside rivers in the Guayaquil basin, is advocated.
- To offset the increase in flood risk from climate change in the Bogotá basin, at least 3% of the land area needs to be reforested. In the Guayaquil basin, a similar increase in tree cover, is inadequate to meet the climate induced increase in flood risk.
- Restoring and safeguarding areas of recent deforestation may contribute to each country achieving its 30x30 protected areas goal;
- The method employed here to identify areas for NbS implementation may also be used to identify routes to connect areas important for conservation, creating an ecological network.

I conclude that focusing on reforesting areas of recent deforestation *exclusively* is not sufficient if the aim is to eliminate the negative impacts of flooding. However, there are other benefits to restoring and safeguarding these areas. Reforestation scenarios need to be more ambitious than replacing what has been recently lost.

5.2 Introduction

Previous chapters have shown how landscape features, called Natural Infrastructure (NI), interacting with hydrological variables, influence flood risk under current conditions, and also under future climate scenarios, i.e., current risk and future risk. In this chapter, I will explore the potential to mitigate the current and future flood risk by adding additional NI to the landscape. Incorporating more NI, in the form of green water storage (i.e., canopy cover, soil, and wetlands), will increase the water storage capacity, thus reducing the flood risk ratios (FRR) and fully, or partially, mitigating the risk. The use of NI to address a societal problem, in this case flood risk, means that it can be considered a Nature-based Solution (NbS). NbS (described fully in Chapter 2) are defined by the European Commission[53], as

[53] https://ec.europa.eu/info/research-and-innovation/research-area/environment/nature-based-solutions_en

"solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions."

This chapter will focus on increasing canopy cover as a flood risk reduction strategy, as increasing tree cover also increases soil storage in the *WaterWorld* model (see Chapter 3 for details on model application). I do not consider wetland storage for this exercise despite them being important locally. This is because they tend to be small (<1km^2), isolated, and have limited storage capacity relative to the other storages at the basin scale.

Increasing canopy cover can result from a number of actions: preventing deforestation, afforestation, reforestation and/or rewilding (left to regenerate naturally), as discussed in detail in Chapter 2 (section 2.2). The approach taken depends on the physical environment and local policy context. Afforestation and reforestation can be less desirable, as this approach tends to focus on a limited range of species and requires capital. Rewilding is associated with many co-benefits, is less costly compared to active planting, but it needs longer time spans to reach its benefit potential.

The generally accepted view has been that significant forest cover impact on flood flows is mainly limited to small watersheds (up to 500 km in area), has very local impacts (<100km^2) and involves only small flood events (Calder & Aylward, 2006; Dadson et al., 2017; FAO-CIFOR, 2005; Stratford et al., 2017). For these reasons, it has been suggested that forests alone will not be able to protect entire river basins from catastrophic events (FAO-CIFOR, 2005). This view is often contrary to public and policy-maker perception. However, this might also be a case of "little evidence does not mean no evidence". Reasons for the lack of evidence could be due to mostly small catchments being studied (Filoso et al., 2017; Marapara et al., 2021a), the relatively short lengths of available data records, and the difficulty in larger catchments of isolating a forestry effect from the mix of land uses, activities, variability of climate, managing forests in phases, and forests occupying only a small proportion of the catchment (Nisbet et al. 2011; Marapara et al. 2020). Marapara et al. (2020) assert that there needs to be a better understanding of how changes in the quantity, location and type of tree cover translate into particular changes in flood magnitude and frequency under varying geoclimatic and other drivers.

Among the most frequently asked questions, when considering forestation for the purpose of flood risk reduction, are: 1) how much of the catchment needs to be afforested or have an increase in tree cover, i.e., the scale or extent of the tree cover increase, and 2) does the placement or location of the additional tree cover within the catchment play a role in mitigating flood risk. A third common question relates to whether the type of tree, either conifer or broadleaf or mixed, impacts flood risk reduction. However, the land use scenarios cannot account for the type of tree, so I will not discuss this last question further.

5.2.1 Extent, or scale, of forestation

Studies that have examined the extent or scale of forestation needed to reduce flood risk, or related proxies such as discharge or high flow, report mixed findings. There does appear to be consensus that the smaller the area of woodland in a catchment, the less the effect on reducing flood peak (Burton et al., 2018), forestation efforts will be ineffective if the afforested area is too small relative to the desired water retention (Wahren et al., 2012); and forest related hydrological effects are very difficult to discern when <20% of a catchment is affected (Cornish, 1993; Nisbet et al., 2011). It follows that, as the proportion of land that forests and trees cover increases, the stronger the hydrological signal (Marapara et al., 2020).

Until recently, most studies examining the effect of forestation on hydrology have been focused on small basins (<40 km^2) and relatively short term (<10 years; Filoso et al., 2019; Marapara et al., 2020). Two recent studies focus on large catchments; one is a modelling study (Buechel et al., 2022), with associated model assumptions, and the other is an observational or monitoring study (Bathurst et al., 2022). The study by Buechel et al. (2022) is specifically focussed on large catchments (~500-10,000 km^2) in Great Britain. They modelled 12 catchments and found that median modelled flow is reduced by 2.8% ± 1.0 (1 SD), or 10 mm yr−1 ± 2.1 (1 SD), for a ten-percentage point increase in catchment broadleaf woodland (Buechel et al., 2022). The observational study by Bathurst et al. (2022) on four large catchments (434-1545 km^2) in Chile, over a 50-year period, with 18-54% increases in forest cover, found that partial forestation rates of up to 50%, while markedly affecting annual evapotranspiration and runoff, have less certain effects on peak discharges (Bathurst et al., 2022). They found that forestation increases must exceed 20% of the catchment area to cause observable increases in annual evapotranspiration and decreases in annual runoff, in agreement with observations for small catchments (Bathurst et al., 2022). However, in contrast with observations for small catchments, forestation rates of even 50%, while

markedly affecting annual evapotranspiration, had a less certain impact on flood peak discharge (Bathurst et al., 2022).

5.2.2 Placement of forestation/ effect of position within the landscape

The position of the tree planting scheme within the catchment, either in the upper (uplands), middle, or lower catchment (lowlands); or catchment, cross-slope, riparian or floodplain type woodland (as categorised by the Environment Agency, 2018), is thought to influence the effectiveness of the tree cover intervention. This is likely because climate (especially rainfall) and other hydrologically important variables differ across the landscape. Spatial targeting of forestation interventions is also a consideration in terms of spatial planning and how the land is used for other purposes such as agriculture. If there is only a small amount of land available to forest due to land ownership considerations or due to costs of planting and maintenance, then ensuring that the tree schemes are placed in the most strategic position is of utmost importance to policy makers and implementation agencies.

While other studies have examined the effect of forestation position within the landscape, with contrasting conclusions (see Broadmeadow & Nisbet, 2004; Burton et al., 2018; Dixon et al., 2016; Marapara et al., 2021; Wahren et al., 2012), my approach will base spatial prioritisation on targeting and avoiding certain land types to ensure sustainability and to avoid unintended negative consequences (discussed in Chapter 2, section 2.2.3). Namely, I propose spatial prioritisation criteria based on: i) targeting areas of recent net deforestation, ii) avoiding areas of high biodiversity value, and iii) targeting low-value land.

Targeting areas of recent net deforestation and low-value land

Reforesting an area that was previously forested and now degraded is highly recommended when selecting appropriate areas for reforestation (di Sacco et al., 2021). As such, this study will target areas of recent net deforestation, which is a parameter of the restoration scenario (see Methods).

For determining forestation site location, it is also important to target low value land. There is concern that mass tree planting schemes could threaten food security by taking up land that is, or could be used, for food production (Doelman et al., 2019, 2020). As flat land has the most utility, land on a slope will be the least sought after for development or farming. In this study, I target land of least agricultural intensity and/or on a slight slope (see Methods).

Avoiding areas of high biodiversity or conservation value

Afforesting areas of high biodiversity or conservation value is not advocated for many reasons (Bond et al., 2019; Holl & Brancalion, 2020) but also depends on what is to be planted and what it will be replacing. Planting of monocultures has strong evidence of being detrimental to local biodiversity (Stephens & Wagner, 2007; Wang et al., 2019) whereas planting of native mixed tree species is beneficial as long as it is not replacing other important habitat, such as peatland, páramo or other high-value natural grasslands (Bonnesoeur et al., 2019; Brockerhoff et al., 2008; Ilstedt et al., 2007; Wang et al., 2019). The model used in this study cannot differentiate between type of tree (native or non-native, conifer or broadleaf) used for the forestation scenario, instead, steps were taken to avoid land that could be important for biodiversity, i.e., Protected Areas (PAs) and Key Biodiversity Areas (KBAs). The International Union for Conservation of Nature (IUCN; Dudley, 2008) defines a PA as, "*a clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values*".

KBAs are sites contributing significantly to the global persistence of biodiversity and identified by applying the criteria and thresholds set out in "A Global Standard for the Identification of Key Biodiversity Areas" (IUCN, 2016). Although there is strong overlap between KBAs and PAs, not all KBAs will be PAs and not all PAs will be KBAs. KBAs derive from scientific identification, while PAs are a conservation tool with legal recognition and governance arrangements[54].

5.2.3 Study basins

This chapter will focus on two of the six basins covered in the rest of the thesis. Focusing on a subset of the basins will allow more depth and insight, which is not possible to do when comparing all the basins. The London and Jakarta basins were excluded as the results from the climate change scenarios (Chapter 4) showed a projected decrease in precipitation and associated flood risk for these basins, i.e., flood risk decreases thereby removing the need for climate motivated mitigation. The Chennai and Nairobi basins had high precipitation and flood risk projections under climate change but are excluded as they are very small in area, and very densely populated (particularly Chennai), and thus have limited scope for widespread NI mitigation. The remaining basins, Bogotá and Guayaquil, were chosen as they both showed increases in projected precipitation and flood risk under climate scenarios

[54] https://www.keybiodiversityareas.org/assets/8f1535aed3316ae2b720364019f8cb1c

(Chapter 4), and they contrast each other in that one is a relatively small basin with an inland city of interest (Bogotá) and the other is a large basin with a coastal city of interest (Guayaquil). This is an important consideration, as Vose et al., (2011) in their paper on the critical needs for forest ecohydrological research in the 21st century, state one of the critical needs is to conduct hydrologic research at different spatial scales to allow better understanding of (1) watershed ecosystem behaviour across scales and (2) the ability to generalise response patterns across scales.

The Bogotá and Guayaquil upstream watersheds differ vastly in scale (by an order of magnitude), yet they are similar in that they are both in tropical South America and may have similar types/levels of investment for NI interventions. See Figure 5.1 for the geographical context of the Bogotá basin and Figure 5.2 for the Guayaquil basin showing: rivers, urban areas, Protected Areas, Key Biodiversity Areas, elevation, and land cover.

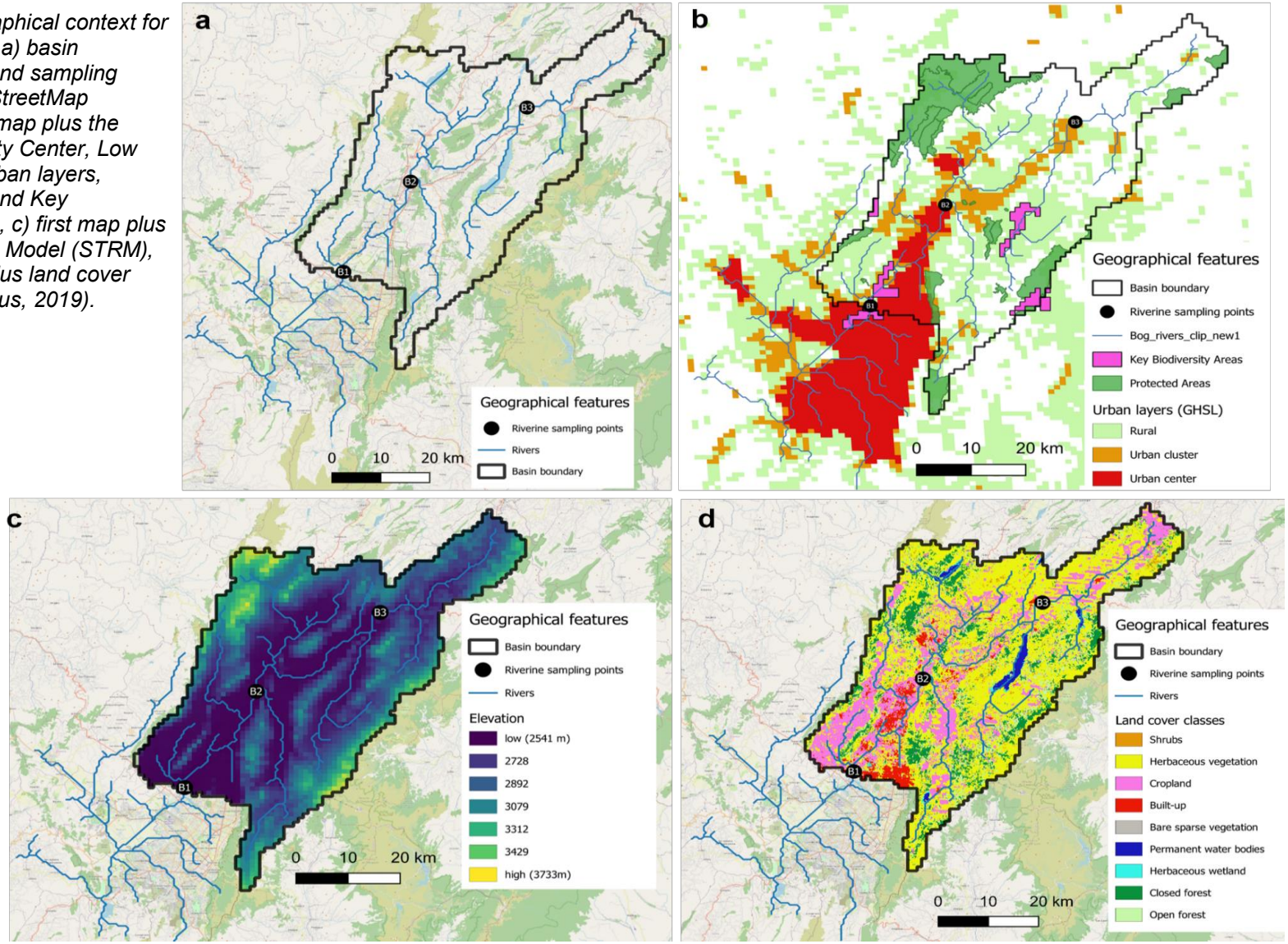


Figure 5.1 Geographical context for the Bogotá basin, a) basin boundary, rivers and sampling points with OpenStreetMap basemap, b) first map plus the Rural, High Density Center, Low Density Center urban layers, Protected Areas and Key Biodiversity Areas, c) first map plus a Digital Elevation Model (STRM), and d) first map plus land cover classes (Copernicus, 2019).

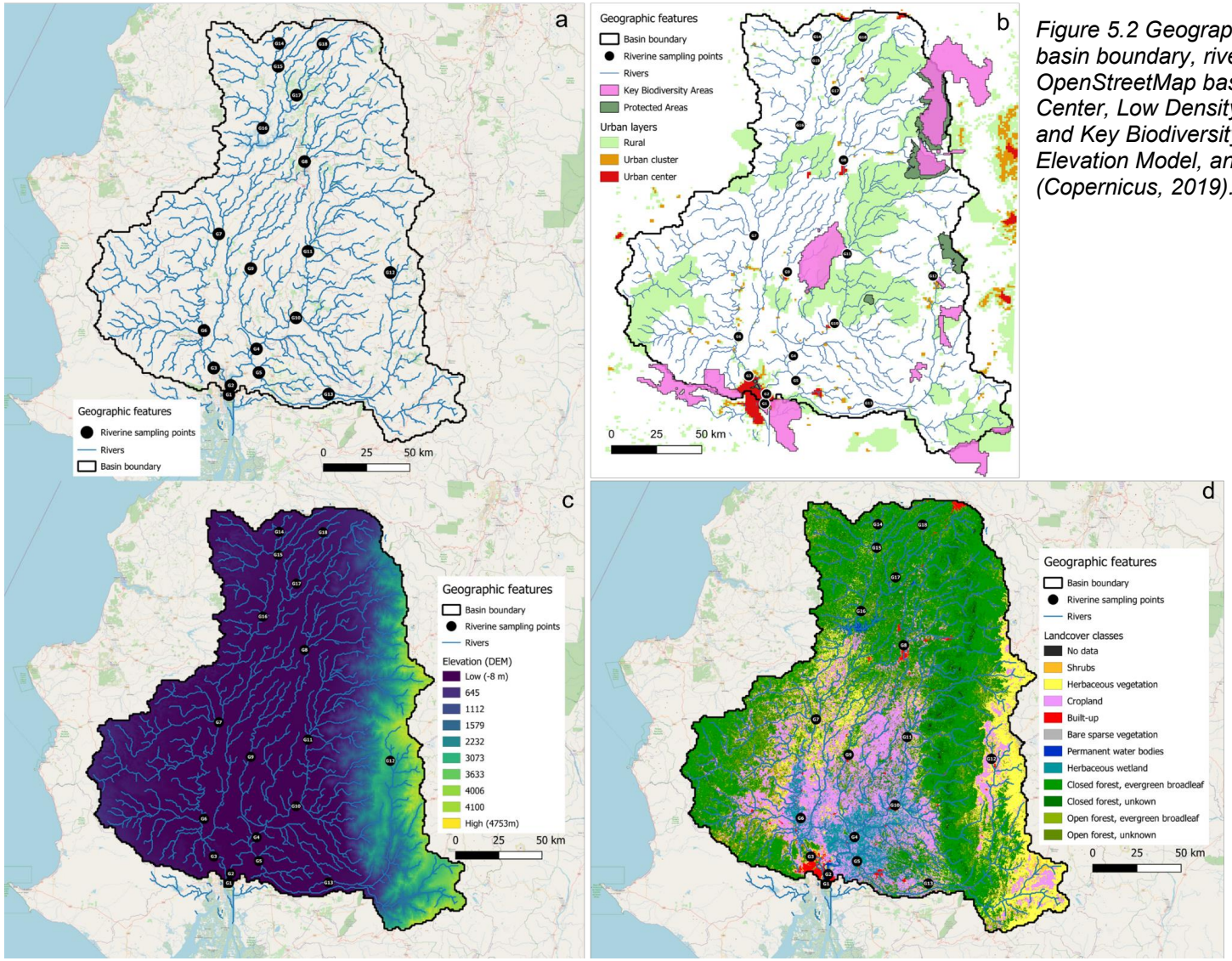


Figure 5.2 Geographical context for the Guayaquil basin, a) basin boundary, rivers and sampling points with OpenStreetMap basemap, b) first map plus the High Density Center, Low Density Center urban layers , Protected Areas and Key Biodiversity Areas, c) first map plus a Digital Elevation Model, and d) first map plus land cover classes (Copernicus, 2019).

5.2.4 Chapter aims and objectives

The aim of this chapter is to explore and evaluate the impact of different forestation scenarios to mitigate flood risk as modelled by *WaterWorld* (i.e., the ratio of annual runoff to upstream natural flood storage) in the basins upstream of the cities of Bogotá and Guayaquil. To achieve this aim, the following objectives were set:

1) Evaluate the amount (scale or extent) of additional NI needed to reduce current levels of flood risk.
2) Determine if NI flood mitigation is more effective in certain places than others.
3) Determine if a scenario for NI driven flood mitigation can reduce the enhanced flood risk that results from the higher precipitation projected under climate scenarios, i.e., future flood risk.
4) Based on the findings, consider if there is an ideal and/or realistic forestation target to recommend to NbS investors?

5.3 Methods

5.3.1 Land use and cover change scenarios in *WaterWorld*

Choosing the scenario method

There are four main options for building forestation scenarios in the public version of *WaterWorld*: 1) Pre-defined rules, 2) Define your own rule, 3) the QUICKLUC land use change model v2.1, and 4) Restoration scenarios, with six sub-options. Although most of these options were experimented with in the pilot phase of this study, only those that were used in the final study are described, i.e., 1) Pre-defined rules and 4) Restoration scenario - option two. These are summarised in Table 5.1. The '*Create Land Cover Type - Pre-defined Rule*' is used to examine different levels of forestation (as a percentage of total area across the whole catchment) excluding protected areas, to examine the effect on flood risk ratios (FRR). The '*Restoration option two scenario'* (Restoration of tree cover in areas of recent net deforestation), has in-built limits avoiding tree cover gain on built-up land and water pixels, and was combined with a Zone of Interest (ZOI) to create a mask targeting and avoiding certain land types.

Table 5.1 Summary of the land cover change and restoration scenario options available in WaterWorld.

Scenario option	Description
Create Land Cover Type - Pre-defined Rule (Figure 5.3):	This option allows you to set percent cover for tree, herb and bare to achieve the land cover that you wish. The total cover in a pixel must add to 100%. The pre-defined rule allows the set covers to be applied according to one or more of the following pre-defined rules: ● land outside protected areas (%), ● land inside protected areas (%), ● land near roads and rivers (%), ● land near existing deforested areas (%), ● land at low elevations (%), ● land at mid elevations (%), ● land at high elevations (%), ● all land (%). Different covers of tree, herb and bare can be defined for each of these rules. In addition, changed areas can be given one of *WaterWorld's* land uses (e.g., cropland.) or be left unchanged from their baseline land use. Population can also be changed in the areas in which land cover has changed.
Restoration - option two (GFC) (Figure 5.4)**:**	Restoration of tree cover in areas of recent net deforestation, for a specified number of years. In this case, forest recovers at the same rate that it was lost. The *WaterWorld* model describes the workings of this scenario as follows: The fraction of the pixel per-year lost to deforestation over the last two decades is multiplied by the user-defined restoration period, converted to tree cover and added to the current tree cover in the pixel. Tree cover cannot be more than 100 percent. Land use can change over any pixel in which tree cover has changed. Land cover and land use changes are only applied where the use-defined mask is true. Herb and bare cover are adjusted to the new tree cover at their original ratios to each other. Pixels with a cover of urban>50 percent or water greater than 50 percent are excluded from any changes as they are considered urban areas or water bodies. The post-restoration land use is user-defined (the default being natural, i.e., non-human land use). The new land use is applied to the area under recovery which may be a fraction of the pixel as determined by the change in tree cover. The fraction of urban land use may not be the same as the bare cover fraction as tree canopies can overlay pavements. In both Restoration scenario options, the current (2020) baseline is compared with the scenario in an equilibrium fashion (i.e., once the full period scenario has been applied) not a transient fashion (i.e., each year of the scenario).

Screenshots of the model setup for each scenario are shown in Figures 5.3 and 5.4.

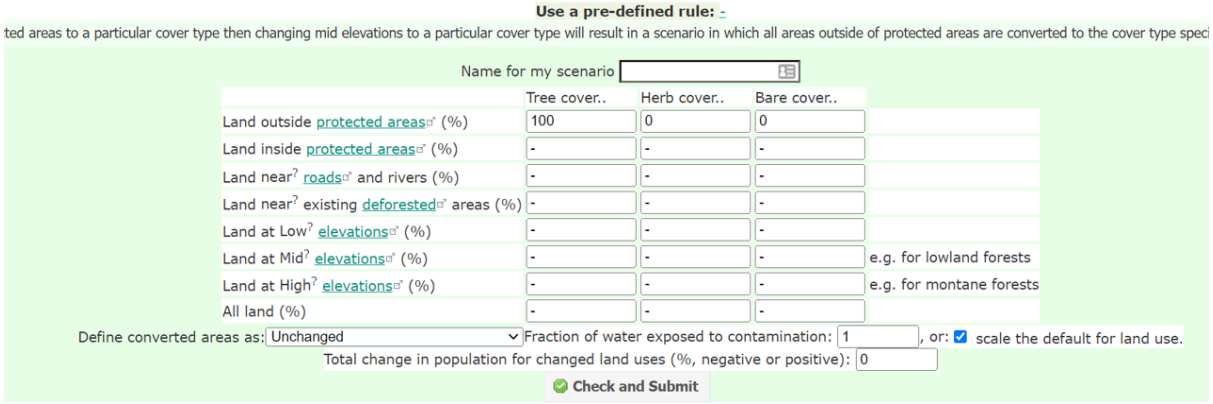


Figure 5.3 Screenshot of Pre-defined rule model interface within WaterWorld *showing setting land cover to 100% tree cover.*

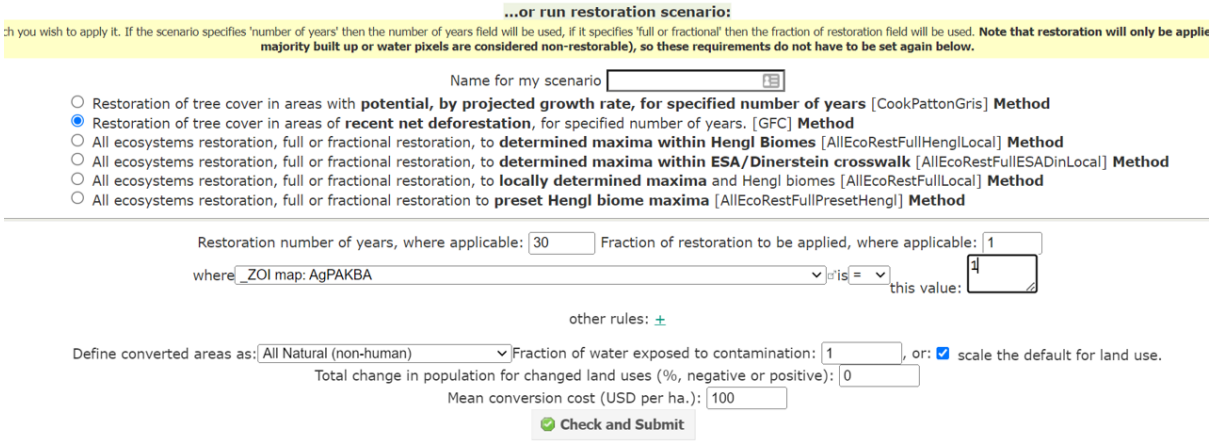


Figure 5.4 Screenshot of the Restoration Scenario model interface within WaterWorld *showing the selection for option 2 with a ZOI selected.*

5.3.2 Exploring levels, or scales, of forestation

The 'pre-defined rule' was used to explore the effect of various levels of forestation outside protected areas (Fig. 5.3). I ran the model with different levels of forestation (targets: 100%, 75%, 50%, 25%, 10% and 5%) outside protected areas for both entire major hydrological basins in which the study basins reside: Colombia-Ecuador for Guayaquil and Magdalena for Bogotá. The larger basins, rather than the smaller city basins, were used for this analysis in order to understand the wider range of landscape conditions that influence forestation impacts on flood risk. This knowledge could also inform the criteria in the spatial targeting scenarios.

For each grid cell, the tree cover is increased to meet the target level of tree canopy cover. For example, if a pixel currently has 5% tree canopy cover, under the scenario, tree cover

will increase by 95% to meet the 100% target or increase by 45% for the 50% target. The flood risk ratio (FRR; Storage to total capacity ratio) for each level of forestation is calculated by the model, and I measure the change from baseline as percent change difference (pcd; eqn 1). A pcd of 0% indicates no change from baseline. To show neutralisation of flood risk, a pcd of -100% is required. FRR would reach zero when accumulated runoff is equal to accumulated storage. In this case, not all rainfall is evaporated because there are still existing stores of water.

Storage to total capacity was used here rather than Storage to Total Green Capacity (Chapter 3) because the first includes floodplains and water bodies and is better at understanding total flood risk mitigation. Knowing the green storage ratio would inform us about the green contribution, but not the overall flood risk. Change in total also represents a change in green, since it is only the green storage capacity that the scenarios are changing.

Finally, to see how the increase in tree cover influences FRR across the basin, 1,000 points in the basin were randomly selected and the change in FRR at these points for the 50%, 25% and 10% scenario was compared. The downstream average of change in tree cover against change in FRR for the three scenarios was calculated. Downstream averaging cumulates across the whole map to highest to lowest points so at a point the average is everything upstream of that point. In this case, it cumulates the tree cover values and divides by the number of cells. The results from this exercise were difficult to interpret and so are reported in **Appendix E1 (Fig. E1 to E6)**.

5.3.3 Creation of a 'low-value land' target mask

My aim for creating a mask to select sites for forestation is to avoid areas important to biodiversity and to target sites of recent net deforestation and low-value land. To do this, multiple Zones of Interest (ZOI) were created using various data layers in *WaterWorld* (Table 5.2), either on their own or in combination. Defining a ZOI uses Boolean sieve analysis to create maps which have pixel values of 1 for areas where the rules defined are met, or zero for other areas. Built Up Land, Water, Crop and Pasture was not used in these ZOIs as they are accounted for in the Restoration Scenario restrictions (see above).

Table 5.2 Datasets within WaterWorld used to create the exclusion and targeting ZOIs.

Avoid/Target variable	Dataset within *WaterWorld*	Reference
Protected Areas	**Protected Areas** World Database on Protected Areas (WDPA) Annual Release Dec 2020 (web download version), The WDPA is a joint product of UNEP and IUCN, prepared by UNEP-WCMC, supported by IUCN WCPA and working with Governments, the Secretariats of MEAs and collaborating NGOs. For further information protectedareas@unep-wcmc.org	(UNEP-WCMC and IUCN, 2019)
Key Biodiversity Areas	**Key Biodiversity Areas** These data represent the combination of global Important Bird Areas developed and maintained by the BirdLife partnership and Key Biodiversity Areas developed and maintained by Conservation international and partners. For a full list of collaborators and supporters, please contact science@birdlife.org or data@conservation.org.	(Birdlife International, 2016)
Agricultural suitability	**Mean rain-fed crop suitability (low inputs) units 0-10,000**	(Mulligan, 2013)
Slope	**Slope gradient (degrees from horizontal)**	(Lehner et al., 2008)

The first and most permissive rule was for avoiding both Protected Areas and Key Biodiversity Areas. This ZOI was created by setting Protected Areas = 0 AND Key Biodiversity Areas = 0 (the resulting ZOI is titled PAKBA). The second ZOI included the first ZOI rules plus setting agricultural suitability to < 1,000 (titled AgPAKBA). The third ZOI included the first ZOI rules plus Slope gradient to > 5 degrees (titled SlopePAKBA). The final ZOI included all the ZOIs (titled AgSlopePAKBA).

Flood risk trajectories

After completion of a scenario run, *WaterWorld* generates a 'Flood Risk Trajectory' map that spatially shows the change in risk compared to the baseline condition. The risk classes are: high-risk decreases, high-risk becomes low risk, low-risk decreases, low-risk becomes high-risk, high-risk increases, or low-risk increases. High-risk is a FRR of >1 and low-risk is a FRR of ≤1. Flood Risk Trajectory maps were generated for each spatial targeting scenario for both basins.

Area and percentage of basins

Each cell has a resolution of ~1 km^2. The area that each trajectory class covers is calculated by counting the number of cells or pixels of each class and converting to km^2.

It is possible to calculate the area that each of these trajectories covers by counting the number of cells of each class and multiplying by 1. The percentage of the basin that each class represents is calculated by multiplying the number of cells in each class, dividing by the total number of cells in the basin, and multiplying by 100%.

Hydrological variables

The hydrological components that make up the FRR, such as water balance, evapotranspiration, fog input and runoff, change are calculated in *WaterWorld* and examined as frequency distributions of the change in values for these components and thumbnail maps of the location of the positive values and the negative values generated. The frequency distribution graphs subtract the most common class and any extremes, i.e., the zeros are removed. **These results are presented in Appendix E.**

5.3.4 Compare flood risk decreases from forestation scenarios to flood risk increases from climate scenarios

To demonstrate whether the forestation scenarios are a nature-based adaptation to climate change related flooding, I compared the changes in accumulated flood risk ratio (FRR) for the forestation scenarios to the changes in FRR under climate change scenarios calculated in Chapter 4. I did this in two ways. First, I compared the basin means (pcd) of FRRs from the climate scenarios to the basin means (pcd) of FRRs from the forestation scenarios, as well as comparing these with the mean, minimum and maximum FRRs of the river sampling points under climate scenarios. The forestation scenarios are set for 30 years from now, which corresponds to the RCPs for the 2050s time period. However, the mean, minimum and maximum values for the climate scenarios compared to here, encompass both time periods, 2050s and 2070s, to show if the NbS can mitigate even the more extreme climate induced FRRs.

Second, I overlaid the maps of where forestation scenarios showed decreases in FRR to two types of climate scenario maps: 1) where the mean FRR of all the climate scenarios is greater than one, i.e., high-risk (this doesn't account for change from baseline so the FRR may have been high-risk before climate scenarios), and 2) where the climate scenarios showed an increase in FRR greater than 10 percent of the baseline, i.e., FRR increases under climate scenarios.

For 1: I took the mean of the climate scenarios raster stack (from Chapter 4) and isolated the high-risk cells using raster algebra (>1). I multiplied the resultant raster by 3 so that all CC high-risk cells have a value of 3 rather than 1. This is to differentiate it sufficiently from the raster that it will be added to. For each forestation scenario, I isolated the cells which showed a decrease in FRR from baseline (difference map < 0). I then added the high-risk climate scenario raster to the forestation raster so that the resultant raster shows 1= forestation decreases (green in the map), 3 = CC high-risk (pink in the map), 4 = overlap (blue in the map) and 0 = no overlap nor increase or decrease for either layer.

For 2: I took the cumulative map of the climate scenarios greater than 10 percent of baseline (from Chapter 5) and converted all the values > 0 to 1 to create a binary map. I multiplied the resultant raster by 3 so that all CC high-risk cells have a value of 3 rather than 1. This is to differentiate it sufficiently from the raster that it will be added to. For each forestation scenario, I isolated the cells which showed a decrease in FRR from baseline (difference map < 0). I then added the high-risk climate scenario raster to the forestation raster so that the resultant raster shows 1= forestation decreases (green in the map), 3 =CC high-risk (pink in the map), 4 = overlap (blue in the map) and 0 = no overlap nor increase or decrease for either layer.

5.4 Results

5.4.1 Impact of the extent/amount of forestation on flood risk ratios

The impact of varying extents of forestation, in terms of percentage area of basin covered, on the flood risk ratio was investigated by aggregating results at the basin scale, river point scale, and at the major hydrological basin scale, rather than for the smaller local basin, i.e., the Magdalena basin for Bogotá and the Colombia-Ecuador basin for Guayaquil.

Basin scale

The change in flood risk ratio was compared for six levels of forestation (100%, 75%, 50%, 25%, 10% and 5%) in the Magdalena basin, outside of protected areas (Fig. 5.5). The results suggest a considerably lower (less steep) change in the flood risk ratio (FRR) between 50 and 100% forestation (−3.36%) compared to change in the FRR between 10 and 50% forestation (−11.47%). The greatest impact on flood risk lies between 10 and 50% forestation at the major hydrological basin scale (Fig 5.5).

In the Colombia-Ecuador basin, outside of protected areas, there are four percentage points difference in FRR between 100% and 50% levels of forestation compared to much steeper reductions for the lower levels of forestation (12 percentage points for 5% forestation and 29 percentage points for 25% forestation; Fig. 5.5). The Colombia-Ecuador basin has a greater reduction in flood risk for the same level of forestation compared to the Magdalena basin (Fig. 5.5).

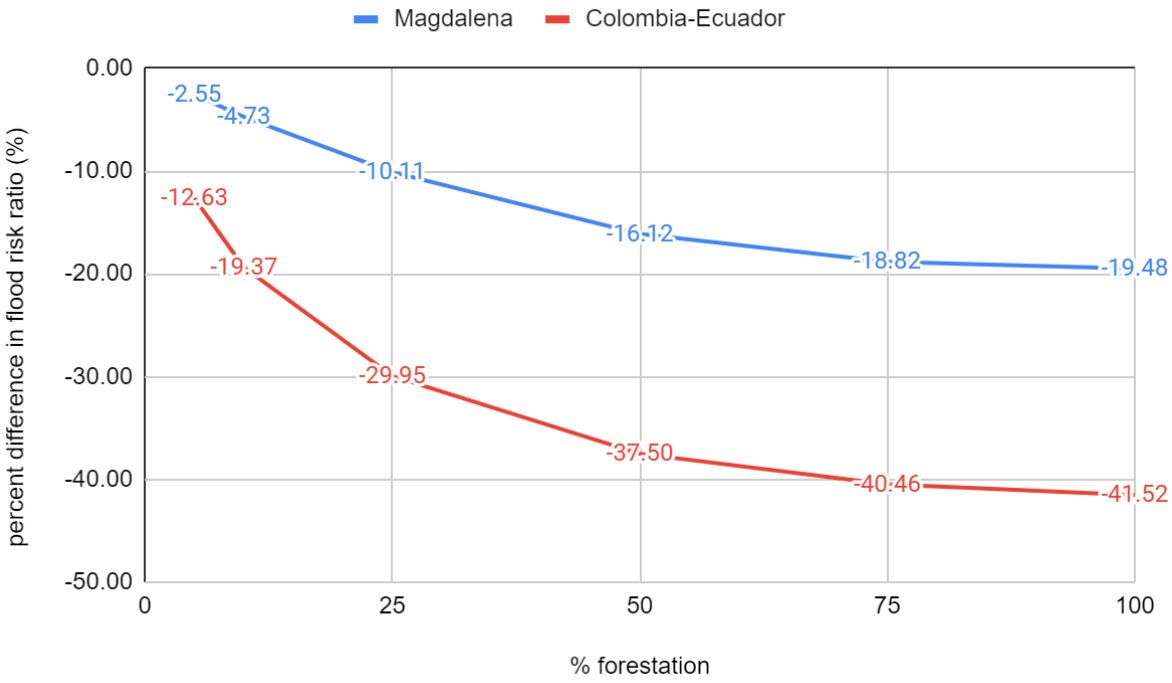


Figure 5.5 Relationship between amount of land afforested and change in flood risk ratio for the Magdalena basin, Colombia and for the Colombia-Ecuador basin.

River point scale

A single FRR sum value for an entire basin provides a general indication of the impacts of different levels of forestation. To determine more localised impacts, the change in FRR was compared at the river sampling points (described in Chapter 4).

The changes in flood risk at three river sampling points in the Bogotá basin are shown in Figure 5.6. As these are river sites, the levels of flood risk reduction were far greater than those seen for the whole basin. Once again, there was a levelling out in flood risk reduction between 100%, 75% and 50% levels of forestation. Sample point B3, the most upstream point located just before entering the urban cluster (See Fig. 5.1b for location), shows the greatest reduction in flood risk. B3 is high-risk in the baseline (FRR=1.2) but neutralises (=1) at 10% forestation and becomes low-risk from 25% forestation. These reductions in the ratios look large due to being percentages. The original baseline values are sitting near 1 for

these sample points, so the reduction after intervention ranges from just over half a percentage point to -0.07 percentage points of the FRR.

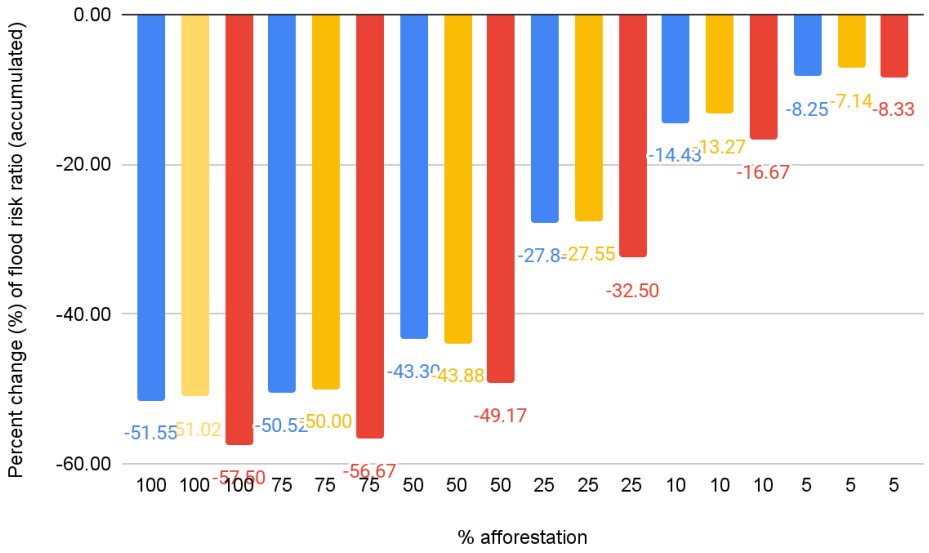


Figure 5.6 The change in flood risk ratio for three river sampling points upstream of Bogotá, under different levels of forestation, shows that FRR varies widely across the basin for the same level of forestation. The blue, yellow and red colour bars represent the three sampling points: blue = sampling point B1, yellow = sampling point B2 and red = sampling point B3.

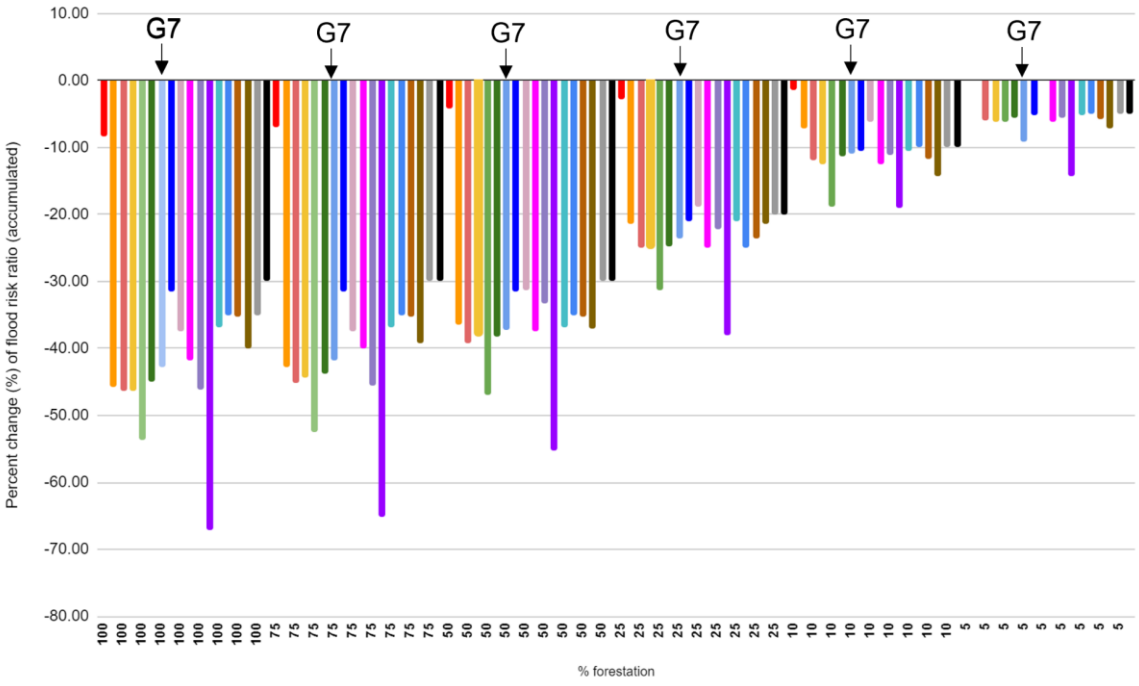


Figure 5.7 The change in flood risk ratio for 18 river sampling points upstream of Guayaquil, under different levels of forestation, shows that FRR varies widely across the basin for the same level of forestation. The red bar indicates sampling point G1 and the black bar represents sampling point G18. Point G7 is highlighted as the only point that reduces from high-risk to low-risk for every level of forestation (data not shown).

The results for the 18 river sampling points in the Guayaquil upstream are shown in Figure 5.7. At three of the river sample sites (G1, G2 and G9), in the Guayaquil basin, there was no change in flood risk ratio at the 5% forestation level (Fig. 5.7). Overall, it is evident that no level of forestation will completely mitigate the current levels of flood risk. Even a 100% increase in tree cover across the basin only offsets the flood risk at specific river points by between 30% and 67% in the Guayaquil basin. Point G12 shows far greater reductions than all the other sampling points. This point is located near the headwaters of the Rio Salinas, north-west of the town of Guaranda, in the eastern part of the basin, in the Andes. The number of points that move from high-risk (>1) to low-risk (≤ 1) decreases from nine in the 100% forestation scenario to 7 in the 75% level, to 6 in the 50% level, to 1 for the 5, 10 and 25% levels (data not shown). In the Guayaquil basin, there were a number of points that moved from high to low-risk under the general forestations scenarios, with the number of points decreasing as the level of forestation dropped. Point G7 (highlighted by the black arrows in Fig. 5.7) is the only point that reduces to low-risk for every level of forestation (data not shown). G7 is located on the Rio Doule near the town of Balzar in the western part of the basin.

Table 5.3 shows the average percent change in FRR, and standard deviation, for all the points for each level of forestation for both basins. Like the basin values, the point values show a greater reduction in the Bogotá basin than the Guayaquil basin. The 100% level of forestation reduces FRR by ~50% in the Bogotá basin and ~40% in the Guayaquil basin. The standard deviation indicates a much smaller range of variation for the Bogotá basin than for the Guayaquil basin. Both basins showed the range of variation decreasing with decreasing level of forestation.

Table 5.3 The average percent change difference (pcd) in Flood Risk Ratio (FRR) and standard deviation for all the river sample points in the Bogotá (n=3) and Guayaquil basins (n=18).

Level of forestation	Average FRR reduction	Std deviation	Average FRR reduction	Std deviation
	Bogotá basin		Guayaquil basin	
100	-53.36	3.60	-40.26	11.79
75	-52.39	3.71	-39.11	11.50
50	-45.45	3.23	-35.20	9.81
25	-29.30	2.78	-22.78	6.74
10	-14.79	1.73	-11.10	4.02
5	-7.91	0.66	-5.43	3.31

5.4.2 Effect of spatial targeting forest restoration scenarios on flood risk ratios

Change in tree cover due to the scenarios

The maps of the ZOIs and resultant change in tree cover due to the four scenarios (PAKBA, AgPAKBA, SlopePAKBA and AgSlopePAKBA) are shown in **Appendix E (Figs. E7 to E10 for the Magdalena hydrological basin and the Bogotá city basin, and in Figure E11 to E14 for the Colombia-Ecuador major hydrological basin and the Guayaquil basin)**. The changes are summarised in Table 5.4 for the major hydrological basin and smaller basin.

Table 5.4 The different levels of change in tree cover percentage as a result of the ZOIs for the Magdalena major basin, Bogotá basin, Colombia-Ecuador major hydro basin and Guayaquil basin. First number represents the absolute change (%) and the number in square brackets represents the percent change difference.

	Change in average tree cover percentage			
ZOI/Basin	**Magdalena**	**Bogotá**	**Colombia-Ecuador**	**Guayaquil**
PAKBA	3.43 % [+6.79%]	3.24% [+9.81%]	1.4 % [+2.08%]	2.78% [5.46%]
AgPAKBA	1.72 % [+3.41%]	3.24% [+9.81%]	0.53 % [+0.78%]	0.35% [+0.72%]
SlopePAKBA	0.46 % [+0.92%]	0.94% [3.06%]	0.19 % [+0.27%]	0.22% [+0.45%]
AgSlopePAKBA	0.38 % [+0.75%]	0.94% [3.06%]	0.17 % [+0.25%]	0.21% [+0.43%]

The land area covered by each ZOI and the resultant change in average tree cover percentage for those scenarios shows that some scenarios result in identical or very similar changes (Table 5.4). For example, in the Bogotá basin, the PAKBA and AgPAKBA scenarios are identical, as are the SlopePAKBA and AgSlopePAKBA scenarios. Going forward, only two of these scenarios, PAKBA and SlopePAKBA will be discussed for the Bogotá basin. In the Guayaquil basin, the SlopePAKBA scenario and the AgSlopePAKBA scenario produce very similar changes in tree cover percentage. Going forward, the AgSlopePAKBA will be removed as the SlopePAKBA scenario targets some land on the western edge of the basin, which the AgSlopePAKBA scenario excludes.

In both basins, it is noticeable that the scenarios did not exclude all the PAs that are shown in Figures 5.1 and 5.2. The PAs that were excluded in the scenarios are shown in Figure 5.8. The excluded PAs are small (in number and land area) in comparison to the polygons provided by the World Database on Protected Areas (WDPA). *WaterWorld* uses WDPA data but focuses on designated, internationally recognised PAs only (IUCN categories 1-6). WDPA includes all polygons provided by countries and what countries submit varies from year to year; the WDPA publishes everything received. For my scenarios, this may mean that forestation may occur in areas that are currently designated national "Forest Reserves Protectress Regional" and "Integrated Management Regional District" in the Bogotá basin, and/or “Ecological Reserves”, “Fauna Production Reserve”, “Wildlife Refuge”, and a “National Recreation Area” in the Guayaquil basin. However, the restoration scenario is for land that has been deforested in the last 30 years, so unless that forest was plantation, then it may be possible and even appropriate for forestation to occur in these reserves, subject to

ground-truthing and adherence to the land management/biodiversity plan (although beyond the scope of this thesis).

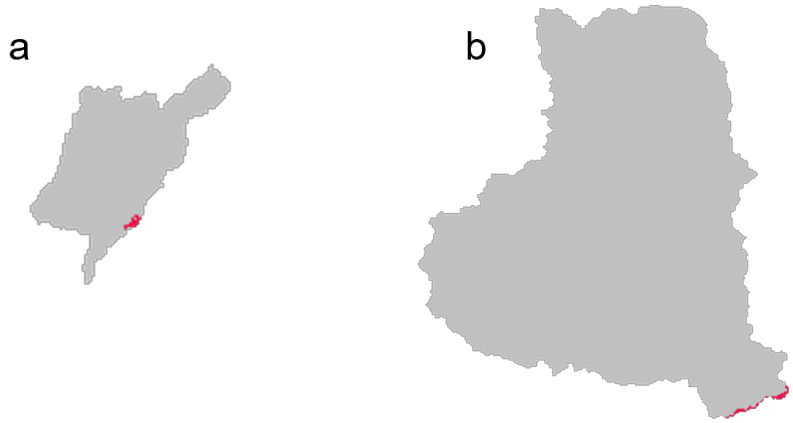


Figure 5.8 Delineation of Protected Areas in WaterWorld for, a) the Bogotá basin, and b) the Guayaquil basin.

Hydrological variable contribution

Figure E1 (Appendix E) shows the changes in hydrological variables (water balance, evapotranspiration, fog input and runoff) that make up the FRR change in the Bogotá basin. Figure E15 (Appendix E) shows maps and frequency distribution graphs of the changes in hydrological variables (water balance, evapotranspiration, fog input and runoff) that make up the FRR change in the Bogotá basin. These are summarised below for the two scenarios, PAKBA and SlopePAKBA, and compared against each other for their change in values, first as absolute change (Fig. 5.9a) and then as percent change from baseline (Fig. 5.9b) for the Bogotá basin. The PAKBA scenario incurs much greater increases compared to the SlopePAKBA scenario, for all the hydrological variables considered.

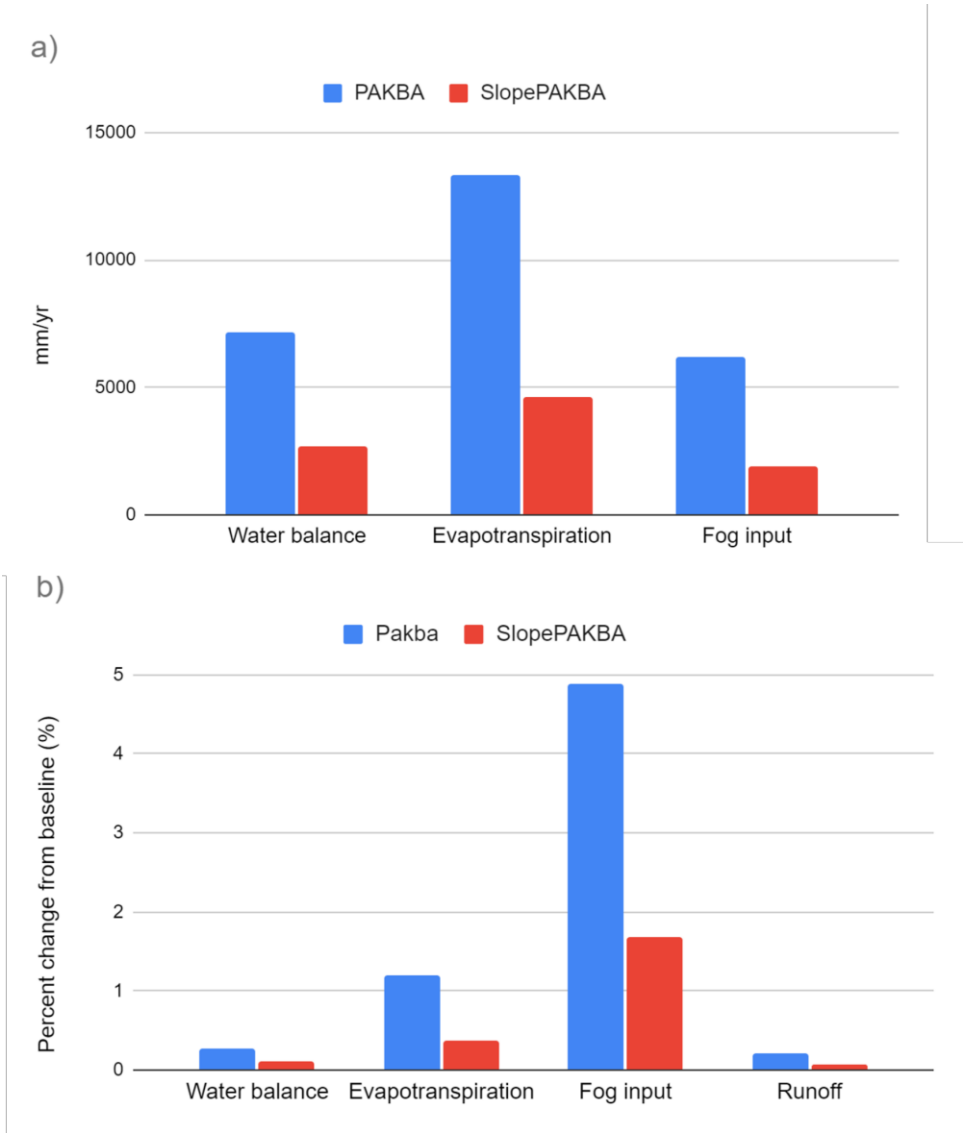


Figure 5.9 Absolute change (mm/year; a) and percent change difference (%; b) from the baseline for various hydrological variables under the PAKBA and SlopePAKBA forestation scenarios in the Bogotá basin. Runoff is not shown in panel (a) as its values do not fit on the same axis.

Figure E2 (Appendix E) shows the changes in hydrological variables (water balance, evapotranspiration, fog input and runoff) that make up the FRR change in the Guayaquil basin. Figure E16 (Appendix E) shows maps and frequency distribution graphs of the changes in hydrological variables (water balance, evapotranspiration, fog input and runoff) that make up the FRR change in the Guayaquil basin. These are summarised below for the three scenarios, PAKBA, AgPAKBA and SlopePAKBA, and compared against each other for their change in values, first as absolute change (Fig. 5.10a) and then as percent change from baseline (Fig. 5.10b) for the Bogotá basin.

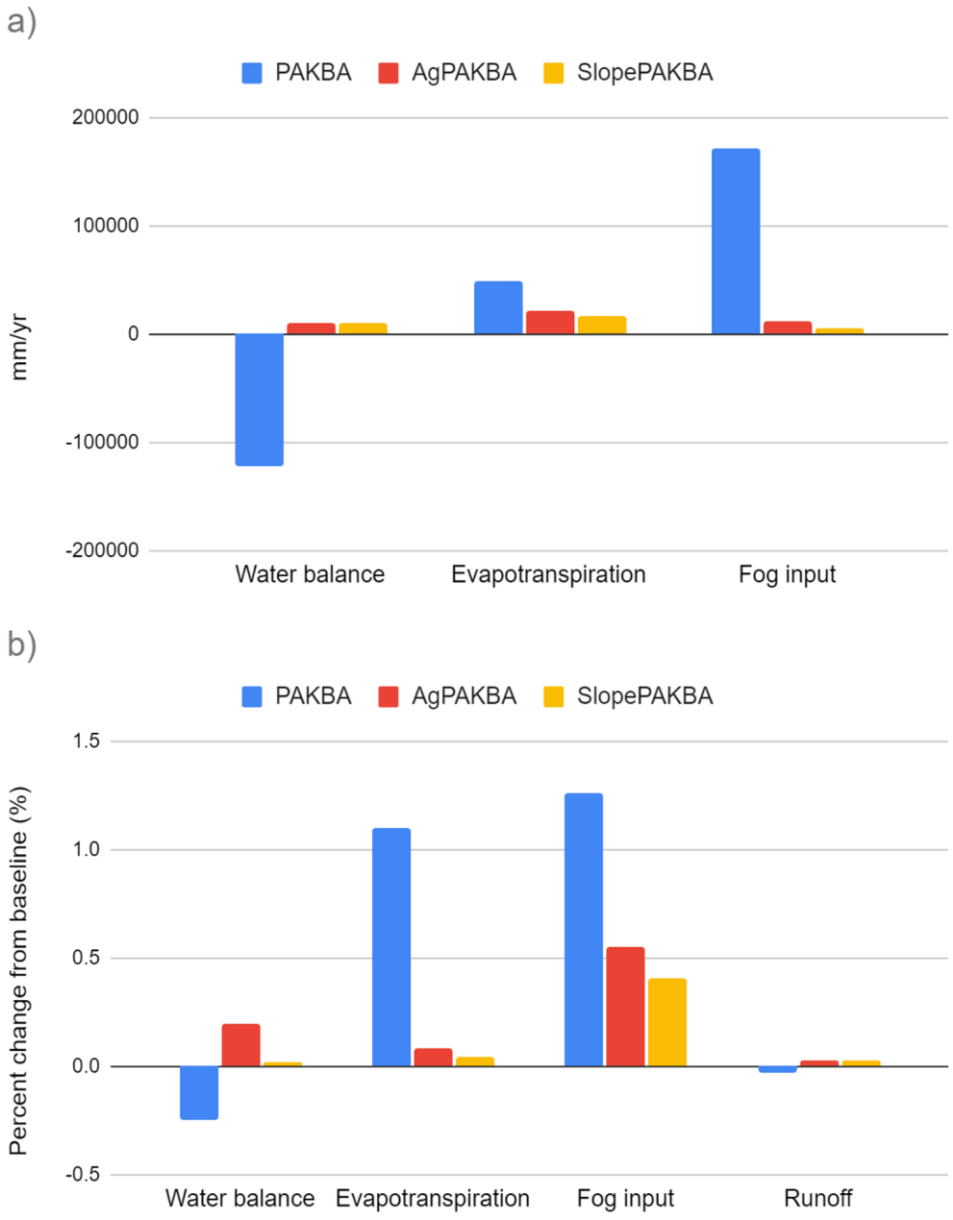


Figure 5.10 Absolute change (mm/year; a) and percent change difference (%; b) from the baseline for various hydrological variables under the PAKBA, AgPAKBA and SlopePAKBA forestation scenarios in the Guayaquil basin. Runoff is not shown in panel (a) as its values do not fit on the same axis.

In the PAKBA scenario, water balance decreases by -0.25% (Fig. 5.10b). This is different to the PAKBA scenario for the Bogotá basin, which had overall increases in water balance. Evapotranspiration and fog input increases but total runoff decreases slightly (as expected due to the decrease in water balance). The AgPAKBA and Slope PAKBA scenarios show increases for all the hydrological variables, with the AgPAKBA having slightly bigger increases than SlopePAKBA (Fig. 5.10).

Basin scale changes in flood risk

The effect of the strategic scenarios on flood risk ratios at a basin scale are shown in Figure 5.11.

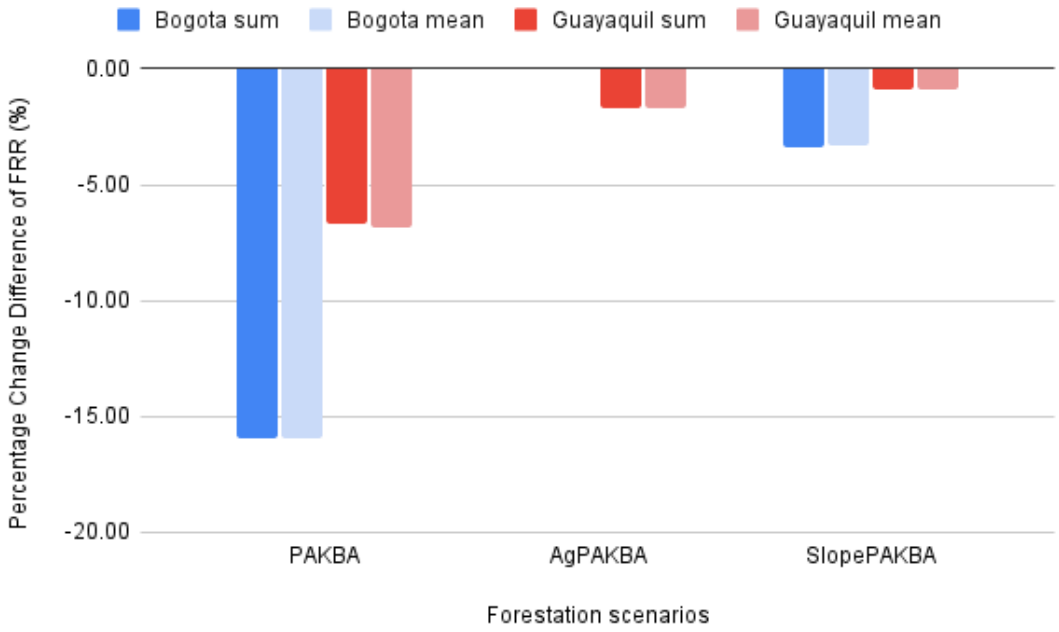


Figure 5.11 Percentage change in flood risk ratio (FRR), storage to total capacity (non-accumulated), under restricted forestation scenarios in the Bogotá basin (blue bars) and in the Guayaquil basin (red bars).

In the Bogotá basin (Fig. 5.11), there was a nearly 16% reduction in FRR for the PAKBA scenario (given a +3.24% change in tree cover) but only a 3.37% reduction for the SlopePAKBA scenario (given a +0.94% change in tree cover). In the Guayaquil basin, there is a steep drop in flood risk reduction between the PAKBA scenario (given a +2.78% change in tree cover) and the AgPAKBA scenario (+0.35% change in tree cover) from -6.72% to -1.72% but then a marginal drop between the AgPAKBA and SlopePAKBA (+0.22% change in tree cover) from -1.72 to 0.88% FRR (Fig. 5.11).

River point scale change in flood risk

The effect of the strategic forest restoration scenarios was examined at the river point scale (Table 5.5). Examining the change at points provides an indication of the effect on downstream sites. In both scenarios, the most downstream point, B1, has the greatest reductions compared to the other points. Overall, even though the percent change differences look significant as mitigation, we can see that the change in absolute terms is minimal: (range: ~-0.01 to -0.07 percentage points). The differences for the Guayaquil basin river points are marginal, with no points moving from high-risk to low-risk, and one point

under the PAKBA scenario, two points under the AgPAKBA scenario and five points under the SlopePAKBA scenario not displaying a reduction in FRR (Table 5.5).

Table 5.5 Change in FRR at river sampling points as a result of forestation scenarios at the river basin scale in the Bogotá basin (points B1-B3) and the Guayaquil basin (points G1-G18). Green highlighted cells indicate where FRR has decreased from >1 (high-risk) to 1 or below (low-risk).

Scenario	River pt	Baseline FRR (%)	Scenario FRR (%)	Absolute change in FRR (%)	Percentage change in FRR (%)
PAKBA	B1	1.01	0.94	-0.07	-6.93
	B2	1.06	1	-0.06	-5.66
	B3	1.45	1.39	-0.06	-4.14
SlopePAKBA	B1	1.01	0.99	-0.02	-1.98
	B2	1.06	1.04	-0.02	-1.89
	B3	1.45	1.44	-0.01	-0.69
PAKBA	G1	0.07	0.07	0.00	0.00
	G2	1.39	1.35	-0.04	-2.95
	G3	0.79	0.77	-0.03	-3.66
	G4	1.53	1.48	-0.05	-3.04
	G5	1.64	1.59	-0.05	-3.04
	G6	0.81	0.78	-0.03	-3.31
	G7	0.99	0.96	-0.02	-2.50
	G8	1.71	1.70	-0.01	-0.56
	G9	1.54	1.51	-0.03	-2.14
	G10	1.61	1.56	-0.05	-3.01
	G11	1.77	1.69	-0.08	-4.67
	G12	3.09	2.70	-0.40	-12.80
	G13	1.90	1.85	-0.04	-2.26
	G14	1.64	1.63	-0.01	-0.66
	G15	1.37	1.35	-0.02	-1.30
	G16	1.18	1.16	-0.02	-1.63
	G17	1.65	1.64	-0.01	-0.76
	G18	1.99	1.97	-0.02	-1.00
AgPAKBA	G1	0.07	0.07	0.00	0.00
	G2	1.39	1.38	-0.01	-0.61
	G3	0.79	0.79	0.00	-0.20
	G4	1.53	1.52	0.00	-0.30
	G5	1.64	1.60	-0.04	-2.22
	G6	0.81	0.81	0.00	-0.21
	G7	0.99	0.98	0.00	-0.26
	G8	1.71	1.71	0.00	-0.12
	G9	1.54	1.54	0.00	-0.10
	G10	1.61	1.60	-0.01	-0.52
	G11	1.77	1.77	0.00	0.00
	G12	3.09	2.70	-0.40	-12.80
	G13	1.90	1.89	-0.01	-0.48
	G14	1.64	1.63	0.00	-0.05
	G15	1.37	1.36	-0.01	-0.71
	G16	1.18	1.17	-0.01	-0.57
	G17	1.65	1.65	0.00	-0.03

Scenario	River pt	Baseline FRR (%)	Scenario FRR (%)	Absolute change in FRR (%)	Percentage change in FRR (%)
	G18	1.99	1.99	0.00	-0.14
SlopePAKBA	G1	0.07	0.07	0.00	0.00
	G2	1.39	1.39	-0.01	-0.46
	G3	0.79	0.79	0.00	-0.02
	G4	1.53	1.52	0.00	-0.21
	G5	1.64	1.61	-0.03	-1.80
	G6	0.81	0.81	0.00	-0.02
	G7	0.99	0.99	0.00	-0.02
	G8	1.71	1.71	0.00	-0.09
	G9	1.54	1.54	0.00	-0.08
	G10	1.61	1.61	-0.01	-0.40
	G11	1.77	1.77	0.00	0.00
	G12	3.09	2.88	-0.21	-6.95
	G13	1.90	1.89	0.00	-0.17
	G14	1.64	1.64	0.00	0.00
	G15	1.37	1.37	0.00	-0.01
	G16	1.18	1.18	0.00	-0.01
	G17	1.65	1.65	0.00	0.00
	G18	1.99	1.99	0.00	0.00

5.4.3 Flood Risk Trajectories

Flood risk trajectories are shown in Figure 5.12 for the Bogotá basin and Figure 5.13 for the Guayaquil basin for each of the ZOI scenarios. High-risk is defined as a FRR > 1 and Low risk is a FRR is <=1 (as explained in Chapter 3).

In the Bogotá basin, spatially the ‘high-risk decreases' class is fairly evenly distributed across the basin for the PAKBA scenario (Fig. 5.12). Most of the ‘high-risk becomes low-risk’ class appears to be isolated cells except for a line that follows the Bogotá River at the bottom of the basin. In the SlopePAKBA scenario, the ‘high-risk decreases’ class is more scattered and tracks the river networks more clearly (Fig. 5.12).

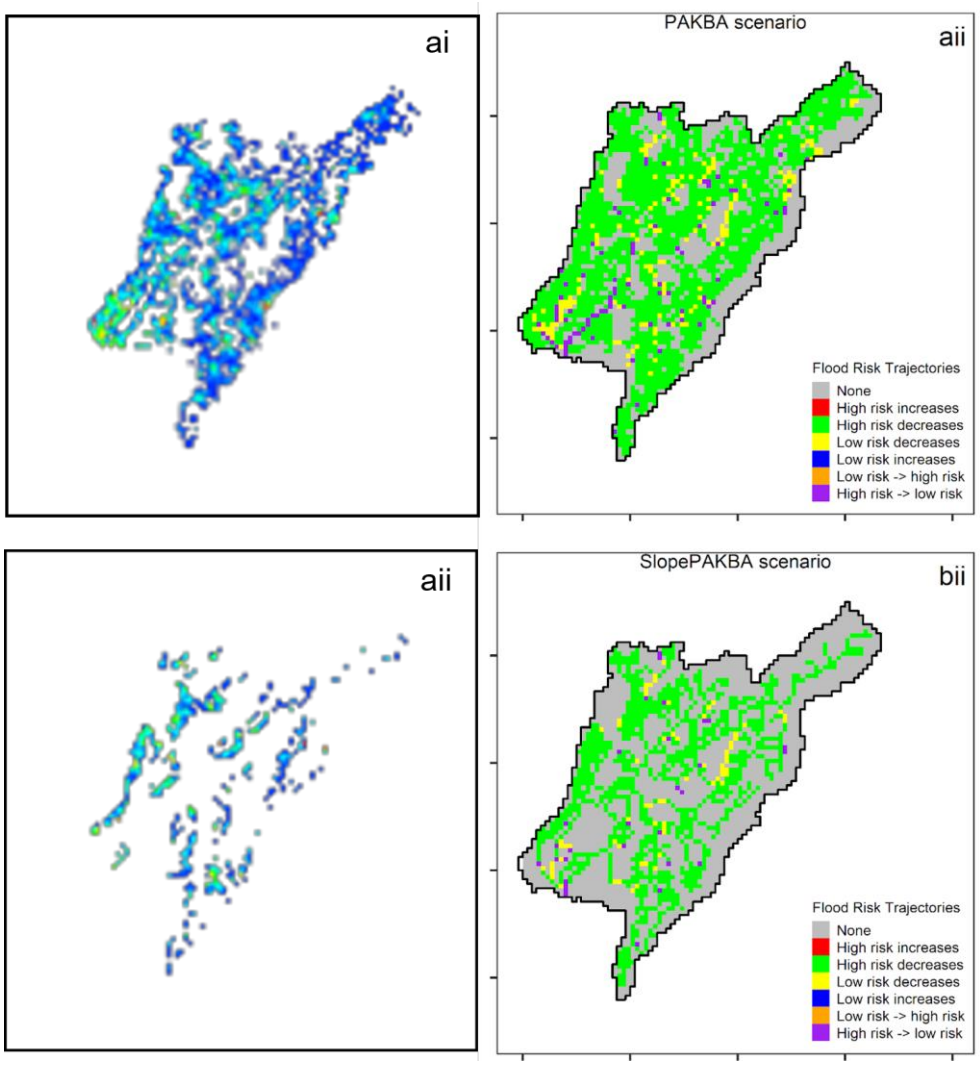


Figure 5.12 A comparison of the change in tree covered ground (left) and the resultant change in Flood Risk Trajectory (right) for each of the two forestation scenarios (a - PAKBA scenario; b - SlopePAKBA) in the Bogotá basin.

I calculated the percentage of the total basin that each class represents and a ratio of the percent of cells in the FRR category per unit forest cover change, measured as percent tree cover change (Table 5.6). The flood risk trajectories for the PAKBA and SlopePAKBA scenarios in the Bogotá basin, show that the most prevalent risk-class is: 'high-risk decreases', followed by' low-risk decreasing' and last, 'high-risk becoming low-risk' compared to the baseline condition. This means that the forestation scenarios succeed in being flood risk mitigation for between 58% and 1% of the Bogotá basin, depending on the spatial targeting (scenario) used, and the associated level of tree cover implemented.

The ratios of the hydrological response of the basin per unit forest cover change give an indication of the sensitivity response to the spatial targeting of the change, rather than the

differences that result from the different scenarios having different magnitudes of forest cover change (Table 5.6). In the PAKBA scenario, 1 km^2 of tree cover increase results in 18 km^2 of high- risk decrease class. While for the SlopePAKBA scenario, that figure nearly doubles; 1 km^2 of tree cover increase results in 35 km^2 of high-risk decrease class. The ratios are closer in size for the 'low-risk decreases' and 'high-risk becomes low-risk' classes. Overall, we can see that the SlopePAKBA scenario is more effective than the PAKBA scenario in terms of 'cost to benefit' and sensitivity, in terms of flood risk, to increase in tree cover.

*Table 5.6 A comparison of the number of pixels of the different risk trajectory classes for each scenario, their percentage of the total basin for the Bogotá basin (calculated by the number of trajectory class cells /2,923*100), and the ratio of percent of basin to percent tree cover change (+3.24 for PAKBA and +0.94 for SlopePAKBA).*

	PAKBA			**SlopePAKBA**		
	number of cells	**percentage of basin**	**ratio of percent of basin: tree cover change**	**number of cells**	**percentage of basin**	**ratio of percent of basin: tree cover change**
high-risk decreases	1,708	58.4%	18.02	971	33.2%	35.32
low-risk decreases	163	5.6%	1.73	69	2.36%	2.51
high-risk -> low-risk	88	3.0%	0.96	30	1.0%	1.06

In the Guayaquil basin, the flood risk trajectories for the PAKBA, AgPAKBA and SlopePAKBA scenarios show that high-risk will decrease, followed by low-risk decreasing and last, in the PAKBA scenario only, high-risk becoming low-risk compared to the baseline condition (Fig. 5.13). Spatially, we can see that in the PAKBA scenario, the 'high-risk decreases' class mostly occupies the middle and western part of the basin and tracks the river networks in the eastern edge (Fig. 5.13). There are also some clusters of 'low-risk decreases' class in the western lower edge of the basin, with a few scatterings of the 'high-risk becomes low-risk' class. For both the AgPAKBA and SlopePAKBA scenario, the 'high-risk decreases' class becomes more diffuse and almost entirely tracks river networks, particularly in the eastern part of the basin (Fig. 5.13).

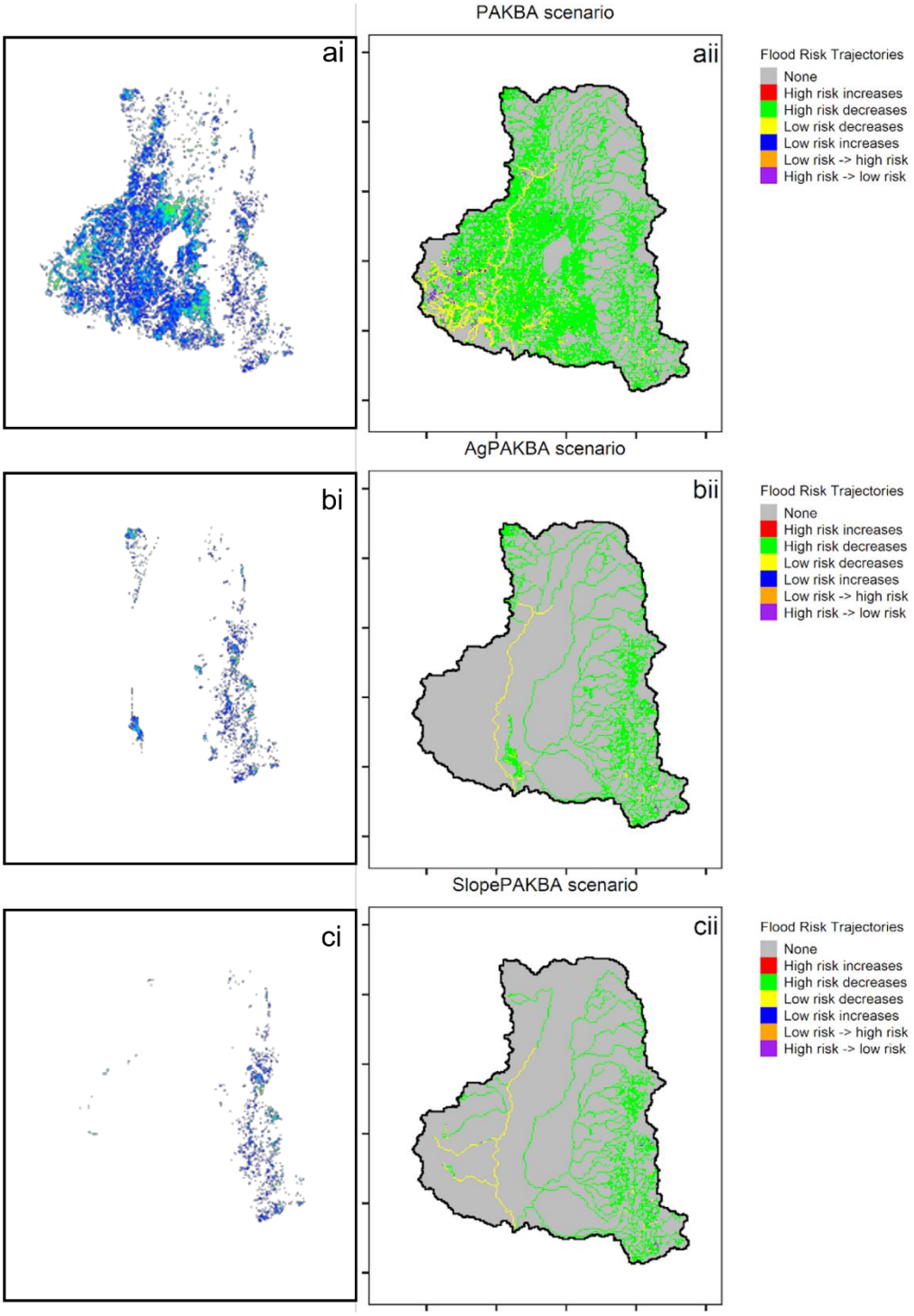


Figure 5.13 A comparison of the change in tree covered ground (left) and the resultant change in Flood Risk Trajectory (right) for each of the three forestation scenarios (a - PKBA; b - AgPAKBA; c- SlopePAKBA) in the Guayaquil basin.

I calculated the percentage of the total basin that each risk class represents in the Guayaquil basin (Table 5.7). The most prevalent flood risk trajectories for the PAKBA, AgPAKBA and SlopePAKBA scenarios are: 'high-risk decreases', followed by' low-risk decreasing' and last, 'high-risk becoming low-risk' compared to the baseline condition (Table. 5.7). This means that the forestation scenarios in the Guayaquil basin succeed in being flood risk mitigation for between 43% and 0.1% of the basin, depending on the spatial targeting scenario used, and the associated level of tree cover implemented. The ratios of the hydrological response of the basin per unit forest cover change show that the SlopePAKBA scenario is the most successful in terms of 'cost-benefit'; 1 km^2 of tree cover increase results in 50 km^2 of high-risk-decrease class. For the AgPAKBA scenario, 1 km^2 of tree cover increase results in 40 km^2 of high-risk-decrease class, and for the PAKBA scenario, 1 km^2 of tree cover increase results in 15.47 km^2 of high-risk-decrease class (Table 5.7). The ratios are closer in size to each other for the 'low-risk decreases' and 'high-risk becomes low-risk' classes but still with the SlopePAKBA showing the most sensitivity, in terms of flood risk, to tree cover change.

*Table 5.7 A comparison of the number of pixels of the different risk trajectory classes for each scenario, and their percentage of the total basin for the Guayaquil basin (calculated by the number of trajectory class cells /37,617*100), and the ratio of percent of basin to percent tree cover change (+2.78% for PAKBA, +0.35 for AgPAKBA and +0.22% for SlopePAKBA).*

	PAKBA			AgPAKBA			SlopePAKBA		
	No. of cells	percent age of basin	Ratio	No. of cells	percent age of basin	Ratio	No. of cells	percent age of basin	Ratio
high-risk decreases	16,173	43%	15.47	5,277	14%	40	4,140	11%	50
low-risk decreases	1,621	4.3%	1.55	299	0.79%	2.26	319	0.84%	3.82
high-risk -> low-risk	409	1.0%	0.36	45	0.11%	0.31	36	0.1%	0.45

5.4.4 Does the change in FRR from forestation scenarios offset the change in FRR for climate scenarios?

To investigate whether the decreases in FRR observed in the strategic forest restoration scenarios offsets the increases in FRR observed under the climate scenarios (Chapter 4), the basin means of the percent change difference in FRRs are compared (Table 5.8).

In the Bogotá basin, the PAKBA forestation scenarios exceed the increase in FRR observed under the combined climate scenarios (Table 5.8). However, the SlopePAKBA scenario does not meet the increase for even the least extreme climate scenario. In the Guayaquil basin, none of the forestation scenarios meet the least extreme of the climate scenario increases. However, the PAKBA scenario comes closest to the climate scenario with the smallest percent increase in FRR (RCP 60 2050s) with a deficit of -2.20 percentage points.

Table 5.8 The range of change at the river sampling points (mean, min and max across RCPs) and the basin mean percent change difference (pcd) in flood risk ratio for the climate scenarios compared with the basin means (grey shade) for each forestation scenario for the Bogotá and Guayaquil basins.

	Scenario				
	Climate scenario change at points from least (min) to most (max) (pcd %)	**Climate scenario basin mean (pcd %)**	**PAKBA basin mean (pcd %)**	**AgPAKBA basin mean (pcd %)**	**SlopePAKBA basin mean (pcd %)**
Bogotá	Mean +8.49 Min +4.78 Max +12.56	+5.5 to +12.5	-15.97	–	-3.33
Guayaquil	Mean +13.47 Min +9.48 Max +23.05	+9 to +27	-7.28	-1.99	-0.99

Forestation on the scale prescribed by these scenarios may not be realistic from both a land use, land ownership or financial perspective. However, it may still be possible to locate any forestation interventions physically in specific locations that are forecast to increase in flood risk under climate scenarios. To determine this, I overlaid maps of where 1) the mean FRR for all climate scenarios is high-risk, i.e., flood risk is high in the future (and possibly now), and 2) the FRR increased more than 10% from baseline under climate scenarios, i.e., climate induced increase in risk (Fig. 5.14 for the Bogotá basin and Fig. 5.15 for the Guayaquil basin). The areas of overlap (blue in the resultant maps) are where the FRR decreases under forestation scenarios (mitigation) coincide with where the FRR increases

under climate scenarios (hazard risk). Forestation in these 'overlap' areas can thus be thought of as a Nature-based Solution or Nature-based Adaptation to climate change as it mitigates a climate-induced risk. Green areas in the maps (Fig. 5.14 and 5.15), show decreasing flood risk in an area where climate change induced risk is not already high or increasing. This mitigation is expected to continue to be effective under climate change and as these values were generated with cumulated metrics, the forestation in these areas can still have an effect in reducing risk downstream. Although co-location of mitigation and climate risk is important, there is also benefit provided downstream in terms of flood risk reduction. Pink areas in the maps (Fig. 5.14 and 5.15) are either where the FRR is high-risk under climate scenarios or where FRR increases more than 10% compared to baseline under climate scenarios. Blue areas in the maps below are the areas of overlap, i.e., where green and pink are co-located.

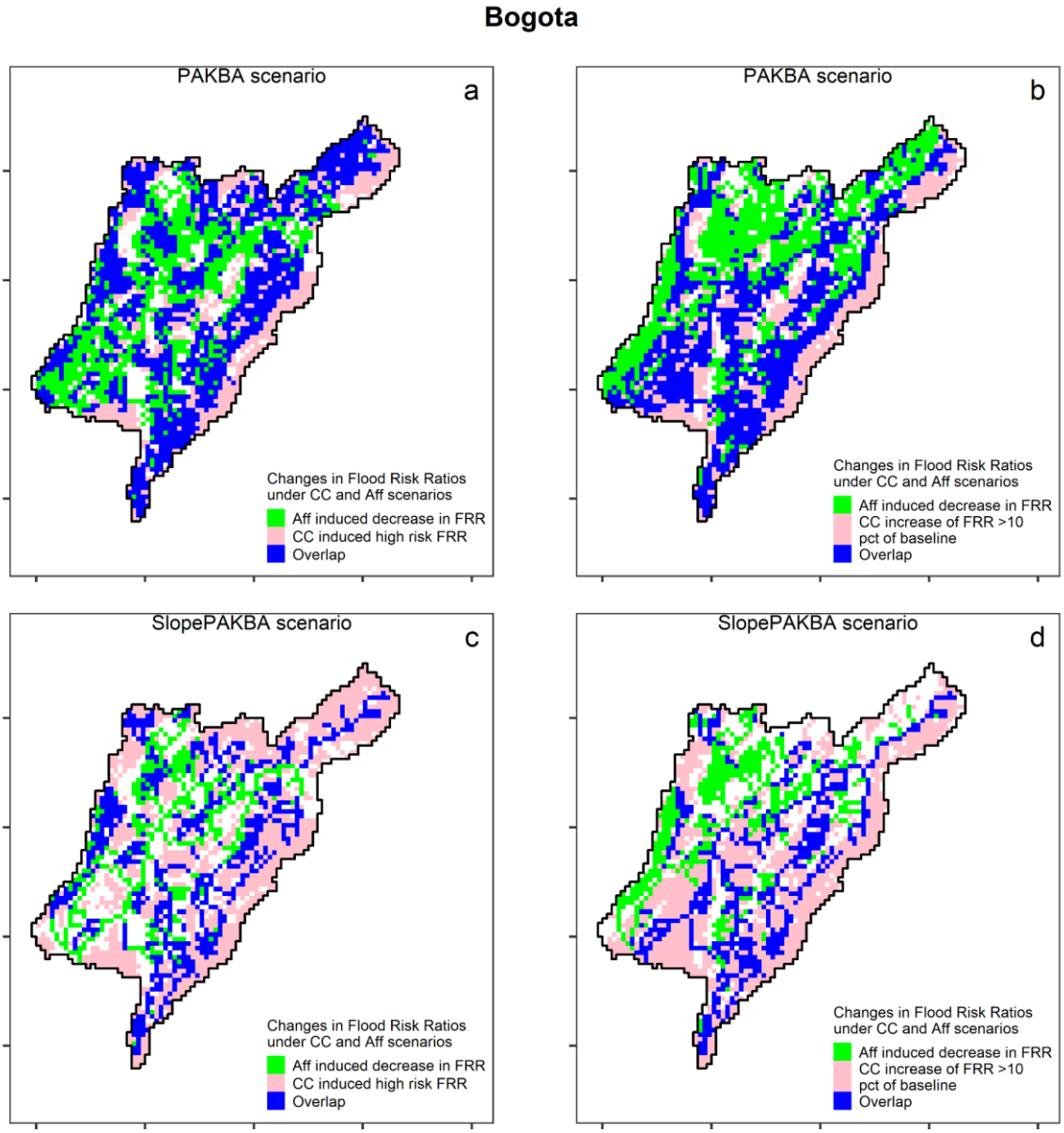


Figure 5.14 Comparison of changes in Flood Risk Ratios for forestation and climate change scenarios in the Bogotá basin. a-b) PAKBA scenario, and c-d) SlopePAKBA scenario. Left panel: The mean of the climate change scenarios where FRR is high-risk (>1). Right panel: Climate change scenarios where increases were > 10 percent of baseline FRR value. The areas of overlap (blue in the maps) are where the FRR decreases under forestation scenarios (mitigation) coincide with where the FRR increases under climate scenarios (hazard risk).

In the maps of the Bogotá basin, there are more areas of overlap for the PAKBA scenario than for the SlopePAKBA scenario (Fig. 5.14). Also, for both forestation scenarios, there is more 'overlap' in the areas where the climate scenarios are 'high-risk' compared to 'increases >10% of baseline FRR' (Fig. 5.14). When extracting the number of cells for the overlap category for each map (Table 5.9): 42.2% of cells overlap in the PAKBA/CC high-risk map and nearly half that, 20.36% for the SlopePAKBA/CC increase scenario.

*Table 5.9 Comparing the number of cells that 'overlap' for the different scenarios as a percentage of the total basin area (number of cells/2923*100), for the Bogotá basin.*

	Number of 'Overlap' or NbS cells			
	CC FRR high-risk		**CC FRR increase >10%**	
	Number of cells	**Percentage of basin**	**Number of cells**	**Percentage of basin**
PAKBA	1,234	42.21%	1,110	37.97%
SlopePAKBA	675	23.09%	595	20.36%

As each grid cell or pixel is ~1 km^2, a total area for the 'overlap' of NbS in each scenario can be calculated. Converting the cells to km^2 and multiplying by 100 converts the area to hectares, which is the unit used in each country's restoration targets.

PAKBA - high-risk: ~1,234 km^2 or 123,400 ha

PAKBA - CC increase: ~1,110 km^2 or 111,000 ha

SlopePAKBA - high-risk: ~675 km^2 or 67,500 ha

SlopePAKBA - CC increase: ~595 km^2 or 59,500 ha

In the Guayaquil basin, it is evident that the PAKBA scenario has more areas of overlap compared to both the AgPAKBA and SlopePAKBA scenarios for both the FRR increases and high-risk areas under climate scenarios (Fig. 5.15), based on the maps and the number of cells for the overlap category for each of these scenarios (Table 5.10). The AgPAKBA scenario has slightly more cells of overlap compared to the SlopePAKBA scenario (Table 5.10) with more overlap in the top north-west corner of the basin. In both these scenarios,

the areas of overlap appear to follow river networks. The areas of increased tree coverage for the AgPAKBA and Slope PAKBA is in the western highland areas. Forestation here cumulates mitigation benefits downstream, hence the highlighting of the river networks.

*Table 5.10 Comparing the number of cells that 'overlap' for the different scenarios as a percentage of the total basin area (number of cells/37,617*100), for the Bogotá basin.*

	Number of 'Overlap' or NbS cells			
	CC high-risk		**CC increase >10%**	
	Number of cells	**Percentage of basin**	**Number of cells**	**Percentage of basin**
PAKBA	17,418	46.3%	14,811	39.37 %
AgPAKBA	5,565	14.79%	3,381	8.99%
SlopePAKBA	4,455	11.84%	2,578	6.85%

As each grid cell or pixel is ~1 km^2 we can get a total area for the 'overlap' of NbS in each scenario. Converting the cells to km^2 and multiplying by 100 to get the area in hectares, which is the unit used in each country's restoration targets:

PAKBA - high-risk: 17,418 km^2 or 1,741,800 ha

PAKBA - CC increase: 14,811 km^2 0r 1,481,100 ha

AgPAKBA - high-risk: 5,565 km^2 or 556,500 ha

AgPAKBA - CC increase: 3,381 km^2 or 338,100 ha

SlopePAKBA - high-risk: 4,455 km^2 or 445,500 ha

SlopePAKBA - CC increase: 2,578 km^2 or 257,800 ha

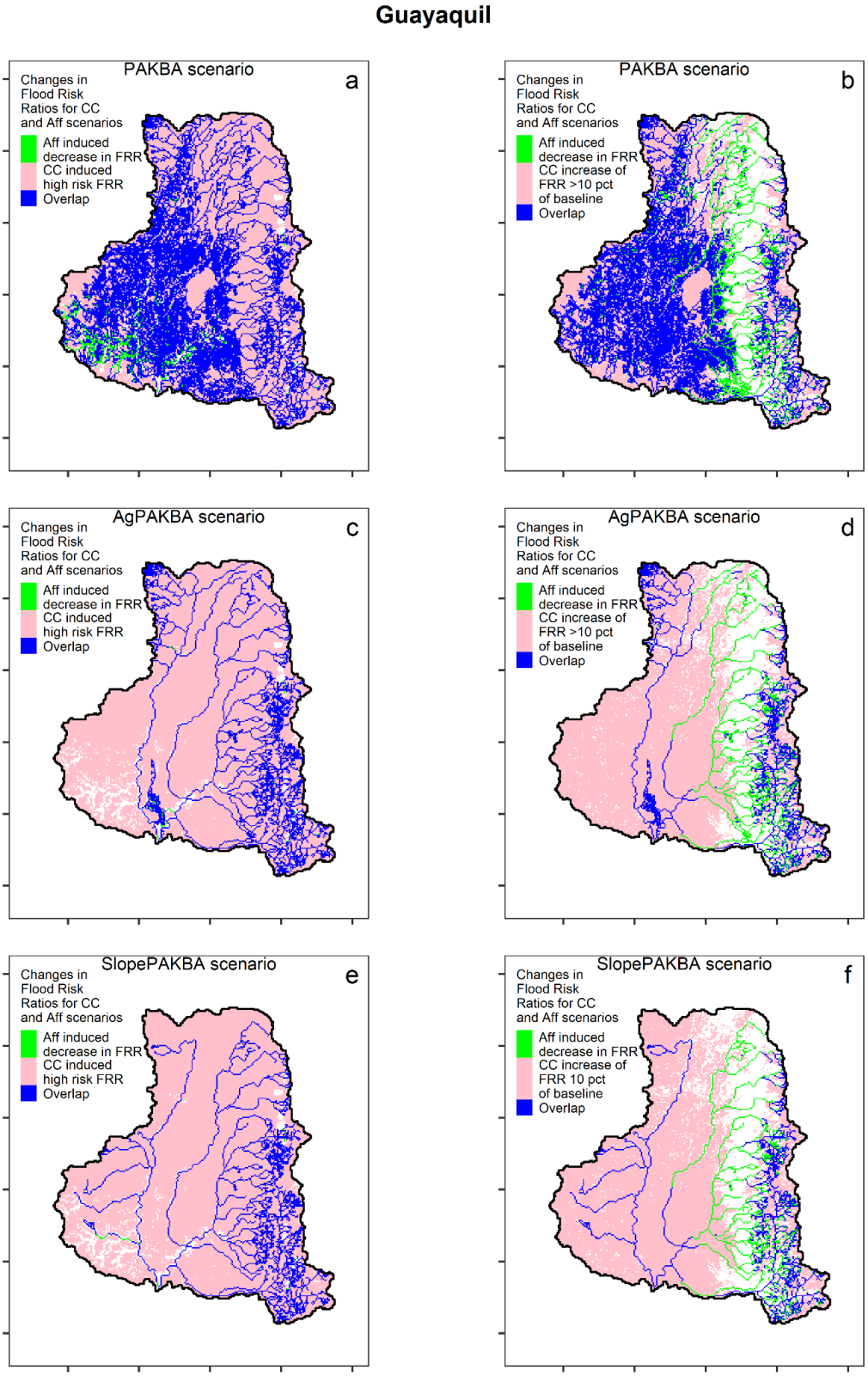


Figure 5.15 Comparison of changes in Flood Risk Ratios for forestation and Climate Change scenarios in the Guayaquil basin. a-b) PAKBA scenario, c-d) AgPAKBA, and e-f) SlopePAKBA scenario. Left: The mean of the climate change scenarios where FRR high-risk (>1), Right: Climate change scenarios where increases were >10 percent of baseline FRR value. The areas of overlap (blue in the maps) are where the FRR decreases under forestation scenarios (mitigation) coincide with where the FRR increases under climate scenarios (hazard risk).

5.4.5 Exploring the characteristics of areas of 'overlap' of forest induced FRR reduction and climate induced FRR increase

In the Bogotá basin, the 'overlap' areas overlaid onto a land cover and river map **(Fig. D19 in Appendix D)** shows these areas coincide with the river networks. In addition, the dominant land cover appears to be herbaceous vegetation. The maps of the DEM and river map masked by the 'overlap' areas show that the 'overlap' areas coincide with the river network and the relatively low elevation areas, as expected for river valleys **(Fig. D20 in Appendix D)**. There are a few small areas of high elevation overlap on the edges of the basin, particularly the upper north-west corner and lower south-east edge. The mean, minimum and maximum elevation values of the overlap areas in the Bogotá basin for each scenario are shown in Table 5.11. The mean elevations of all the scenario overlap areas are lower than the mean for the whole basin. The SlopePAKBA scenario with the CC-increase overlap has the lowest mean elevation at 2,747.51 m compared to the basin mean of 2,830.11 m.

Table 5.11 Mean, minimum and maximum elevation of the overlap areas compared to values for the entire Bogotá basin.

	Mean	Min	Max
Entire basin	**2830.11 m**	**2541 m**	**3733 m**
PAKBA - high-risk	2822.53 m	2544 m	3733 m
PAKBA - CC increase:	2751.48 m	2541 m	3681 m
SlopePAKBA - high-risk:	2806.24 m	2547 m	3674 m
SlopePAKBA - CC increase:	2747.51 m	2541 m	3674 m

In the Guayaquil basin, the overlap areas on land-cover, show different patterns based on the scenario **(Fig. D21 in Appendix D)**. For elevation in the Guayaquil basin (**Fig. D22 in Appendix D**), the overlap areas track the lower elevations in the PAKBA scenarios and the high elevations in the AgPAKBA and SlopePAKBA scenarios. This is reiterated in Table 5.12 which shows the mean, minimum and maximum elevation for the whole basin and then for each of the scenario/climate change overlap areas. The PAKBA scenarios overlap means are lower than the basin mean of 711 m but the AgPAKBA and Slope PAKBA scenario

overlap areas are higher than the basin mean (range 1418 to 1822 m). The max elevation for the overlap areas is above 4000 m for all the scenarios, which may be above the treeline.

Table 5.12 Mean, minimum and maximum elevation of the overlap areas compared to values for the entire Guayaquil basin.

	Mean	Min	Max
Entire basin	**711.18 m**	**-8 m**	**4753 m**
PAKBA - high-risk	502.36 m	-8 m	4540 m
PAKBA - CC increase	426.91 m	-8 m	4540 m
AgPAKBA - high-risk	1418.71 m	-8 m	4540 m
AgPAKBA - CC increase	1643.14 m	-8 m	4540 m
SlopePAKBA - high-risk	1532.98 m	-8 m	4279 m
SlopePAKBA - CC increase	1822.94 m	-8 m	4279 m

5.5 Discussion

The aims for this chapter were to i) evaluate the scale of additional Natural Infrastructure (NI) needed to reduce current levels of flood risk, ii) determine if a scenario for NI can reduce the enhanced flood risk that results from the higher precipitation projected under climate scenarios, i.e., future flood risk, iii) determine if NI flood mitigation is more effective in certain places than others facilitating spatial targeting, and iv) based on the findings, consider if there is an ideal and/or realistic forestation target to recommend to NbS investors in our two catchments. I discuss the results of the chapter for each of these aims below:

5.5.1 Influence of scale of forestation required for mitigating current and future levels of flood risk

Current flood risk

The baseline flood risk in each basin was calculated and described in Chapter 3 and is considered current risk. The results of the forestation scenarios were compared against the baseline to show by how much they increased or decreased.

General scenarios

In the general scenarios, without geographic restriction, other than being outside protected areas, the steepest reduction in flood risk ratios occurs in the lower forestation extents for both major hydrological basins, and weakens at the higher levels of forestation increase, at both the basin sum and river point scale. This non-linear decrease in response suggests that early allocation of forestation (in the model scenario) potentially occurs in the lowlands, given their larger extent compared to uplands. The greater forestation in lowlands leads to higher evapotranspiration losses there because more trees means more evapotranspiration, and average annual amounts of evapotranspiration decrease gradually with elevation (Bruijnzeel et al., 2011a; Gotsch et al., 2016; Oliveira et al., 2014). Therefore, more trees in the uplands have less of an impact on evapotranspiration. The later forestation in the uplands lessens the impact of flood risk reduction due to the characteristic mountain climate, i.e., high precipitation, low evapotranspiration (Bruijnzeel et al., 2011a; Hu et al., 2018; Reiners et al., 1984).

Forestation was more impactful (greater FRR reduction at the major basin scale) for the Colombia-Ecuador basin than for the Magdalena basin. The major basins are fairly similar in scale (~211,506 km^2 for the Colombia-Ecuador major basin and ~265,195 km^2 for the Magdalena basin). A potential reason for the difference in flood risk impact could be the same as mentioned above, i.e., it is due to the ratio of lowlands to uplands. In the two basins, the Colombia-Ecuador basin has more lowlands as it is coastal. As discussed above, altitudinal gradients determine trade-offs between change in evapotranspiration and change in fog inputs on forestation, impacting on water balance and runoff. There is a negative relationship between transpiration and altitude, which is attributed mostly to increased cloud cover (and thus reduced evaporative demand) at higher altitudes, reduced leaf area index (Bruijnzeel et al., 2011), and the lower mean air temperatures at higher elevations when(Jarvis & Mulligan, 2011)rests (Jarvis & Mulligan, 2011), resulting in lower transpiration rates (Oliveira et al., 2014). The significance of this is that the lowlands, in this study, have a much more important role in flood risk reduction compared to uplands. This is at odds with the common practice of foresting the upland parts of catchments (Murphy et al., 2021; Wahren et al., 2012). Upland areas tend to be steep and less permeable and thus intercept large quantities of rainfall, which is why targeting the planting of trees on such high runoff contributing areas is thought to reduce flood risk (Marapara et al., 2020). These high elevation areas are also less suitable for agriculture and so tend to be low-value land. In agreement with our results, Bathurst et al. (2022) propose that planting in the middle or

lowland part of the catchment can increase evapotranspiration and reduce baseflows at the annual scale (but will have relatively little impact at the event scale).

At both the basin and river point scale, this study's results show that no level of forestation, not even 100% forestation outside protected areas, would completely offset the current flood risk ratios, i.e., there would still be more annual rainfall than the capacity to store it in the landscape. This is an important finding because even though complete forestation of a catchment is implausible, this demonstrates that completely neutralising flood risk is unachievable in these basins using NI, and that the goal needs to be on flood risk reduction rather than prevention.

Comparing the results in this study to others is difficult since no studies use the same metric and different studies use different temporal and spatial scales. However, their results are within the same order of magnitude as those found in this study (looking at annual runoff over capacity). As a reminder, at an increase to 25% forest cover, this study found a ~10% and ~30% overall decrease in FRR for the Magdalena and Colombia-Ecuador major basins, respectively. At the river point scale, 25% forest coverage resulted in a ~28%% to ~33% reduction in FRR at the Bogotá basin river points, and a ~3% to ~38% FRR reduction at the Guayaquil basin river points. Looking at a similar increase in forest cover, other studies found: 20% forestation reduced peak discharge by 20% in Argentina (Diaz & Querner, 2005); in the UK, forestation extents of 20-40% resulted in 19% peak magnitude reduction (Dixon et al., 2016); and in Scotland, a 24% increase in tree cover resulted in a 19% Q5[55] flow reduction (Iacob et al., 2017). Looking at larger basins, comparable to our study basins, in Chile, Bathurst et al. (2022) found that forestation of more than 20% of the catchment area resulted in decreases in annual runoff, but that forestation of 50% had less certain impacts on flood peak discharge.

5.5.2 Spatial targeting scenarios

Change in hydrological variables

The flood risk ratios are a result of changes in hydrological variables used within *WaterWorld*. As such, the changes in these hydrological variables were examined to see how they are influenced by the land use change scenario. In *WaterWorld*, water balance is

[55] Q5 (the 95 percentile flow): The flow in cubic metres per second which was equalled or exceeded for 5% of the specified term - a high flow parameter which, when compared with the Q 95 flow provides a measure of the variability, or 'flashiness', of the flow regime.

the sum of precipitation plus fog plus snowfall minus evapotranspiration. Water balance will increase where the increase in fog inputs is greater than the increase in evapotranspiration output. Adding trees to the landscape should cause evapotranspiration output to go up. The impact on water balance will depend on whether the increase in evapotranspiration is more or less than the inputs from precipitation, fog and snowmelt. Runoff is the water balance cumulated downstream, so should increase if water balance increases and decrease if water balance decreases.

In the scenarios examined, rainfall remains constant[56], so any changes in water balance should primarily be due to the interplay between fog input and evapotranspiration loss. In the Bogotá basin, both evapotranspiration outputs and fog inputs increased under the two scenarios, resulting in an overall increase in water balance. The increase in fog is likely a result of the increase in tree cover, as high-altitude forests are especially able to intercept fog and cloud droplets (Bruijnzeel et al., 2011b; Ellison et al., 2017). In the Guayaquil basin, the same pattern was seen for the low-agricultural scenario (AgPAKBA) and slope scenario (SlopePAKBA). This was not the case in the protection scenario (PAKBA). Water balance decreased overall because the evapotranspiration output was greater than the fog input, largely due to the extensive tree coverage in the basin under this scenario, particularly in the lowland plains. The decline in water balance may be an issue for water security and availability, depending on the temporal distribution of the decline.

Change in flood risk ratios

In this study, geographically restricting the forestation to recently deforested low value land (via the Restoration scenario and use of ZOIs) resulted in much smaller percentages of the basins being afforested: ~4% for the Bogotá basin and ~3% in the Guayaquil basin, under the protection scenario (PAKBA). In the Bogotá basin, the increased tree cover by +3.24% (PAKBA scenario) reduced the flood risk ratios by just under 16% and increasing the tree cover by +0.94% (SlopePAKBA scenario) reduced the basin flood risk ratio by 3.37%. A difference of only 2.3% in tree cover results in an additional 12.6 percentage points in flood risk reduction for the Bogotá basin. These are more favourable results than those of Buechel et al. (2022) which showed modelled flow is reduced by 2.8% for a 10% increase in catchment broadleaf woodland in the UK. However, it is not a direct comparison as the variables are different and comparing temperate catchments to tropical catchments should

[56] Trees and forests contribute to the intensification of rainfall through the biological particles they release into the atmosphere, but this is not accounted for in the model.

be done with caution. The results obtained in the Guayaquil basin suggest that relatively small amounts of forestation (<3%) will help to mitigate current flood risk to some degree (≤6.7%). Comparing the results of both basins confirm what other studies have found, that the greatest impacts are seen for greater forest coverage (Burton et al., 2018; Cornish, 1993; Dixon et al., 2016; Iacob et al., 2017; Nisbet et al., 2011; Wahren et al., 2012).

Flood Risk Trajectories

One way to visualise the reduction in impacts is via Flood Risk Trajectory Maps. These maps show where the FRR changes from one class (high-risk or low-risk) to another, or increases or decreases compared to the baseline, due to changes from the scenario. In terms of flood risk, of most interest would be where high-risk areas become less high-risk (i.e., high-risk decreases). The results showed much larger areas where 'high-risk decreases' compared to the areas where 'high-risk becomes low-risk' in both basins and for all scenarios. However, up to this point, the way I have been scrutinising the scenarios is only capturing the difference in magnitude of forest cover change between them. To get an indication of the response to the spatial targeting of the change, I created a ratio of the change in FRR (hydrological response of the basin) per unit forest cover change (percentage increase in forest cover). In the Bogotá basin, the ratio for the slope+protection scenario (SlopePAKBA) was nearly double than that for the protection-only scenario in the 'high-risk decreasing' class, indicating that spatially targeting slopes and avoiding biodiversity areas is the more successful strategy. Similarly, in the Guayaquil basin, the per unit of investment in tree cover was greatest for the slope scenario in the 'high-risk decreasing' class.

This range of extents for different risk classes, and the differences in spatial distribution, may provide national and local authorities with a suite of options for targeting forestation, depending on the objective, budget and land use constraints. For instance, the smallest areas, i.e., the high-risk to low-risk class, could be solely targeted for forestation if authorities want to focus on utilising the least amount of land for some impact. However, foresting only these areas may not result in the maximum flood risk reduction than if the full area of the scenario was forested. Instead, focusing restoration efforts on the land targeted in the slope+protection scenarios will provide the biggest return in flood risk reduction per unit of tree cover, if the aim is to reduce flood risk where it is currently high.

Future flood risk

To determine impact on future risk, the reduction in flood risk from forestation currently was compared to the projected increases in flood risk from climate scenarios. In the Bogotá

basin, at the basin scale, the reduction in flood risk for the protected area scenario (PAKBA) more than offsets the increase in FRR under all the climate scenarios, i.e., it succeeds in being a nature-based solution for flood risk. However, that is not the case for the slope and protected area (SlopePAKBA) scenario; it does not meet or exceed (mitigate) the increase in climate induced flood risk increase. In the Guayaquil basin, none of the forestation scenarios mitigate the increase in flood risk under any of the climate scenarios at the basin scale. The protected area scenario (PAKBA) comes closest. This tells us that in the Guayaquil basin, the increase in tree cover would need to be greater than the 2.78% generated by the protected area scenario to have a chance of meeting the predicted increases in flood risk from even the most favourable (i.e., lowest flood risk impact) emissions scenario (RCP).

In summary, if we want to mitigate the flood risk from climate change, we need to reforest at least 3% of the area recently deforested in the Bogotá basin. In the Guayaquil basin, a similar increase in tree cover in areas of recent deforestation would not suffice.

5.5.3 Influence of spatial targeting of forestation on mitigating current and future levels of flood risk

Current flood risk

Many planting schemes are in upland areas (Wahren et al., 2012) as this is: i) less desirable land for agriculture, ii) has more rainfall, and iii) steeper slopes leading to greater runoff. However, some studies have found that planting in lowland areas (Bathurst et al., 2022; Iacob et al., 2017) or in the riparian or floodplain area (Broadmeadow & Nisbet, 2004; Burton et al., 2018; Dixon et al., 2016) has the biggest impact in mitigating flood risk. In the scenarios examined here, a useful way to visualise the impact on current flood risk is via the Flood Risk Trajectory maps. For both basins, these showed diffuse distribution of the ‘high-risk decreases’ class for the protection scenario for both basins but tracking of river networks for the other scenarios. The ‘high-risk to low-risk’ class tended to be scattered isolated pixels. If these cells were not scattered, but instead clumped, then they would be easier to protect. But since they are scattered and isolated, they will be difficult to protect and a challenge to manage.

Future flood risk

A key aim of this work was to determine areas for locating Nature-based Solutions (NbS) where forestation-induced decreases in flood risk overlap with, and thus offset, climate-induced increases in flood risk. Examining the geographic characteristics of these overlap/NbS areas in the Bogotá basin revealed that they coincide with the river networks and the relatively low elevation areas. In the Guayaquil basin, the overlap areas track the

lower elevations in the PAKBA scenarios and the higher eastern mountain elevations in the low agriculture (AgPAKBA) and slope (SlopePAKBA) scenarios. There is also defined tracking of the river networks, particularly in the eastern part of the basin.

The coincidence of the low agriculture and slope scenarios with high elevation areas could be problematic if it suggests planting trees above the suitable conditions for tree growth. This area of the Guayaquil basin lies within the North-western Andean Montane Forests ecoregion. This ecoregion can be divided into at least three different zones: pre-montane, montane, and upper-montane forests. Pre-montane and montane vegetation types combine, and are referred to as sub-Andean forest, which occurs from elevations of about 1,000–2,800 m. Upper montane or cloud forest ranges are from 2,800-4,000 m[57]. This forest type ends with the treeline where alpine tundra grasslands, known as páramo, begin. The páramo itself is a tall tussock grass-dominated treeless tropical-alpine vegetation belt that extends from approximately 3,400 m to over 4,500 m altitude. The upper ranges of the overlap areas thus coincide with what would be classified as upper montane or cloud forest. The Restoration scenario option 2 (Restoration of tree cover in areas of recent net deforestation) in *WaterWorld*, that was used to create these scenarios, targets areas that have been recently deforested (Hansen et al. 2013), and avoids targeting areas where trees will not grow, or in predominantly natural areas. This should ensure that we are not advocating forestation above the treeline or on ecologically sensitive and important páramo.

These results suggest planting along lowlands and rivers in the Bogotá basin, and in mountains and alongside rivers in the Guayaquil basin. This is not new knowledge but is shown within the context of specific climate scenarios and case studies. Lowland and riparian areas have competing pressures from agriculture and other human land-uses such that policymakers and NbS investors will need strong justifications to 'put-aside' this land for other purposes.

5.5.4 Downstream impact on target cities and beneficiaries

How will these interventions change things for downstream beneficiaries? The change in flood risk ratio (FRR) at the river sample points is the best way to determine this. In the general, non-strategic, forest restoration scenarios (100%, 75%, 50%, 25%, 10%, 5% levels of forestation), the FRR reductions at the river sample points were modest to minimal in

[57] https://www.oneearth.org/ecoregions/northwest-andean-montane-forests/

absolute terms, as the starting values were low. In relative terms, 100% level of forestation reduces the FRR on average across all points by ~50% in the Bogotá basin and ~40% in the Guayaquil basin, which although impressive, is equivalent to roughly only half a percentage point of FRR.

Under the spatial targeting forest restoration scenarios for the Bogotá basin river points, there are three instances in the various scenarios of the FRR decreasing from high-risk to low-risk but the reduction is minimal. In the Guayaquil basin, under the strategic forest restoration scenarios, the differences at the river points are marginal, with many points not displaying any reduction in FRR. For both basins and all scenarios, even though there are reductions in FRR, it is likely that the effect would not be discernible to downstream beneficiaries.

5.5.5 Summary of recommendations for forestation locations

Table 5.13 summarises the main recommendations, discussed above, on where to reforest based on the scale or type of forestation undertaken.

Table 5.13 Summary of recommendation for where to reforest based on the forestation scale or type

	Study basin	
	Bogotá	**Guayaquil**
Forestation scale/type		
Large-scale, general	lowlands	lowlands
Small-scale, spatially-targeted	slopes	slopes
Small-scale; targeted for climate induced flood mitigation	lowlands and rivers	high elevations and rivers

5.5.6 Co-benefits of forestation interventions and recommendations to investors and policymakers

Investors, policymakers and NGOs are under pressure to implement NbS, such as tree planting or forest restoration, mainly for climate change mitigation in the form of carbon sequestration and carbon storage (Chapter 1). However, at large spatial scales, the cost (social and financial) of forestation may be prohibitive. To increase likelihood of adoption, planting schemes thus need to achieve multiple goals, focusing on adaptation as well as mitigation.

A way to help provide justification for 'putting-aside' this land for flood protection is to promote the 'added value' gained from doing so. For instance, in the overlap/NbS areas, what would be the 'additionality' of co-benefits if these areas are reforested/regenerated with native species and protected? For example, as contributions to both countries' 30x30 protected area goals. Currently, Colombia has pledged to restore 1 million hectares, and Ecuador, 500,000 hectares (Chapter 1).

The total basin area for the Bogotá basin is ~2508.49 km^2. Based on the 30x30 protected area goal, 30% of this basin is: 861.63 km^2. There are 31 listed Protected Areas (PAs) in the basin and all but eight are nationally designated and IUCN category VI (protected area with sustainable use of natural resources; UNEP-WCMC and IUCN 2019). The total PAs within the basin account for 1678.42 km^2 or 66.9% of the basin area (calculated from GIS). This is a large percentage, relative to the basin area. The total country average of terrestrial PAs is 16.91%. Forestation in the PAKBA overlap areas would add ~1,110 to ~1,234 km^2 (44.2% to 49.19% of total basin area) to the protected area coverage (although there is some overlap with existing protected areas). Forestation in the SlopePAKBA overlap areas would add ~595 to 675 km^2 (23.7% to 26.9% of the basin area) to the PAs coverage (although there is some overlap with existing protected areas). These are considerable portions of the land area, especially for a peri-urban basin struggling with increased urbanisation and development from agriculture and industry.

Compared to the Bogotá basin, the Guayaquil basin is very large with very little urbanisation; most of the built-up areas are small (Fig. 5.2b). From GIS, I have calculated that the total basin area is ~32,360.61 km^2. Based on the 30x30 restoration goal, 30% of this basin is: 9,708.18 km^2. There are eight listed Protected Areas (PAs) in the basin, and all are nationally designated, but none are reporting an IUCN category (UNEP-WCMC and IUCN, 2019). I have calculated that currently, the total PAs within the basin account for 6,942.77 km^2 or 21.45% of the basin area. An additional 2,765.4 km^2 is needed for 30% of the basin to be protected. The country average for Ecuador is 23.22% of terrestrial land is protected[58]. This work has shown that reforestation in the SlopePAKBA-CC increase overlap area, which has the smallest coverage of the overlap areas at 2,578 km^2 (7.97% of total basin area), would come close to meeting this target.

[58] https://www.protectedplanet.net/country/ECU

Another 'co-benefits' strategy is to use these 'overlap' areas as corridors that provide connectivity between the PAs and the KBAs. Landscape connectivity is defined as "the degree to which the landscape facilitates or impedes movement among resource patches" (Taylor et al., 1993) and is an important part of biodiversity conservation. Indeed, the scientific evidence overwhelmingly shows that interconnected PAs are much more effective than disconnected areas in human-dominated systems, and that this is especially essential in a time of climate change (Hilty et al., 2020). The use of 'ecological corridors'[59] to connect the PAs and KBAs in these basins would create an Ecological Network[60] and contribute to a functionally connected Protected Area Network. Often, researchers use specialist software to help determine the best routes for connecting habitats/resource areas for conservation. Instead, I have used the NbS areas for flood protection to show options for how to connect areas, as shown in Figure 5.16 or Bogotá and Figure 5.17 for Guayaquil. These maps show the PAs and KBAs in relation to the overlap/NbS areas and provide a visual indication of how the overlap areas could potentially link the PAs and KBAs together, thus providing or enhancing connectivity. These delineated areas would provide multi-functional benefits for flood protection and biodiversity conservation, as well as other regulating and cultural ecosystem services.

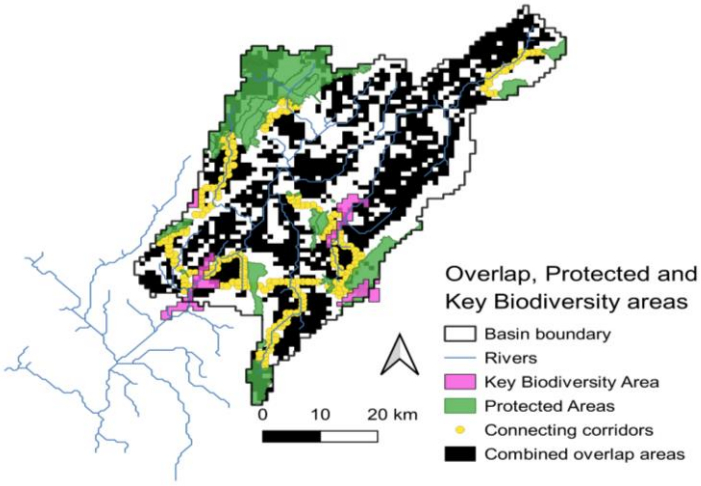


Figure 5.16 Location of Protected Areas, Key Biodiversity Areas and combined 'overlap' areas with potential routes linking them (yellow dots) in the Bogotá basin.

[59] Ecological corridors are defined as "a clearly defined geographical space that is governed and managed over the long term to maintain or restore effective ecological connectivity" (Hilty et al. 2020).
[60] Ecological Networks are "a system of core habitats (protected areas, OECMs and other intact natural areas), connected by ecological corridors, which is established, restored as needed and maintained to conserve biological diversity in systems that have been fragmented" (Hilty et al. 2020).

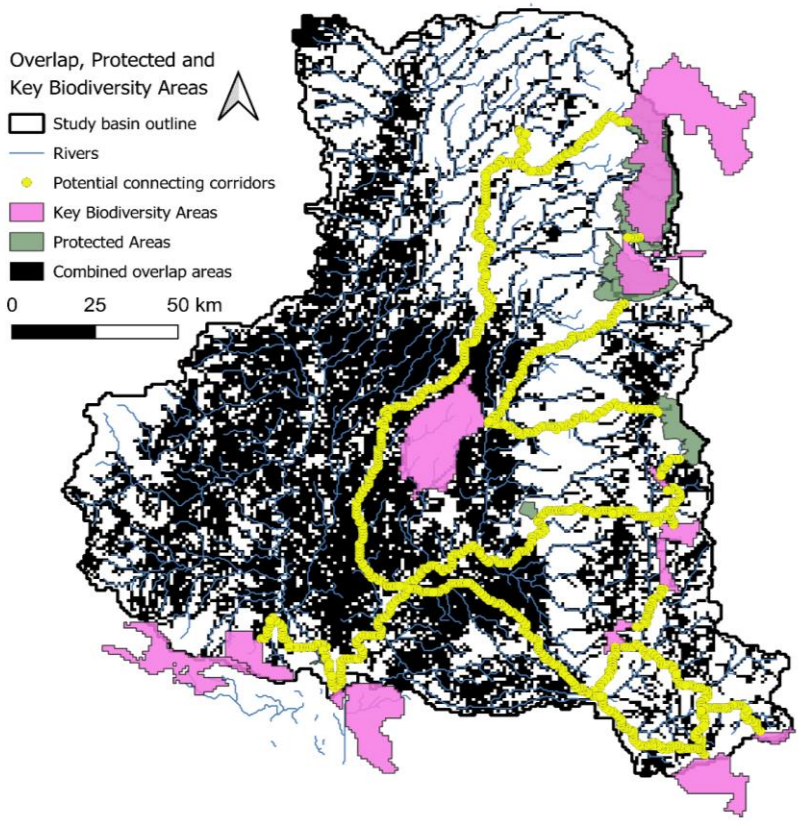


Figure 5.17 Location of Protected Areas, Key Biodiversity Areas and combined 'overlap' areas with potential routes linking them (yellow dots) in the Guayaquil basin.

5.5.7 Assumptions and limitations

The questions that could be explored for this topic, and the results presented here, were limited by constraints of time and the resources available, capacity for field data collection and the capabilities of the model used. Factors that are known to have an influence on hydrology and water use by trees, but which are not accounted for in the *WaterWorld* model V2 are:

- Type of forest/tree type (deciduous, non-deciduous, native, non-native, managed, not managed);
- Growth rates - different tree species in different climates will grow at different rates and thus impact the timing of final water use, limiting our ability to understand how long it might take for the flood mitigation benefits to accrue. *WaterWorld* does have forest restoration scenarios that incorporate growth rates but since our interest is in final benefits, these were not used here;

- Infiltration - Version 2 of the *WaterWorld* model does not account for infiltration so our analysis is constrained to annual flood risk on the basis of cumulated water balance (runoff) over natural flood storage. Version 3 of *WaterWorld* does but is too complex and thus slow-running for the multitude of analyses presented here;
- *WaterWorld* is a monthly model rather than an event-based model so the focus is annual average flood risk rather than modelling flood events. Event based models are available (e.g. Eco:Actuary[61] which is in the same modelling framework as *WaterWorld*), but these are computationally expensive and highly focused. The focus is thus not on extreme flooding events but on annual average flood risk;
- I do not use the monthly output of *WaterWorld* because of the 12x greater computational overhead of post processing the monthly data.

Other limitations and considerations are:

- Accuracy of global datasets - *WaterWorld* uses global datasets which may not be fully accurate for our specific regions; working with local data may have been able to improve aspects of the analysis but these data are often inaccessible and too inconsistent for a study that focuses on inter-basin comparisons.
- Limitation of the user-defined forestation scenarios - these were determined theoretically and not through stakeholder dialogue or a specific investment amount/project; Land tenure/ownership was not accounted for; and the scenario set-up has a maximum of four rules to define environmental constraints (e.g., slope, protected areas etc.).

5.5.8 Lessons and future work

It is important to ask, “How much flood risk reduction is enough?” One of the limitations of this study is that it is difficult to know what a ‘good’ target of flood risk reduction should be: is -1% good enough or does it need to be over -20% to make a difference to people and assets at risk? National and local agencies need to balance the potential costs (capital and maintenance) involved in reforesting these areas (assuming this is active forestation rather than natural regeneration) with the potential benefits for flood mitigation. In the case of the Bogotá basin, a 16% reduction in flood risk for a 3% increase in tree cover (in areas of recent deforestation) may seem worthwhile but reforesting 3% of a small basin may be unrealistic due to competing land-uses. In the Guayaquil basin, a similar increase in tree

[61] http://www.policysupport.org/ecoactuary

cover led to a 6.7% reduction in flood risk. This is a much larger and less urbanised basin, which means that there are more opportunities for utilising land for forestation. This amount of FRR reduction, although smaller than that for the Bogotá basin, may still be important considering the local context and assets at risk. Future work should attempt to understand what different levels of reduction mean in real 'on-the-ground' terms. However, doing this will require combining model results with detailed and intensive monitoring data which is often implausible at the scales considered here.

Focusing on foresting land that has recently been deforested suits aspirations for sensitive restoration but in our basins achieves a very small change in tree canopy, and thus very small reductions in flood risk (as measured by the storage to total capacity ratio). This is especially true when combined with other geographical restrictions to enable targeting of low-value land. Thus, spatial targeting of forestation needs to consider recently deforested land *plus* other land types to achieve a greater percentage of total tree cover and thus flood risk reduction. Future work should explore scenarios that result in much greater levels of tree cover change whilst still prioritising low-value land and protecting areas that are important for biodiversity.

A counterpoint is that, although it may be useful from a strategic perspective to identify large areas to afforest/reforest, this is often not practical or even feasible to implement. Large projects tend to have diminishing returns. Rather, it may be more efficient to do mitigation piecemeal, to focus on avoiding continued deforestation (i.e., no net loss) or to focus interventions on improving agricultural land management, since agriculture covers most of the landscape in these basins. We also need to be mindful of the risks of forestation: higher evapotranspiration through forestation will reduce total water on land and thus, may increase hydrological drought risk in the dry season by causing lower dry season flows.

Organisations, such as conservation NGOs, that are heavily investing in tree planting, and other NbS initiatives, may be more interested in the carbon and biodiversity co-benefits of forests rather than flood risk reduction specifically. These groups tend to identify areas for restoration based on these co-benefits, or more likely, on an opportunistic basis, related to land ownership. A natural next step for the work presented here is to explore the NbS/overlap areas with organisations working in these areas to see if and where these areas coincide with their priority areas and existing engaged stakeholders.

5.6 Summary & Conclusions

This study has employed two types of forestation scenarios to evaluate their effectiveness for reducing flood risk in two basins: Bogotá and Guayaquil. The first approach used general forestation scenarios to explore the effect of different extents of forest coverage, outside of protected areas. The second approach used a spatially restricted 'Restoration' scenario to target areas of recent deforestation and avoid urban, water and other natural land, and incorporated a mask (ZOI) to target low-value land. Of particular interest was the influence of forestation extent and geography on current and future flood risk.

Below, I address the aims set at the beginning of the study, based on the findings:

- *Evaluate the amount (scale or extent) of additional NI needed to reduce current levels of flood risk*: even very small amounts of tree cover, in terms of percentage of basin covered, will reduce flood risk to some degree. For instance, in the Bogotá basin, a difference of only 2.3% in tree cover resulted in an additional 12.6 percentage points in flood risk reduction. But even 100% tree coverage will not completely neutralise flood risk. This means that completely neutralising flood risk is unachievable in these basins using forests as NI, and that the goal needs to be on flood risk reduction rather than prevention.
- *Determine if NI flood mitigation is more effective in certain places than others:* for large-scale forestation, lowlands should be prioritised over uplands for forestation as NI flood mitigation. However, in the spatial targeting scenarios, which resulted in much smaller percentages of tree cover increase, there was greater flood risk reduction in the scenarios which had the higher magnitudes of tree canopy increase, i.e., the protection scenarios, but when the hydrological response per unit of tree cover change was considered for the 'high-risk decreasing' class, then the slope+protection scenarios had greater cost to benefit efficiency. This suggests that targeting slopes should be the preferred strategy for small-scale forestation NbS programmes.
- *Determine if a scenario for NI driven flood mitigation can reduce the enhanced flood risk that results from the higher precipitation projected under climate scenarios, i.e., future flood risk.* In terms of scale, the protection scenario in the Bogotá basin, at nearly 4% forest increase, was able to mitigate the climate-induced flood risk when measured at a basin scale. There were extensive areas where flood-risk-decrease from forestation overlapped with flood-risk-increase from climate scenarios. These

were in the lowlands and rivers in the Bogotá basin, and in the high elevations and alongside rivers in the Guayaquil basin.

- *Based on the findings, consider if there is an ideal and/or realistic forestation target to recommend to NbS investors?* The study has shown that even very small amounts of increased forest cover will contribute to flood risk reduction, however, the change may be so slight that they may not be discernible on-the-ground. Overall, focusing forestation only on areas of recent net deforestation is not adequate for meaningful flood risk reduction.

Interesting and/or novel approaches and outcomes from this study include:

- A useful and possibly unique approach is the use of Flood Risk Trajectory maps; in particular, using these to show the potential paths to connect areas where flood risk is high in the baseline and is decreased by forestation with conservation land such as Protected Areas and KBAs.
- A new approach employed in this study was the combination of flood risk mitigation with future flood risk projections to visualise overlap areas that are opportunity areas for NbS development. These topics, current and future flood risk, are typically looked at separately.

This work confirms what other researchers have suggested: forestation as the sole NbS intervention cannot neutralise current or future flood risk. Rather, national and sub-national entities need to implement a suite of NbS interventions or green-grey hybrid solutions, which combine both natural and built infrastructure, in order to protect downstream assets.

An important overall conclusion is that there is no generic ‘rule of thumb’ for determining the extent or placement of forestation as a mitigation intervention. Each basin has unique spatial properties (geography) and thus basin specific monitoring and modelling approaches are necessary to provide evidence-based recommendations for NbS strategy.

Chapter 6

Conclusions and Future Work

6.1 Introduction

Flooding is the most common and hazardous of all disaster events (CRED-UNDRR, 2020) and is projected to get much worse as continued land use (Tollan, 2002) and climate change takes hold (IPCC, 2021). Restoring nature to mitigate these impacts is increasingly advocated. This thesis takes an ecosystem services approach to evaluate the role that Natural Infrastructure (NI) such as canopies, soil, wetlands, water bodies and floodplains play in providing flood mitigation services to selected global cities, now, under climate change, and under land cover change, such as increased tree cover.

6.2 Summary of findings

The principal aim of the research presented in this thesis was to examine the potential of current Natural Infrastructure (NI) to mitigate flood risk now and under scenarios for climate change and NI restoration. This aim was explored in six catchments, spread across the globe, as study basins against three research objectives. These basins are upstream of the cities of Guayaquil in Ecuador, Bogotá in Colombia, London in the United Kingdom, Nairobi in Kenya, Chennai in India, and Jakarta in Indonesia. The basins are a mix of sizes and occupy both coastal and inland positions. It was not possible to use all six study basins for all the research objectives. The Nairobi basin was excluded from the first research objective due to its relatively small size, which caused issues given the reliance on global datasets for modelling. All six basins were included in the climate change analysis for Objective two. Based on the conclusions from this objective (Chapter 4), only Bogotá and Guayaquil were studied for Objective 3 (Chapter 5).

The results and conclusions of the three objectives (Chapters 3 to 5) are synthesised below. These three objectives were set in Chapter 1 to meet the research aim.

Objective 1: Quantify the role of rural ecosystems in providing flood risk mitigation (ecosystem) services to five global cities under current conditions.

Objective 1 is investigated in Chapter 3 which is in the form of a published journal article (Gunnell et al., 2019).

This research is one of the first to utilise the 'Natural Infrastructure flood risk metrics' available within the WaterWorld modelling platform. These metrics focus on the extent to which the annual runoff is less than or greater than the flood storage capacity, in recognition that if there is sufficient flood storage capacity to hold the annual runoff then, all else being equal, flooding will be less common.

First, the magnitudes and types of 'natural storages' in upstream basins was mapped by calculating the water storage capacity of canopy, soil, wetlands, floodplains and water bodies across five basins, using WaterWorld. The results showed that canopy cover accounts for the greatest storage capacity, followed by soil, floodplains, water bodies and wetlands. The strong influence of canopy storage for some basins is most likely due to its wide coverage across the landscape, and that this canopy store empties to the atmosphere after rainfall events so can be refilled without emptying downstream to the rivers.

These storage components were categorised as either green (canopy, soil and wetlands) or blue (floodplains and water bodies) storage capacity. The results showed that most city upstream basins have a strong reliance on green natural storage, which is driven primarily by canopy cover but also soil storage. This skew towards green storage means that major sources of landscape-level water storage are susceptible to modification or removal, leaving those cities vulnerable to an increase in flood risk. The exception was the Chennai city upstream basin, which has greater blue storage than green. This relatively large volume of blue storage in the system indicates a potential opportunity to increase flood storage by increasing the amount of green storage, particularly through soil conservation measures, but also through wetland creation and restoration.

Due to the vulnerability of green storage to modification, it is important to downstream users that upstream green storage is protected (i.e., falls within designated protected areas). The level of green storage that is protected was investigated and found to be only a third to zero of the green storage in the five upstream basins. London has the greatest amount of protected green storage at 33%. The next greatest green storage protection is in the upper Bogotá basin with 12.5% and then Jakarta at 9.68%. Of concern is the Chennai city upstream basin, which has none of its green storage in protected areas. The Guayaquil upstream basin, which has just over three times more green storage than blue storage, has only 0.85% of this green storage protected. Also, across the sites, the storage that is

protected tends to be remote and in high elevation areas resulting in significant distance between sites of service provision and of potential benefit. This agrees with the work of Joppa & Pfaff (2009) which found that the significant majority of national Protected Area (PA) networks are biased to higher elevations, steeper slopes and greater distances to roads and cities. The level of protection may also not be adequate, such as the green storage protection in "Areas of Outstanding Natural Beauty" of the London basin, to deter the kinds of land modification that could affect storage (for example, poor agricultural practice). Although, it is noted that there are other types of deterrents and protection that are more 'informal', outside of designated areas, such as restrictions on tree felling which require a licence from the government, for instance, from the Forestry Commission in the UK .

The spatial configuration of protection was examined to indicate what type of storage the protected storage comes from as it accumulates downstream. In Bogotá, Jakarta and Guayaquil, it is the protected storage that originates from canopy storage upstream that is greatest and dominates as the storage accumulates downstream. In the London upstream basin, it is soil storage, with canopy storage dominating further downstream. So even though the most important functional storage may be the floodplains, the protected storage is of canopy or soil storage. However, it is not just the green storage that needs protection. The analysis showed that barely any floodplain storage was protected. Floodplains are extremely important for providing a flood buffer but also tend to be built upon, increasing the exposure to flood risk.

To determine which urban areas lie in floodplains, and to what extent, the percentage of blue storage volume that lies in urban areas was calculated. Although less than 1% of the upper Guayaquil basin is urbanised, 6% of the blue storage volume in the basin overlies urban areas. The urbanised part of the Chennai upstream basin was almost all coincident with blue storage.

The WaterWorld surface water storage to capacity ratios (referred to as the Flood Risk Ratios or FRR) for each city basin were calculated to show the spatial distribution of potential flood risk (<1 = low flood risk, >1 = high flood risk). The results for the study basins showed a variety of within-basin patterns as to which storage was contributing to the flood mitigation and where it was located. These patterns indicate that disparate city basins may be categorised into different 'storage/risk' types with associated strategies for intervention,

such as “green heavy” or “green-blue hybrid” and “low-risk dispersed” or “low-risk concentrated”. Each pattern-type may suggest a different strategy for improving or enhancing flood risk mitigation through natural infrastructure storage.

Overall, these results showed that the method of comparing storage capacity to runoff volumes as the flood risk ratios could be a useful way to determine potential flood risk using globally accessible data inputs. The methods outlined in Chapter 3 allow for the identification of priority areas for conservation of flood-relevant natural infrastructure under current conditions and scenarios of land use and climate change.

Objective 2: Model the change in flood mitigation service provision to a number of global cities under different scenarios of climate change. Specifically, to examine different climate change scenarios to see how they vary the water that needs to be stored by a catchment, and therefore change flood risk.

Chapter 4 evaluated all six study basins by looking at how a suite of hydrological variables and the flood risk ratios changed under six climate scenarios (using an ensemble of GCMs, 3 RCPs and 2 future time periods for CMIP5).

The climate scenarios revealed that the upstream basins of Nairobi, Chennai, Bogotá and Guayaquil are projected to have increased rainfall and water balance on an annual scale compared to baseline conditions, and thus also increases in Flood Risk Ratios (FRR). In contrast, rainfall and water balance are projected to decrease compared to baseline on an annual scale in the upstream basins of London and Jakarta, with associated declines in FRR. Further analyses showed that there was seasonal variability (rainfall and water balance increased in some months but not others) to the annual trend. These results are aligned with the regional predictions reported by the IPCC (2021) and World Bank’s Climate Knowledge Portal.

In the observed changes, a ‘distance-to-the-city’ pattern was investigated as greater population density in cities means greater exposure to the hazard, i.e. more people and assets being affected. There was no clear evidence of this across the basins; although some of the highest mean percentage change difference (pcds) did occur close to the city-basin boundary in Nairobi, London, and Guayaquil, the relationship did not decrease linearly away

from the city. For some basins, such as Chennai, Bogotá and Jakarta, the reverse was true. The highest mean pcds were for the most distant points from the city-basin boundary.

To get an indication of the spatially distributed change, I mapped where the flood risk ratios increase compared to baseline, aggregating the results of the climate scenarios for each upstream basin. The FRR change maps showed some patterns among the basins. An association between the number of scenarios agreeing on a >10% increase in flood risk and increasing slope and tree cover was found in the Jakarta and Bogotá basins. Elevation was also a predictor in the Jakarta basin. There was a slight association between where more than three scenarios project increases in flood risk to occur and the NI storage type that predominates in those locations. For half the basins (Nairobi, Chennai, and London) it is the soil NI storage type, associated with the increases in flood risk ratios. For the other basins (Bogotá, Jakarta, and Guayaquil) it is canopy NI storage that is associated with the greatest number of scenarios showing an increase in flood risk ratios (>10%). This is probably a result of soil and canopy NI storage being the most prevalent and widely distributed of the NI storage types.

The performance of various climate scenarios was examined by RCP and time period. The expectation was that the results would progress from less to most severe/extreme as the RCPs progress, with RCP 4.5 2050s being the least extreme and RCP 8.5 2070s being the most extreme, for rainfall and subsequently change in FRR. However, this was only true for points in half of the basins studied: Chennai, Jakarta, and Guayaquil. For the upstream basins of Nairobi and Bogotá, it was scenario RCP 6.0 for the 2070s which caused the greatest increases in flood risk ratio, and in the London upstream basin, it was scenario RCP 6.0 for the 2050s which caused the greatest increases in flood risk ratio, due to the changes in rainfall under that scenario. RCP 8.5 for the 2050s produced the second lowest increases in flood risk ratios, even being slightly lower than RCP 4.5 2070s. RCP 4.5 for the 2050s produced the lowest increases in flood risk ratios, which is what we would expect. These unexpected discrepancies could be a result of the GCMs used or excluded in the multi-model ensembles for the different RCPs in WorldClim. RCP 4.5 uses 19 GCMs, RCP 6.0 uses 12 and RCP 8.5 uses 17 GCMs (see Section 4.5.5). However, it is worth highlighting that the RCP scenarios are considered worst case, or not, on the basis of radiative forcing (caused by global GHG emissions), which translates to global temperature but may not align with global rainfall. Moreover, the study sites are a very small sample of the globe, so it is

not surprising that the global worst-case scenario does not produce the locally worst-case rainfall in these small areas.

The results of this chapter showed where flood risk ratios are projected to increase/decrease under climate change scenarios in six study basins. This provided an important base to determine where the interventions utilised in Chapter 5 could act as nature-based solutions to flood risk.

Objective 3: Determine the impact on flood risk of installing additional natural infrastructure (NI). Specifically, to evaluate the amount and spatial-targeting of additional tree canopy cover (via forestation) needed to mitigate the increase in flood risk.

Chapter 5 focused on only two of the basins: Bogotá and Guayaquil. It investigated how different extents of increased forestation and spatial targeting of low-value land, using scenarios based on reforesting areas of recent net deforestation, impact flood risk. I assessed this for both current risk, by comparing to baseline (Chapter 3), and for future risk, by comparing to the results of the climate scenarios (Chapter 4).

The effect of extent or scale of forestation, outside protected areas, was examined by modelling the impact on FRR of increases in forestation by 5%,10%, 25%, 50%, 75% and 100% in the major hydrological basins of Colombia-Ecuador and Magdalena. The results were non-linear: the steepest reduction in FRR occurs between 5% and 50% extent of forestation for both major hydrological basins and weakens between 50% and 100% level of afforestation, at both the basin sum and river point scale. This indicates that the lowlands may have a greater role in flood risk reduction than the uplands since canopy storage and evaporative losses from tree cover are great in lowland climates. This is at odds with current practices of preferentially foresting uplands. Forestation was more impactful (greater FRR reduction at the major basin scale) for the Colombia-Ecuador basin than for the Magdalena basin, which is also probably a result of the Colombia-Ecuador basin having a greater extent of lowlands than uplands.

Interestingly, at both the basin and river point scale, the results showed that even 100% forestation (outside protected areas) would not completely offset the current flood risk ratios,

i.e., there would still be more annual rainfall than the capacity to store it in parts of the landscape.

Using a restoration scenario that focused on areas of recent net deforestation in combination with spatial targeting of low-value land, resulted in less than 4% of the basin's areas being forested. I found that these scenarios could contribute to mitigating flood risk at the basin scale, but the reduction at the river point scale is marginal, suggesting a negligible difference experienced by downstream beneficiaries.

To get a sense of how these restoration scenarios could mitigate against the increased flood risk from projected climate scenarios, i.e., future risk, the areas showing decreased risk from forestation were overlaid with the areas of increased risk from climate. In the Bogotá basin, at the basin scale, one scenario more than offset the increase in FRR under all the climate scenarios, i.e., it succeeds in being a nature-based solution to climate induced flood risk, but that was not the case for the other scenarios. In the Guayaquil basin, none of the forestation scenarios mitigate the increase in flood risk under any of the climate scenarios at the basin scale. If we want to mitigate the increase in flood risk from climate change, we need to afforest at least 3% of the area recently deforested in the Bogotá basin. In contrast, a similar increase in tree cover in areas of recent deforestation in the Guayaquil basin would not reduce flood risk; much greater extents of forestation are needed.

Examining the geographic characteristics of nature-based solution (NbS) areas in the Bogotá basin revealed that they coincide with the river networks and the relatively low elevation areas. In the Guayaquil basin, the overlap areas track the lower elevations in the protection scenarios and the higher, eastern mountain elevations in the low-agriculture and slope scenarios. There is also defined tracking of the river networks, particularly in the eastern part of the basin. These results suggest restoration along lowlands and rivers in the Bogotá basin, and in mountains and alongside rivers in the Guayaquil basin.

Overall, focusing only on reforesting areas of recent forest loss is not sufficient to achieve meaningful flood risk reduction, both currently and under climate scenarios. However, it is still possible to lessen the impact of increased flood risk now and under climate change by using this approach, although only marginally. There could be added-value in 'putting-aside'

this land for restoration and safeguarding as these areas may contribute to each country achieving its 30x30 protection goal. The method used to identify areas for NbS implementation may also help to identify routes to connect areas important for conservation, creating an ecological network.

From a purely flood risk mitigation perspective, national and sub-national agencies will need to implement a suite of NbS interventions or green-grey hybrid solutions, which combine both natural and built infrastructure, to protect downstream assets.

6.3 Wider significance and contributions of the study

This study has demonstrated that the method applied for this research question (NI metric in the WaterWorld modelling platform) can be a useful way to determine potential 'natural' flood risk using globally available data. I was the first user of these metrics, and by using them extensively, across many basins and multiple scenarios, have significantly 'road-tested' them and demonstrated that the NI metrics are stable, with no obvious errors or conceptual issues. In this way, I have advanced the use of WaterWorld and through the publication of Chapter 3 have promoted it and the NI metrics.

Unlike other eco-hydrology studies that focus on an individual basin or a series of basins within a region, this study compares two to six basins with differing basin characteristics and climatology across five continents. This work contributes to filling the gap identified in the literature of a lack of studies on large basins and across scales (Filoso et al. 2017; Vose et al., 2011). Although focusing on only one or two basins would have allow for more in-depth analysis and opportunities for on-the-ground verification, comparing across basins produced generalisable results, tested the ability to identify patterns and demonstrated the versatility of the methodological approach. It must be highlighted that WaterWorld can be run for anywhere globally. The study basins in this thesis are representative of many types of catchments around the world. The NI metrics presented here will be particularly relevant to catchments that have high flood risk from riverine or overland flooding generated from rural areas, and upstream of areas that have increased vulnerability due to increased exposure from rapid population growth, such as many cities in Africa and Asia (Tellman et al., 2021).

This multi-basin perspective highlighted some common themes, such as the heavy reliance on green natural water storage in some basins, the lack of protection for this storage, and

where protected, its remoteness from downstream beneficiaries. This analysis, and the methods described, can assist in establishing the amount and locations of green storage to be protected, restored, or enhanced. Equally, it points to adding additional criteria, such as natural flood protection potential, for the establishment of protected or safe-guarded land, other than the more conservation-based criteria of high/rare biodiversity or habitat uniqueness/ intactness.

This study is comprehensive for studying the impact of climate change on hydrology and flood risk in six geographically disparate locations, at the basin scale, using an ensemble of models from CMIP5, for three RCP scenarios. A review of the literature found no other examples with such a breadth of geography, climate models and scenarios at the basin scale.

A novel output of this thesis has been the maps showing consensus and discrepancy areas of the flood risk ratios for the six climate scenarios. The depiction of the number of scenarios that agree on the change acts is an indicator of the likelihood of the change occurring. These maps and associated analysis can be used by a diverse range of stakeholders, from city planners and protected area managers to national governments and civil society organisations, to indicate future flood risk. Subsequently, these can help to determine the optimal locations for further, more detailed analysis, planning and investment in green flood storage for both now and in the future.

Current and future flood risk are typically assessed separately. An innovative approach employed in this study was the combining of flood risk mitigation with future flood risk projections to visualise overlap areas that are opportunity areas for NbS development.

6.4 Avenues for future research

Future work should:

- Investigate how projected urban expansion will remove important natural flood storage and thus impact current flood risk as well as exposure to it.
- Examine what co-benefits, in the form of ecosystem services, are associated with current levels of green natural flood storage (wetlands, tree canopies and soil) and if these can be enhanced with targeted increases of that storage.

- Compare these results with those of other ecosystem services models, such as InVEST or LUCI, to take an ensemble approach.
- Apply alongside monitoring in a paired catchment study to validate the model outcomes in a specific setting where significant volumes of data are available.

6.5 Concluding remarks

Most often, flood modelling and ecosystem assessments require complex data and software, technical expertise and data rich environments for the inputs. This study has made use of a simple to use but sophisticated modelling platform that can be used in any basin globally, allowing standardised comparison between multiple basins. The methods, applications and scenarios developed here could be applied in other basins using the same easily accessible tools.

Taking an ecosystem services approach, by measuring the contribution of natural infrastructure to flood regulation, is important for highlighting their importance relative to grey infrastructure and, where the evidence justifies it, advocating for their protection, and in some cases, enhancement.

Overall, this thesis has successfully applied sophisticated software tools and GIS analysis to better understand the role of natural infrastructure in flood risk reduction under current, future climate and land use change contexts. This has aided the identification of priority areas for conservation of flood relevant natural infrastructure. This approach can be used by others to identify strategies to reduce flood risk and evaluate whether nature-based solutions are a suitable alternative, or valuable addition, to conventional options. Finally, it has illustrated the power of spatial modelling, which together with an ecosystem approach, can be used to provide evidence in support of solutions to environmental and societal challenges.

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Appendices

Appendix A - Umbrella Literature Review

Below are the exact search strings used in the umbrella literature review:

Search 1

Web of Science
Search terms: TI=(review AND (forest OR "tree planting" OR afforestation OR reforestation OR "forest restoration") AND (*hydrolog* OR water OR flood*) NOT quality)
Results: 41
After initial screening of title and abstract: 10

Scopus: TITLE ((forest OR {tree planting} OR afforestation OR reforestation OR {forest restoration}) AND (*hydrolog* OR water OR flood*) AND review AND NOT quality)
Results: 45
After initial screening of title and abstract: 9

Combined with duplicates removed: 12

Search 2

Scopus
TITLE-ABS-KEY (({Nature-based solutions} OR nbs OR {Ecosystem Services} OR {Ecosystem-based Adaptation}) AND (flood* OR {flood regulation} OR {flood mitigation} OR {flood control} OR {flood protection} OR {flood management} OR {water quantity} OR *hydro* OR {water yield} OR {flood peak} OR {risk reduction}) AND (tree* OR {tree planting} OR afforestation OR reforestation) AND review) AND (LIMIT-TO (DOCTYPE , "re"))

Results 24, after initial screening of title and abstract: 9

WoS
TS=(("Nature-based solutions" OR nbs OR "Ecosystem Services" OR "Ecosystem-based Adaptation") AND (flood* OR "water quantity" OR *hydro* OR "water yield" OR "risk reduction") AND (tree* OR forest OR afforestation OR reforestation)) limit to review articles

Results 125, after initial screening of title and abstract: 20

Removed reviews

Table A-1 summarises all the papers that were removed from the umbrella review and the reason for non-inclusion.

Table A1. Reviews excluded from the umbrella review and reasons for non-inclusion

Reference (author_year)	Title	Reason removed
Altunel_2020	Examining the PALSAR-2 Global forest/non-forest maps through Turkish afforestation practices	EO observation comparison - no impact on flooding
Antonarakis_2020	Uncertainty in parameterizing floodplain forest friction for natural flood management, using remote sensing	Measuring uncertainty in roughness using RS
Brink_2016	Cascades of green: A review of ecosystem-based adaptation in urban areas	no synthesised quantitative impacts reported
Burton_2018	Reviewing the evidence base for the effects of woodland expansion on biodiversity and ecosystem services in the United Kingdom	no synthesised quantitative impacts reported
Castro-Diez_2019	Global effects of non-native tree species on multiple ecosystem services	native vs non-native comparison rather than forested vs unforested
Castro-Diez_2021	Effects of widespread non-native trees on regulating ecosystem services	native vs non-native comparison rather than forested vs unforested
Chausson_2020	Mapping the effectiveness of nature-based solutions for climate change adaptation	no synthesised quantitative impacts reported
Cooper_2021	Role of forested land for natural flood management in the UK: A review	narrative review
Cosandey_2005	The hydrological impact of the mediterranean forest: a review of French research	not a review of other studies
David_2016	Water and forests in the Mediterranean hot climate zone: a review based on a hydraulic interpretation of tree functioning	narrative review
Depietri_2012	Heat waves and floods in urban areas: a policy-oriented review of ecosystem services	narrative review
Eisenbies_2007	Forest operations, extreme flooding events, and considerations for hydrologic modeling in the Appalachians - A review	narrative review
Ellison_2012	On the forest cover-water yield debate: From demand- to supply-side thinking	narrative review
Ellison_2017	Trees, forests and water: Cool insights for a hot world	narrative review
Farooqi_2021	Reconciliation of research on forest carbon sequestration and water conservation	narrative review
Feixiang_2016	Hydrological services by mountain ecosystems in Qilian Mountain of China: A review	narrative review

Goeking_2020	Forests and Water Yield: A Synthesis of Disturbance Effects on Streamflow and Snowpack in Western Coniferous Forests	forest loss -post-disturbance
Gribovszki_2019	Hydrological role of Central European forests in changing climate-review	narrative review
Kordrostami_2021	Identification of optimum afforestation areas considering sustainable management of natural resources, using geo-environmental criteria	method/framework for determining land suitability
Kuyah_2016	Trees in agricultural landscapes enhance provision of ecosystem services in Sub-Saharan Africa	not catchment/landscape scale
Marapara_2021	Disentangling the factors that vary the impact of trees on flooding (a review)	narrative review
McEachran_2021	Nonstationary flood-frequency analysis to assess effects of harvest and cover type conversion on peak flows at the Marcell Experimental Forest, Minnesota, USA	forest harvest (deforest)
Mengist_2020	A global view of regulatory ecosystem services: existed knowledge, trends, and research gaps	no synthesised quantitative impacts reported
Mngumi_2020	Ecosystem services potential for climate change resilience in peri-urban areas in Sub-Saharan Africa	narrative review
Page_2020	Assessing the significance of wet-canopy evaporation from forests during extreme rainfall events for flood mitigation in mountainous regions of the United Kingdom	no direct evidence
Perevochtchikova_2019	Systematic review of integrated studies on functional and thematic ecosystem services in Latin America, 1992-2017	no quantitative impacts reported
Price_2011	Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: A review	narrative review
Rodriguez_2016	China's conversion of cropland to forest program: a systematic review of the environmental and socioeconomic effects	only 2 studies for flood regulation
Ruangpan_2020	Nature-based solutions for hydro-meteorological risk reduction: a state-of-the-art review of the research area	no synthesised quantitative impacts reported
Sach_2019	Water regime of douglas-fir and forest stands with douglas-fir: Review [Vodní režim douglasky a lesních porostů s douglaskou: Review]	narrative review
Schonenberger_2001	Cluster afforestation for creating diverse mountain forest structures — a review	narrative review
Seddon_2020	Understanding the value and limits of nature-based solutions to climate change and other global challenges	narrative review
Sing_2018	A review of the effects of forest management intensity on ecosystem	narrative review

	services for northern European temperate forests with a focus on the UK	
Stanturf_2017	Contemporary forest restoration: A review emphasizing function	narrative review
Stratford_2017	Do trees in UK-relevant river catchments influence fluvial peaks? A systematic review	not peer-reviewed
Taramelli_2019	Monitoring Green Infrastructure for Natural Water Retention Using Copernicus Global Land Products	review of methods
vanDijk_2007	Planted forests and water in perspective	narrative review
Venkatesh_2014	Hydrological impacts of afforestation - A review of research in India	narrative review
Verhagen_2016	Effects of landscape configuration on mapping ecosystem service capacity: a review of evidence and a case study in Scotland	narrative review
Vicente_2018	Water balance of Mediterranean Quercus ilex L. and Pinus halepensis mill. forests in semiarid climates: A review in a climate change context	narrative review

Appendix B - Ecosystem service and hydrological modelling

Table B1 lists examples of published studies that have examined Hydrological Ecosystem Services. Table C2 summarises examples of studies that have examined hydrological ecosystem services at different scales.

Table B1. Comparison of different models and tools used for ecosystem service analysis and hydrological modelling. Listed in alphabetical order.

Method	Description	Scale	Input data	Output	Strengths	Weaknesses	References
ARIES Artificial Intelligence for Ecosystem Services SuDS.arieso nline.org	Allows users to evaluate trade-offs between ES and to identify hidden stakeholders who may benefit from services within area of interest. The tool uses probabilistic Bayesian networks to uncover relationships between input data and ES values. ES: flood control, sediment regulation, subsistence fisheries, salmon yield, nutrient filtration, water supply, and several non-water related services.	30m – 10 km grid cells	Local data	Can download output into GIS data files. The map outputs display where ES are provided and where people benefit from those services as well as the flow paths between the source regions and use regions.	Visualising ecosystem service dynamics. Trade-offs. Flow characteristics between provider and user. Can be used to generate scenarios to explore changes in ES provision and use based on changes in ES supply or demand. Climate change scenarios futures.	Lack of transparency of the model code due to complexity. ARIES framework is very data demanding and a similar approach at the European scale is not feasible (Stürck et al. 2014).	Vigerstol & Aukema 2011
Grid to Grid (G2G) Developed by CEH and continued by the EA	The Grid-to-Grid hydrological model is a tool developed for translating rainfall into river flows to predict potential river flooding.	1km - UK	Regional climate model (RCM) precipitation estimates; gridded estimates of precipitation and potential evaporation; relies on digital datasets of landscape and soil properties		The Grid-to-Grid Model can also be used to forecast how peak river flows may change in different parts of the country due to climate change.		Bell et al. 2007; Eigenbrod et al. 2011
InVEST Integrated Valuation of Ecosystem services and Tradeoffs	Models and maps a suite of ecosystem services (ES) across the landscape to elucidate general patterns and changes in ES caused by land cover changes or	Local, regional and global but case-studies local or regional. 30m – 10	Data format in GIS raster grids, GIS shapefiles or database tables.	Performs calculations on a pixel basis. Outputs are GIS maps of intermediate modelling steps, final biophysical service levels and economic estimates for each pixel across the landscape.	Trade-off scenarios. Examining changes in ES provision under different land use changes. Relatively quick assessment of services across the landscape.	Inability to account for seasonal or sub-seasonal variability, groundwater and water resource infrastructure that redistributes water flow.	(Nelson et al. 2009; Bai et al. 2013)

Method	Description	Scale	Input data	Output	Strengths	Weaknesses	References
	climate change impacts. Simple (tier 1) and complex (tier 2) models. freshwater services: nutrient filtration, hydropower, irrigation, avoided reservoir sedimentation, storm peak mitigation.	km grid cells. Mostly large river basin scale.					
JULES Joint UK Land Environment Simulator	JULES is a process-based Dynamic Global Vegetation Model that simulates the fluxes of carbon, water and energy between the atmosphere and the land surface at a point.						Best et al. 2011, Clark et al. 2011
KINEROS	A distributed, physically based, event model describing the processes of interception, dynamic infiltration, surface runoff and erosion from watersheds characterised by predominantly overland flow.	Watersh eds	Digital elevation model (DEM), land cover data, soil data, hydrological and climatic data	Matrix tables and maps	Suitable for application in small watersheds with predominant surface runoff during the flood event as well as the possibility to estimate the influence of land cover/ecosystems.	Not applicable for floods caused by snow melting. Model results do not correspond directly to the land cover data, requiring additional processing. The model is event-based, so parameters like evapotranspiration cannot be taken into account.	Nedkov & Burkhard 2012
LUCI	LUCI is a spatially explicit decision support tool which illustrates the impacts	sub-field to national scale	Digital elevation model (DEM): grid size of 5x5m to 10x10m		ability to simultaneously model different spatial	LUCI is still in development. At the time of this research project it was only	Sharps et al. 2017

Method	Description	Scale	Input data	Output	Strengths	Weaknesses	References
Land Utilisation Capability Indicator **https://www.lucitools.org/**	of land use on various ecosystem services. Compares the current services provided by the landscape with estimates of their potential capability. ES included: Agricultural production Erosion risk and sediment delivery Carbon sequestration Flood mitigation Habitat provision Water quality – Nitrogen and Phosphorus	simultaneously	Land cover information Soil information Other optional information that can be used as input include a stream network, rainfall, and evapotranspiration.		scales such as field to catchment built-in trade-off tool allows the user to compare multiple ecosystem services at once	available to use in a limited number of global regions, namely UK and New Zealand.	
LUISA	LUISA is a dynamic, spatial modelling platform which simulates future land use changes based on biophysical and socio-economic drivers.	1 ha			Specifically designed to assess land-use impacts of EU policies. Simulates future spatial patterns of a number of land-use groupings, namely urban areas, industrial and commercial areas, arable land, permanent crops, semi-natural vegetation and forest land.		Maes et al. 2014
STREAM (Spatial Tools for River basins and Environment and	GIS based spatially distributed rainfall runoff model optimized for the analysis of the hydrological impact of land use and climate	Large river basins					Stürck et al. 2014; Aerts et al. 1999

Method	Description	Scale	Input data	Output	Strengths	Weaknesses	References
Analysis of Management options)	changes in large river basins						
SWAT Soil and Water Assessment Tool (Developed by USDA's Agriculture Research Service.)	Simulates hydrologic processes and determines parameters affecting the water cycle. Evaluates impact of land use changes on watershed yield, sediment, and agricultural pollutants in a river basin. FW services: water yield, sedimentation, water quality.	Sub-basin	Requires detailed data inputs. Daily precipitation, topography, soil type, snow water equivalent.	Outputs describe water movement from evapotranspiration to subsurface flow to volume of water applied for irrigation. Also detailed output on movement of nutrients through a watershed.	Long term trends. Users can specify land management practices.	Requires detailed data inputs, time to learn the model, expertise in hydrology. Not for one-time events.	(Notter et al. 2012; Githui et al. 2009)
VIC Variable Infiltration Capacity Model	Large-scale gridded hydrologic model. Where water yield and stream flow are main variables of interest. Model estimates water movement between the atmosphere, ground surface, soil layers and subsurface by precipitation, evapotranspiration, infiltration and runoff. ES: Water yield	1-50km grid cells	Meteorological data, elevation, land cover and soil characteristics. Multiple land covers (13) including bare soil are considered in the VIC model. It also accounts for the top vegetation cover.	Hourly water yield and evapotranspiration. Flows with routing model. Dozens of output variables for each timestep, per pixel.	Most appropriate for large river basins. Used for studying the effects of climate changes on streamflow generation	Less useful for comparing across several services. Not intended for study areas smaller than a river basin.	http://SuDS.hydro.washington.edu/Lettenmaier/Models/VIC/
WaterGAP	The global freshwater model WaterGAP computes water flows and storages as well as water withdrawals and consumptive uses on all continents. Thus it quantifies the	Global 0.5° geographical latitude × 0.5° geographical	Time series of climate data (e.g. precipitation, temperature and solar radiation) and physiogeographic information like characteristics of surface water bodies				http://SuDS.watergap.de/ McDonald et al. 2014; Döll & Zhang 2010

Method	Description	Scale	Input data	Output	Strengths	Weaknesses	References
	total renewable water resources as well as the renewable groundwater resources of a grid cell, river basin, or country	longitude,	(lakes, reservoirs and wetlands), land cover, soil type, topography and irrigated area.				
WaterWorld	A spatially explicit, physically based global model for water balance. Is capable of producing a hydrological baseline representing the mean water balance for 1950–2000 and allows users to apply ensemble scenarios for climate change or land cover change	1km – 1 ha tiles; local to continental	None. Comes with all data required for application.	Maps, graphs, GIS files	Well suited to heterogeneous environments with little or no available data. WaterWorld connects with the following tools: WEAP, AQUEDUCT, TESSA	Black box. Poor or no documentation for many features.	Van Soesbergen & Mulligan 2014
WEAP	Calculates water demand, supply, runoff, infiltration, crop requirements, flows, and storage, and pollution generation, treatment, discharge and instream water quality under varying hydrologic and policy scenarios						Yates et al. 2005

Table B2. Examples of studies that have examined hydrological ecosystem services at different scales.

Reference	Aim	Scale/ Where	How
(Chan et al. 2006)	Explored the trade-offs and opportunities for aligning conservation goals for biodiversity with six ecosystem services (carbon storage, flood control, forage production, outdoor recreation, crop pollination, and water provision). Their aim was to develop networks of conservation areas for each service.	Regional/ Central Coast eco-region of California, United States	They assembled these networks using MARXAN, an optimization algorithm developed to find systems of spatially cohesive sites that efficiently meet a suite of biodiversity targets. For the flood control part of the study, their model identified the areas important to maintain a natural flooding regime and reduce the risk of extreme flood events attributable to impervious surfaces in a watershed. The feature value in the model varied with land cover in various categories and distance to the floodplain to reflect the flood-mitigation contribution of vegetation in floodplains, wetlands, the riparian zone, and beyond.
(Tratalos et al. 2007)	Looked at a bundle of ES: availability and patch characteristics of tree cover, gardens and green space; storm-water run-off; maximum temperature; carbon Sequestration.	3 sites along urban-rural gradient in 5 UK cities	For surface water runoff, used the SCS-CN model: $Pe = (P-0.2S)^2/(P+0.8S)$,where Pe denotes surface run-off, P, precipitation and S, the maximum potential rainfall retention of the catchment. S is calculated as 2540/CN− 25.4, where CN is the curve number calculated by the Soil Conservation Service for each combination of land cover and soil type. Using the Soil Conservation Service classifications as a basis, soil curve numbers were assigned to the various cover types. Following Whitford et al. (2001), **average run-off** from a 12mm storm event, a common occurrence in UK cities, was calculated for the area of each study site. Areas of water bodies were not included.
(Egoh et al. 2008)	A study to develop national-scale maps of selected ecosystem services in South Africa examined surface water supply, water flow regulation, carbon storage, soil retention and accumulation.	National/ South Africa	For the water flow regulation service the researchers used groundwater contribution to surface runoff as the most direct measure of the water regulation function of a catchment. Data on the percentage contribution of groundwater to baseflows were obtained per quaternary catchment and expressed as a percentage of total surface runoff
(Luck et al. 2009)	A global scale study of biodiversity and ecosystem services in watersheds aimed to integrate strategies for conservation and service protection by explicitly incorporating human need into prioritisation strategies	Global	This study created a priority index for each ecosystem service composed of multipliers based on the benefit to cost ratio, threat to the service, opportunity for enhancement etc. They generated global maps of watersheds showing congruent or divergent ecosystem service and biodiversity conservation priorities.

(Eigenbrod et al. 2011)	Looked at the impact of increasing urbanisation on flood mitigation. Explicitly link upstream changes in flows to downstream beneficiaries. They looked at three ecosystem services – flood mitigation, agricultural production and carbon storage at the scale of Britain.	National/ Britain	For the flood mitigation component they used an existing grid-based hydrological model (Grid-to-Grid (G2G)) of Britain to map the impacts of projected changes in dense urban and suburban land cover between 2006 and 2031 on freshwater flood mitigation services provided by the landscape. They quantified loss of flood mitigation provided by the landscape that the hydrological model predicts will occur through the conversion of nonurban land to urban land by calculating the change in flood risk (percentage increase in peak flow at the 2 year return period) for 1x1 km UK grid squares containing a significant river component (grid squares with a drainage area greater than 20 km^2 or for which the observed river length is greater than 500 m.
(Stürck et al. 2014)	Address the spatial distribution of ecosystem service supply and demand focused solely on flood regulation services. The studies' aim was to provide a spatially explicit indicator of flood regulation supply in Europe.	Continental/ Europe	The index was based on the response of hydrographs to environmental variables carried out with the hydrological model STREAM, where the effects of five environmental variables (catchment types, catchment zones, precipitation types, crop factor, water holding capacity (WHC)) on discharge volumes following precipitation events were estimated. The output of their analysis was a map of the current supply of flood regulation and the potential supply under current conditions of natural vegetation. They found that they could identify priority areas for investments in ecosystem service flood regulation supply through conservation and land use planning.

Appendix C – Sensitivity Analysis of NI metric input variables

Below are graphs (Figures C1 to C5) that shows how a change in the input parameter by set degrees, influences the outputted total storage (km3) for each basin. The default values are shown in Figure B1.

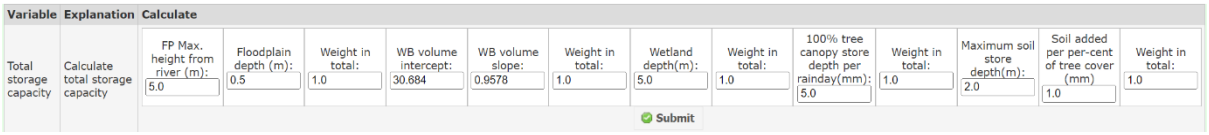


Figure C1. Screenshot of default parameter input screen for Natural Infrastructure metric in the WaterWorld PSS.

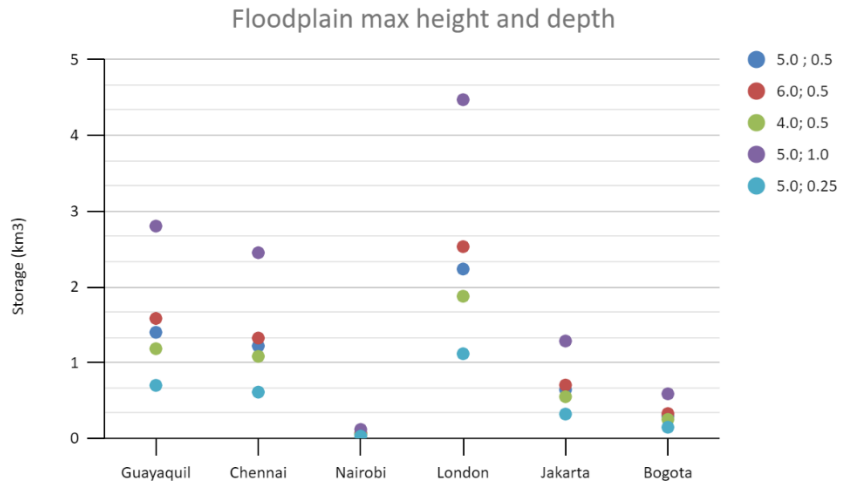


Figure C2. Change in tree floodplain max height (default 5m) and depth parameter (default 0.5mm) and resultant change in storage (km3) for each basin.

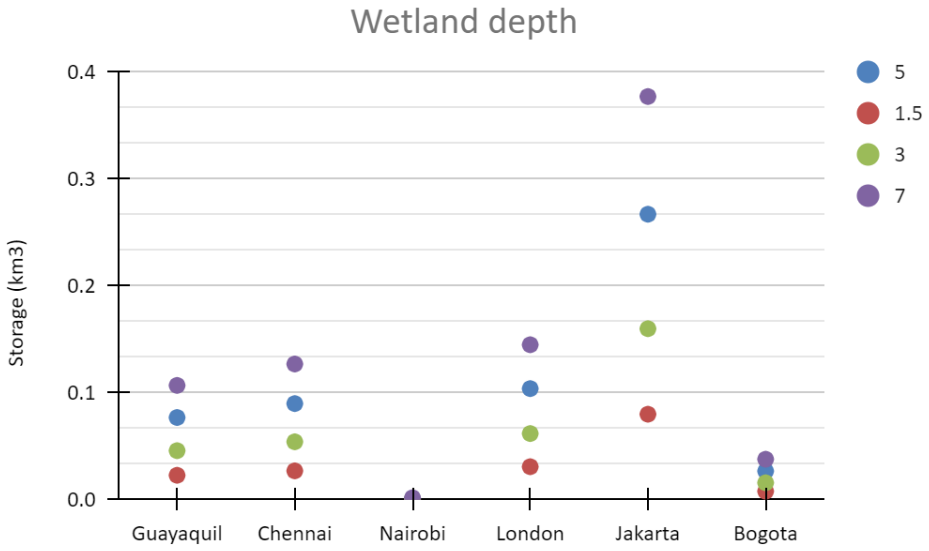


Figure C3. Change in wetland depth parameter (default 5m) and resultant change in storage (km3) for each basin.

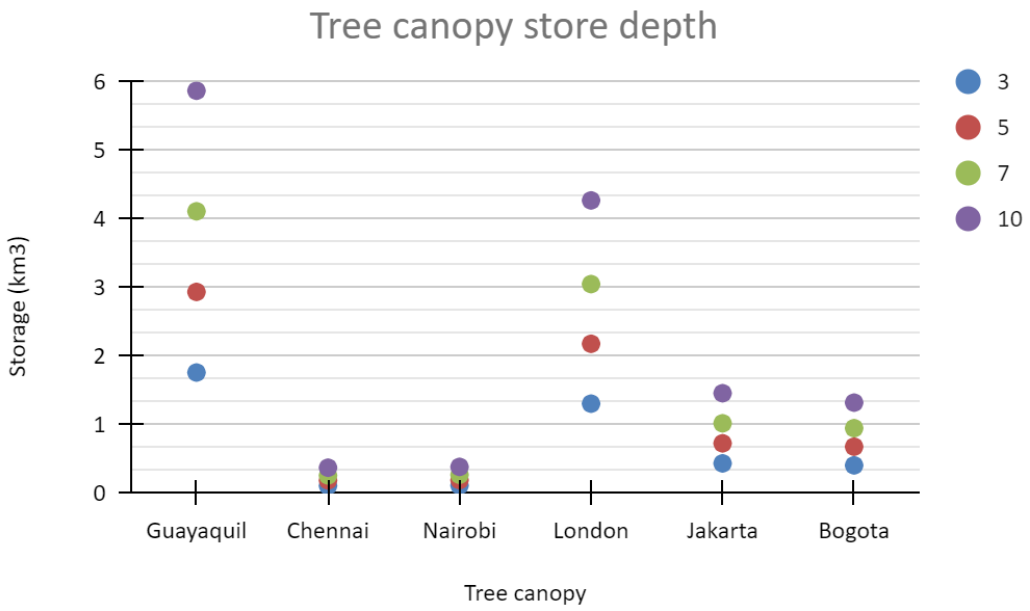


Figure C4. Change in tree canopy store depth parameter (default 5mm) and resultant change in storage (km3) for each basin.

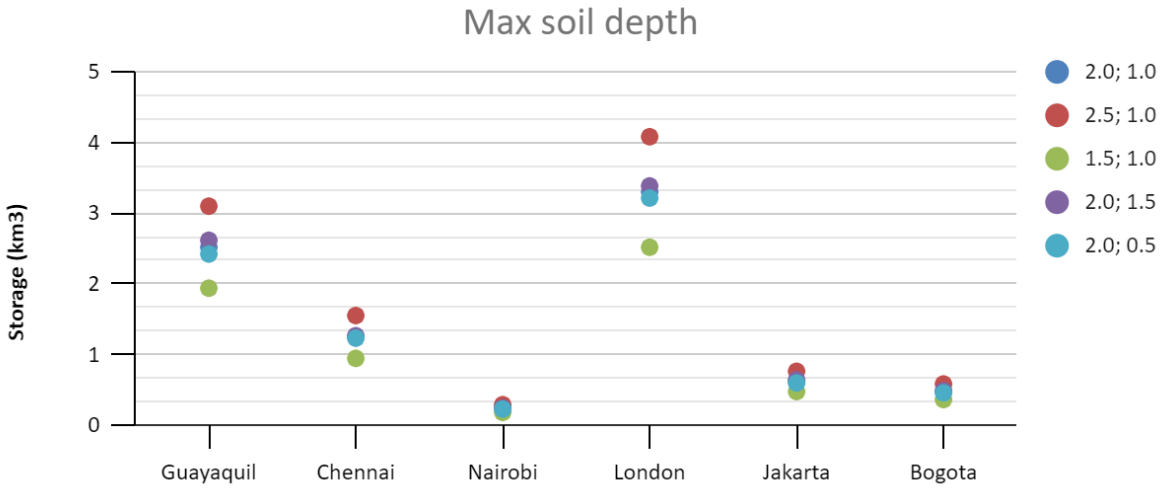


Figure C5. Change in max soil store depth depth parameter (default 2mm) and resultant soil added percent of tree cover (default 1mm), and the resultant change in storage (km3) for each basin.

Appendix D - Climate change

D1. Study basins and river sampling points

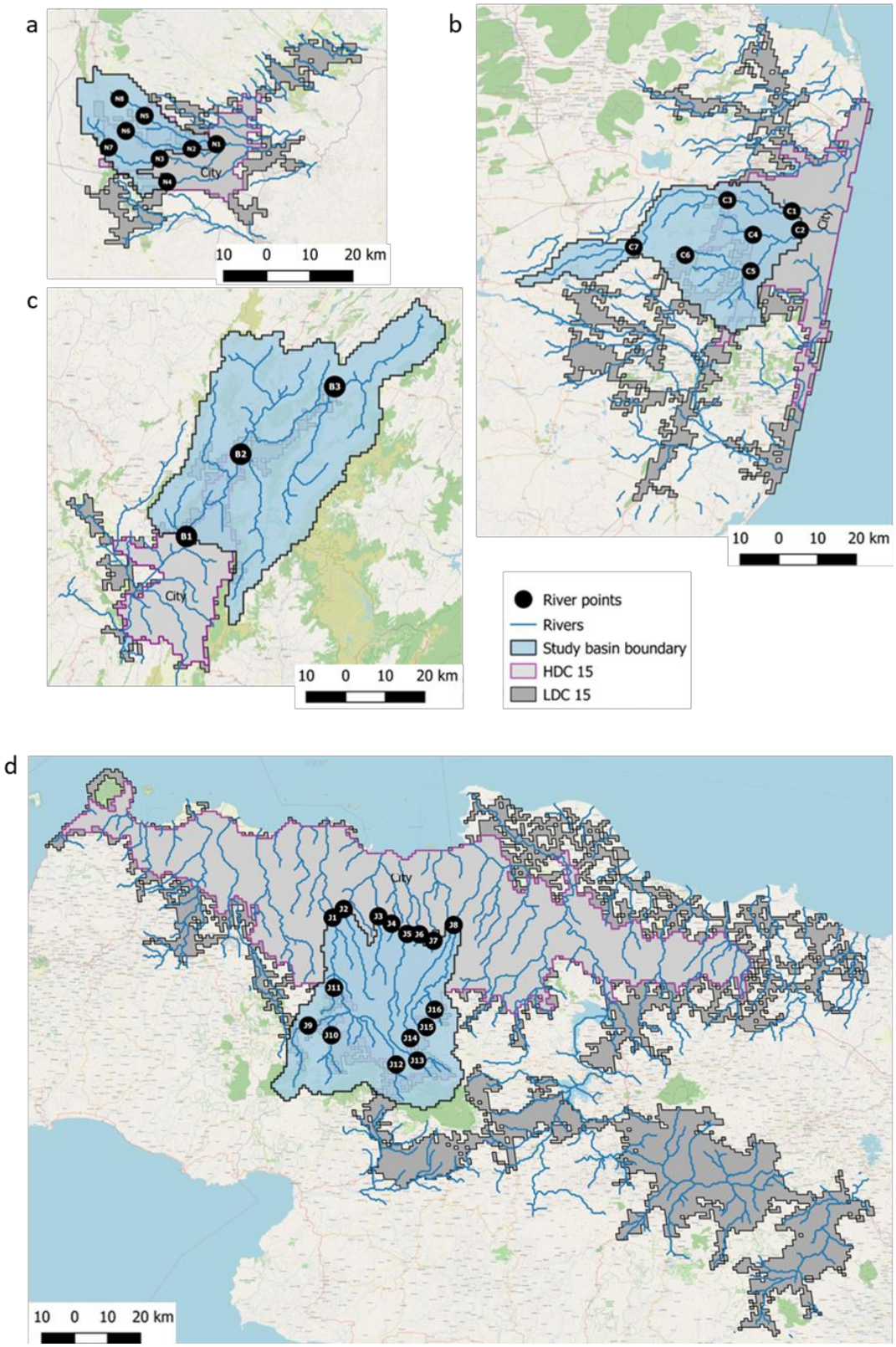


Figure D1. Position of river points within the upstream watersheds of (a) Nairobi, (b) Chennai, c) Bogotá and (d) Jakarta, overlaying an OpenStreetMap basemap.

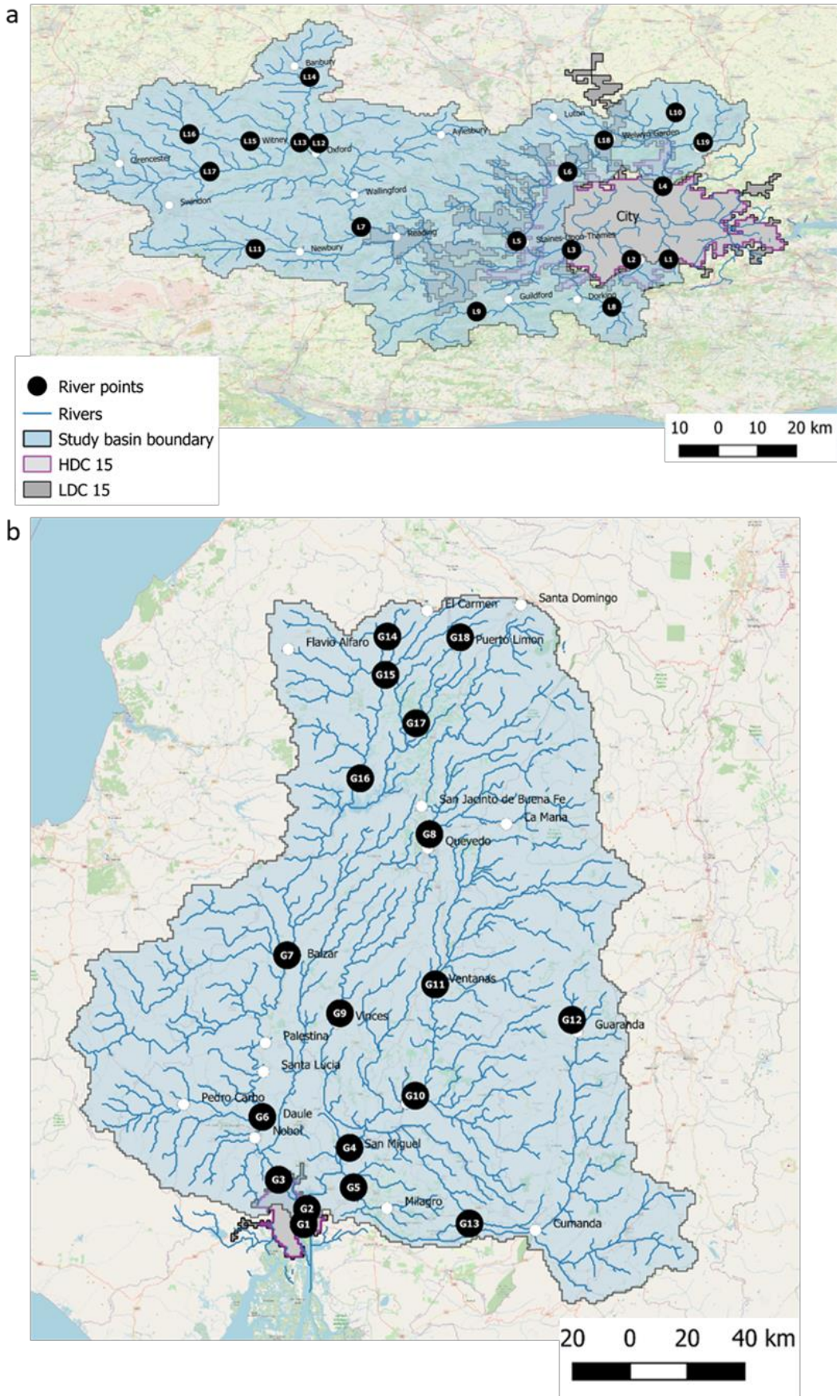


Figure D2 Position of river points within the upstream watersheds of (a) London and (b) Guayaquil, overlaying an OpenStreetMap basemap.

D2. Standard deviations for the impact of climate scenarios on hydrological variables

Graphs showing +1SD and -1SD for each climate change scenario (Figure C3).

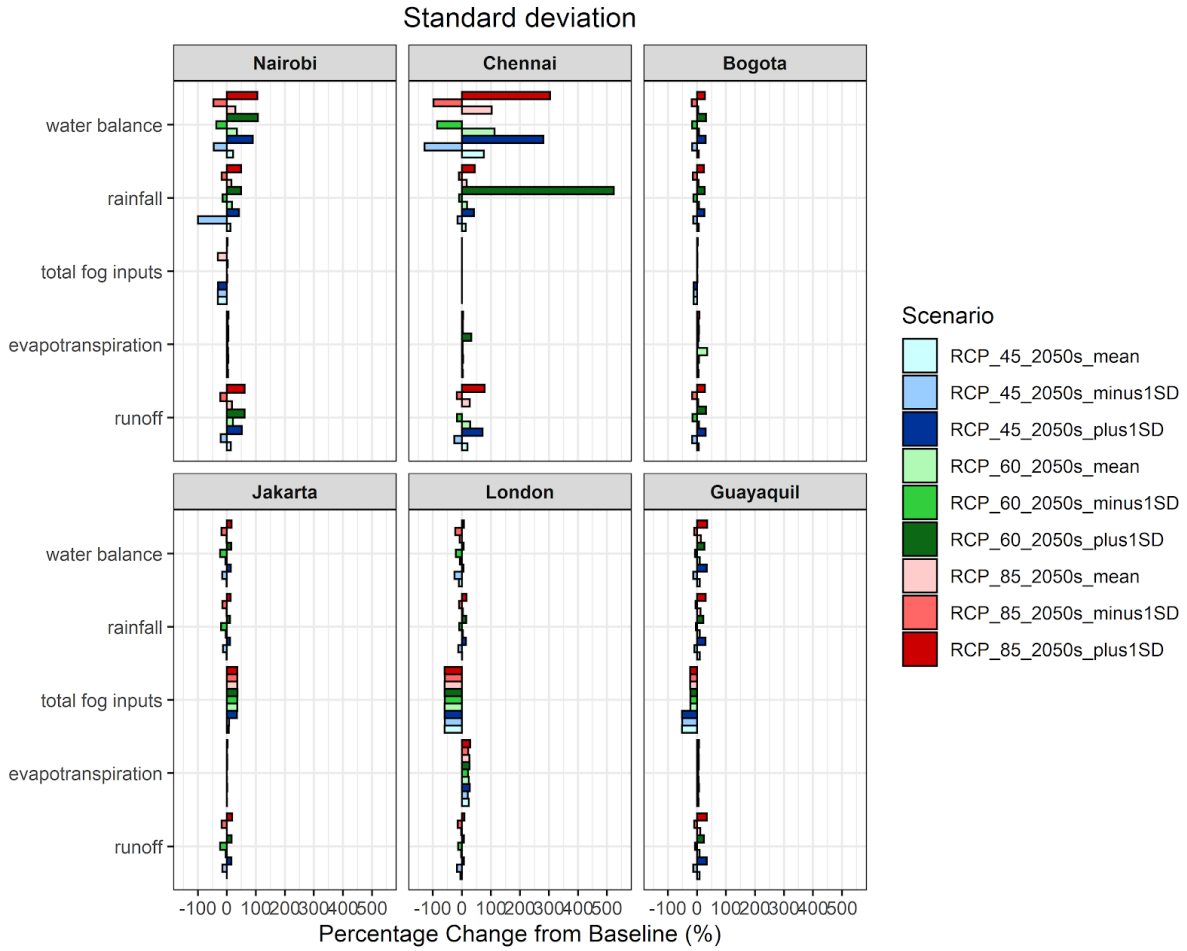


Figure D3. The influence of plus or minus 1 standard deviation on the percent change difference for the annual water balance variables as a result of different climate change scenarios.

D3. Seasonal impacts on rainfall and water balance

Seasonal rainfall

Although water balance shows how overall water availability changes with climate scenarios, examining differences in seasonal rainfall may give a sense of “seen & felt” impacts that could translate into the potential for flooding. Figure C4 shows the seasonal change in rainfall means for each of the upstream city basins compared to the RCP scenarios. Figure C5 shows the seasonal percent change difference (pcd) for rainfall for each of the upstream city basins compared to the RCP scenarios.

Seasonal rainfall means for Nairobi show an increase in rainfall compared to the baseline mean for DJF, MAM and SON seasons, and a slight decrease for JJA.

Chennai shows almost similar rainfall means between baseline and scenario for the DJF and MAM seasons but increases in scenario means for the JJA and SON months.

Bogotá shows almost similar rainfall means between baseline and scenario results for all the seasons (with slight increase for DJF and MAM). Jakarta shows decreases in rainfall means for MAM (slight), JJA and SON, and very similar rainfall means for DJF. London shows almost no difference between baseline and scenario rainfall means, except for RCP85 2070s

in JJA and RCP45 2070s in SON. Guayaquil shows an increase in rainfall means for DJF and MAM seasons and almost no difference between baseline and scenario means for JJA and SON.

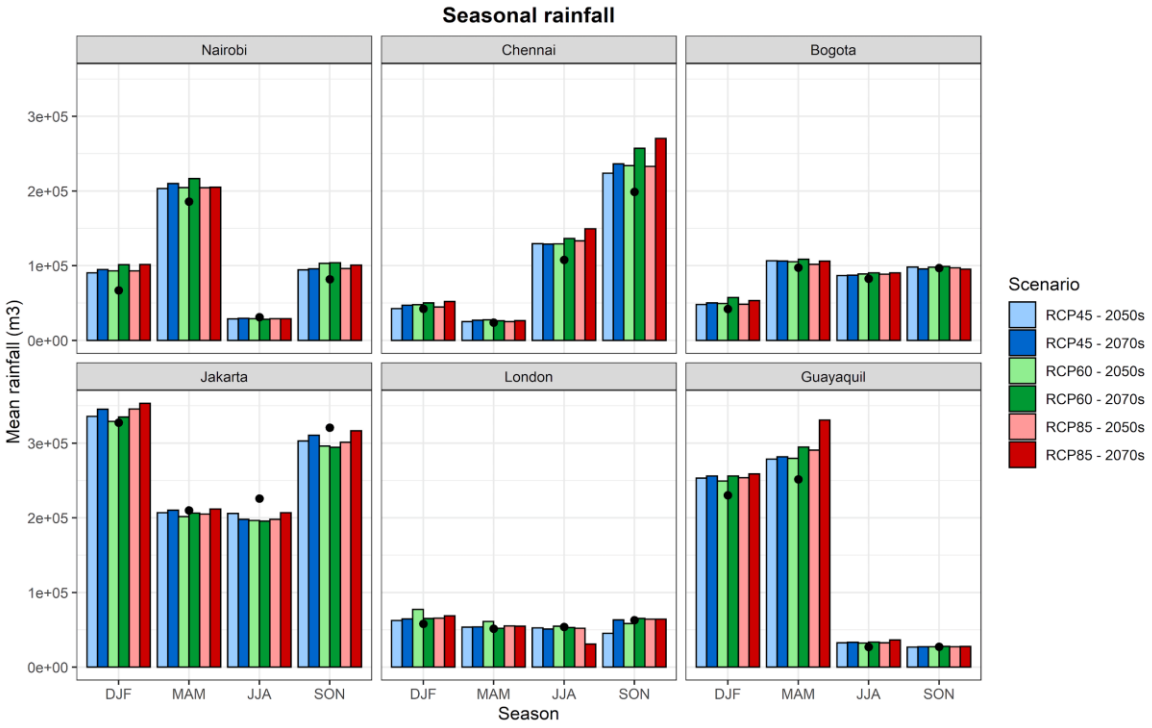


Figure D4 Seasonal impacts of climate scenarios on mean rainfall (m3) for the six upstream city basins. The baseline mean is represented by the black dot. RCP_45_2050s denotes RCP 4.5 for the 2050s time slice, and so forth.

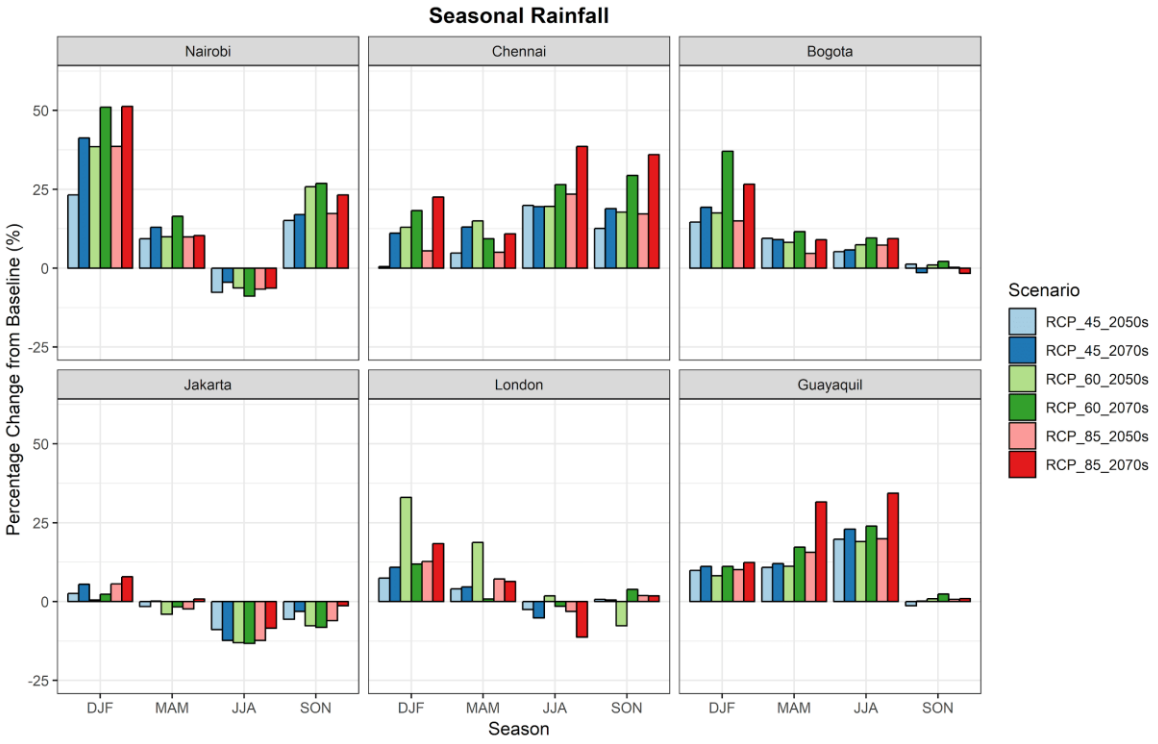


Figure D5 Seasonal impacts of climate scenarios on rainfall, shown by percent change difference, for the six upstream city basins.

Examining the pcd provides an indication of the relative change in values. The Nairobi basin has positive pcds for DJF, MAM and SON, with the greatest increase in the DJF season, but for JJA, seasonal rainfall declines (Fig. C.3).

Chennai shows positive pcds for all seasons and all scenarios bar almost no change for RCP45 2050s in DJF.

Bogotá shows positive pcds for all seasons except SON, where RCP45 2070s and RCP85 2070s show declines in rainfall.

Jakarta shows negative pcds for three of the seasons, MAM, JJA and SON, except for the RCP85 2070s scenario in the MAM season displaying a very small increase of 0.83%. The DJF season shows an increase in pcds for all scenarios.

London shows an increase in pcds for seasonal rainfall for the DJF and MAM seasons and mixed results for the JJA and SON months: in JJA the pcds are negative except for the RCP60 2050s scenario; and in SON the pcds are slightly positive except for the RCP60 2050s scenario.

Guayaquil shows positive rainfall pcds for all seasons and RCPs except for the SON season where the pcd increase is marginally positive for all the RCPs except for RCP45 2050s, which is marginally negative.

Seasonal water balance

Figure C6 shows the seasonal change in water balance means (m^3) for each of the upstream city basins compared to the RCP scenarios. Figure C.5 shows the seasonal percent change difference (pcd) for water balance for each of the upstream city basins compared to the RCP scenarios.

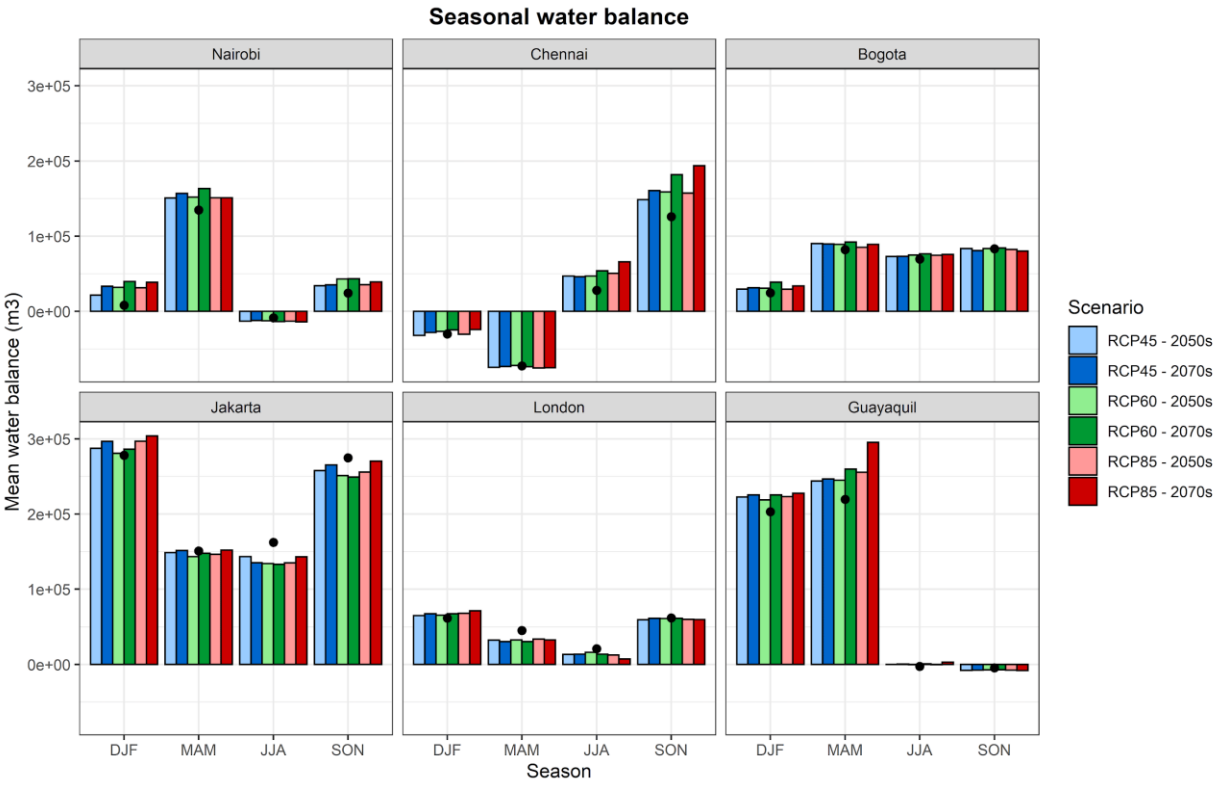


Figure D6 Seasonal impact of climate projections on mean water balance (m3) for the six upstream city basins. Black dot represents the baseline mean.

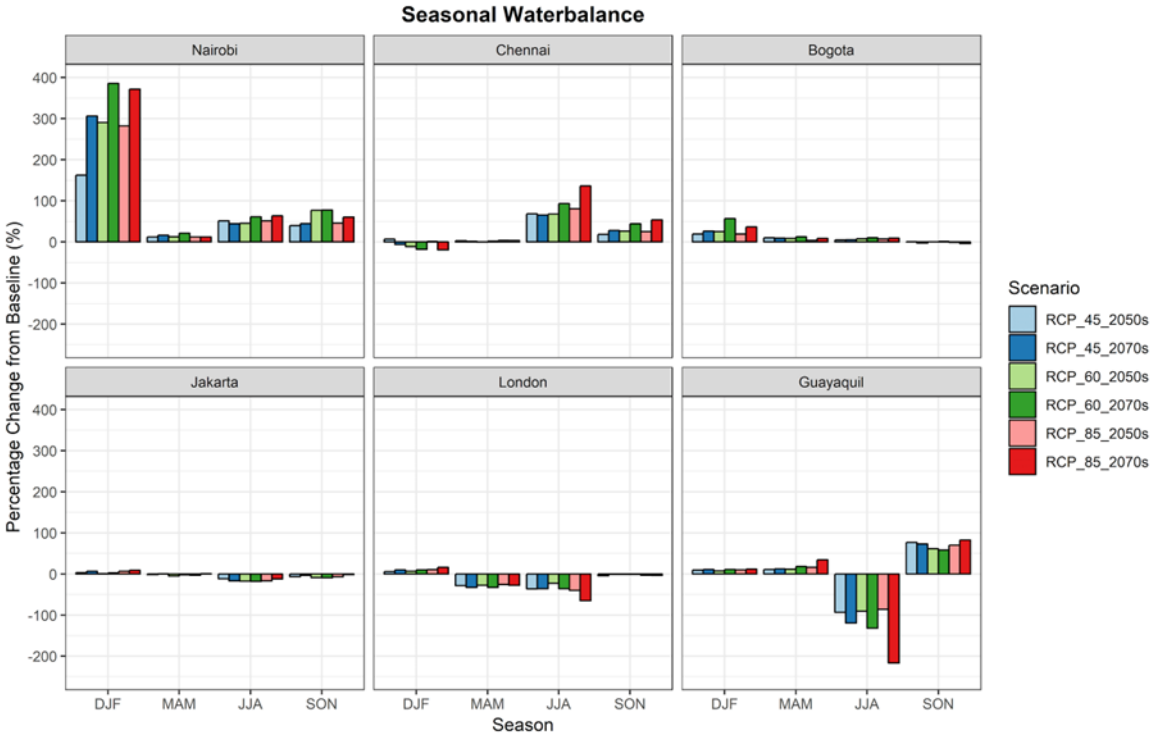


Figure D7 Seasonal impacts of climate scenarios on mean water balance, shown by percent change difference, for the six upstream city basins.

The increase or decrease in absolute mean water balance for different seasons may be different to the seasons showing the greatest pcd (Fig. C6). For instance, in the Chennai basin, the months of SON have the highest water balance, but JJA showed the greatest percentage change increase. For the Nairobi upstream basin, the scenario water balance means are greater than the baseline means for all seasons except JJA, where they are negative. For the Chennai upstream basin, water balance is negative (for baseline and scenario means) for half the year (DJF and MAM months). A negative water balance means that evapotranspiration is supported by drawdown of soil and surface stores of water. The baseline means are almost equal to the scenario means for DJF and MAM seasons (negative water balance). The scenario means are greater than the baseline for JJA and SON. For the Bogotá upstream basin, baseline means are very similar to scenario means for all seasons, with a slight increase In the RCP60 2070s scenario. In the Jakarta upstream basin, baseline means are similar to scenario means for DJF and MAM but scenario means are below the baseline for JJA and SON. In the London upstream basin, baseline means are close to scenario means for DJF and SON but scenario means are below baseline for MAM and JJA seasons. In the Guayaquil upstream basin, scenario means are greater than baseline means for DJF and MAM but similar for JJA and SON months (Fig. C.4).

In terms of percentage change difference (pcd), Nairobi shows positive increases for all seasons and all RCPs, with the greatest increase in the months of December, January and February (DJF) (its summer) with an increase of 162 to 385% in water balance compared to baseline conditions (Fig. C7). Chennai's largest increase in water balance was for the months of June, July and August (JJA), followed by September, October and November (SON). There is a projected decrease in water balance for the months of DJF for four of the RCPs. Bogotá's largest increase in water balance is in DJF, with slight increases for MAM and JJA. The SON months are mixed, showing a slight (1%) increase to slight decrease (-3.95%) depending on the RCP. Jakarta shows decreases in projected water balance for all

seasons except DJF which has a very slight increase of between +0.39% to +9.23%. The London upstream basin also has decreases in water balance for all seasons except DJF, from +5 to +16%. Guayaquil shows the highest increase in projected water balance for the SON months, followed by MAM and DJF. However, the JJA months show a large decrease (-93 to -216%) in projected water balance (Fig. C7).

From Discussion:

Of interest for these two basins is that although the annual pattern shows an overall decrease, there is variability at the seasonal scale. From a flooding perspective, seasonality is important given the significance of antecedent conditions. For instance, an increase in rainfall at the end of the wet season is potentially more problematic than at the end of the dry season because NI stores are already full. In the Jakarta basin, although rainfall and water balance declined compared to baseline on an annual scale, the seasonal analysis shows that there is an increase compared to baseline in the DJF season, which coincides with the region's monsoon season. In the London basin, rainfall increases most months for the majority of scenarios but declines in the JJA months, which is the region's summer. This is consistent with other studies which predict wetter winters and drier summers for the UK generally, and for the Thames basin specifically (Environment Agency, 2009).

The Nairobi basin showed an overall increase in rainfall and water balance on an annual scale, but the seasonal view revealed rainfall declines in the JJA months compared to baseline. As JJA is Kenya's relatively cool and dry season, this indicates that the dry season will be getting drier, whilst the wet seasons will be getting wetter.

There is no projected decrease in seasonal rainfall for Chennai or Guayaquil. Seasonal increases in rainfall, mostly translated to seasonal projected increases in water balance, but not always. In Chennai, rainfall increases in all the seasons, but water balance decreases in DJF months and is only slightly positive in the MAM months. In Guayaquil, the SON months had the lowest increases in rainfall, but it is the JJA months that display decreases in water balance. JJA coincides with the dry winter season in Ecuador. Declines in water balance that are not matched to declines in rainfall may be due to increased rates of evapotranspiration resulting from increased warming and/or increases in vegetation cover in those months.

D4. Summary of city basin FRR changes for close-to-city points

To determine the existing versus projected ability of the city natural infrastructure to cope with the changes in flood risk, I collated the values for the sampling points that occur on the city-basin boundaries (multiple points represent different river entry points into the city) for the different scenarios, comparing the scenario value to the change from baseline (pcd) in Table D1.

Looking at the differences between the scenario means (a) and the pcd means (b) in Table D1 illustrates how the flood risk ratios in some basins can be relatively small but represent a big change (in terms of percent change difference).

For the Bogotá points, the mean values are not above one (low flood risk) so technically they should still have enough capacity to cope with the increases in FRR. The biggest increase is under RCP 6.0 for the 2070s. Next highest is RCP 6.0 2070s and RCP 8.5 2070s which are identical, as are values for RCP 4.5 for 2050s and 2070s. RCP 8.5 2050s had the lowest values.

In the Jakarta upstream basin, there are eight rivers that enter the city from the study basin. The scenario means for these sampling points range from 9.26 to 10 (Storage to Total Capacity flood risk ratios). For the majority of the scenarios, the change is negative, indicating a decrease in flood risk ratio compared to baseline conditions. The exception is under RCP 8.5 for the 2070s, with a mean pcd of 2.53.

In the London basin, there are four rivers that enter the city from the study basin. For the sampling points on these rivers, even though the mean values are slightly above one, the values decrease compared to the baseline values.

In the Guayaquil basin, three rivers enter the city from the study basin. The scenario means for these sampling points were all under one, ranging from 0.13 to 0.17, indicating low flood risk. However, the change from baseline is high, ranging from 36 to 85 mean pcd. Scenario RCP 8.5 2070s is the scenario causing the biggest change in flood risk ratios.

Table D1 Comparing points (min, max and mean) closest to the city-basin boundary by climate scenario for a) FRR scenario sum (%; mean highlighted pink), and b) percent change difference (%; mean highlighted purple), from baseline.

			City upstream basin					
Scenario			**Nairobi (N1-N4)**	**Chennai (C1-C2)**	**Bogota (B1)**	**Jakarta (J1-J8)**	**London (L1-L4)**	**Guayaquil (G1-G3)**
4.5_2050s	a	min	0.15	0.76		1.43	0.41	0.02
		max	4.95	29		19.02	3.67	0.32
		mean	2.27	14.88	0.51	9.6	1.48	0.13
	b	min	8.07	20.83		-3.93	-12.41	20.01
		max	82.25	26.67		-1.26	-2.61	48.32
		mean	39.25	32.92	6.25	-2.76	-7.57	36.35
4.5_2070s	a	min	0.23	0.82		1.44	0.41	0.02
		max	5.49	31		19.21	3.75	0.34
		mean	2.7	15.91	0.51	9.7	1.52	0.14
	b	min	28.07	29.17		-2.97	-10.41	26.79
		max	182.25	36.67		0.07	-0.42	61.18
		mean	85.39	32.92	6.25	-1.8	-5.45	46.16
6.0_2050s	a	min	0.24	0.82		1.37	0.42	0.02
		max	5.51	31		18.28	3.79	0.32
		mean	2.72	15.91	0.52	9.26	1.53	0.13
	b	min	28.69	29.17		-7.67	-9.42	21.74
		max	191.6	36.67		-5.23	0.49	53.34
		mean	88.7	32.92	8.33	-6.78	-4.69	39.73
6.0_2070s	a	min	0.3	0.94		1.4	0.41	0.02
		max	5.97	35		18.66	3.72	0.35
		mean	3.07	19.97	0.55	9.46	1.5	0.14
	b	min	39.43	45.83		-5.75	-11.33	32.06
		max	264.5	56.67		-3.25	-1.28	71.32
		mean	123.81	51.25	14.58	-4.72	-6.35	53.99
8.5_2050s	a	min	0.2	0.81		1.43	0.41	0.02
		max	5.29	31		19.11	3.75	0.36
		mean	2.54	15.91	0.5	9.69	1.52	0.14
	b	min	20	29.17		-3.59	-10.41	34.2
		max	143	35		-0.59	-0.42	75.87
		mean	67.67	32.09	4.17	-2.35	-5.45	57.29
8.5_2070s	a	min	0.23	1		1.51	0.41	0.03
		max	5.55	38		20.01	3.7	0.41
		mean	2.74	28.75	0.52	10.16	1.5	0.17
	b	min	29.13	58.33		1.07	-12.23	54.4
		max	179.45	66.67		4.71	-1.88	111.89
		mean	86.36	62.5	8.33	2.53	-6.9	85.5

D5. Testing the correlation between distance to city boundary and mean pcd of flood risk ratios from climate scenarios

Table D2 to D7 comprise Spearman's Rank Correlation data tables and calculated Spearman rank coefficient (Rs) to test correlation between distance from city boundary and mean pcd (%) for river sampling points in each basin.

Table D2. Nairobi

Point	Distance (km)	Rank dist	Mean pcd (%)	Rank pcd	Difference between ranks (d)	d2	
N1	0	8	99.4	2	6	36	
N3	0.25	7	27.5	5	2	4	
N4	0.5	6	26.7	6	0	0	
N2	0.98	5	174	1	4	16	
N7	15.2	4	50.2	3	1	1	
N6	18.25	3	29.7	4	-1	1	
N5	19.95	2	25.2	8	-6	36	
N8	28.3	1	25.7	7	-6	36	
						130	sum of d2
						-0.55	**Rs**

Table D3. Chennai

Point	Distance (km)	Rank dist	Mean pcd	Rank pcd	Difference between ranks (d)	d2	
C1	0.18	7	35.4	7	0	0	
C2	0.6	6	43.1	6	0	0	
C4	16.9	5	60.2	4	1	1	
C5	20.7	4	59.6	5	-1	1	
C3	22	3	66.7	3	0	0	
C6	42.4	2	84.5	2	0	0	
C7	57.1	1	88.5	1	0	0	
						2	sum of d2
						0.96	**Rs**

Table D4. Jakarta

Point	Distance (km)	Rank dist	Mean pcd	Rank pcd	Difference between ranks (d)	d2	
J3	0.6	16	-2.45	8	8	64	
J8	0.8	15	-0.93	3	12	144	
J4	1	14	-2.48	9	5	25	
J2	1.5	13	-3.59	13	0	0	
J1	1.8	12	-2.32	7	5	25	
J6	2.5	11	-2.69	10	1	1	
J5	2.6	10	-3.79	14	-4	16	
J7	3.4	9	-2.95	11	-2	4	
J11	21.2	8	0.215	2	6	36	
J16	31.6	7	-1.2	5	2	4	
J14	37.4	6	-3.97	15	-9	81	
J10	41.1	5	-2.2	6	-1	1	
J15	41.3	4	-0.233	4	0	0	
J9	44.7	3	-3.33	12	-9	81	
J13	47.1	2	3.06	1	1	1	
J12	54.2	1	-4.29	16	-15	225	
						708	sum of d2
						-0.04	**Rs**

Table D5. Bogotá

Point	Distance (km)	Rank dist	Mean pcd	Rank pcd	Difference between ranks (d)	d2	
B1	1	3	7.98	2	1	1	
B2	29.6	2	6.31	3	-1	1	
B4	69.2	1	27.5	1	0	0	
						2	sum of d2
						0.5	**Rs**

Table D6. London

Point	Distance (km)	Rank dist	Mean pcd	Rank pcd	Difference between ranks (d)	d2	
L2	0.8	19	-6.83	9	10	100	
L4	1.3	18	-1.02	1	17	289	
L1	1.5	17	-5.51	5	12	144	
L3	1.5	16	-11	17	-1	1	
L5	28.3	15	-6.43	7	8	64	
L19	33.2	14	-5.4	4	10	100	
L10	47.8	13	-6.98	10	3	9	
L8	49.3	12	-9.12	12	0	0	
L18	52.1	11	-9.53	15	-4	16	
L9	58	10	-5.66	6	4	16	
L6	69.3	9	-13.4	19	-10	100	
L7	115.2	8	-5.29	3	5	25	
L11	161.9	7	-12.6	18	-11	121	
L12	177	6	-9.15	13	-7	49	
L13	179.3	5	-5.02	2	3	9	
L14	210.4	4	-9.34	14	-10	100	
L15	213.2	3	-10.7	16	-13	169	
L17	223.7	2	-8.3	11	-9	81	
L16	240.4	1	-6.63	8	-7	49	
						1442	sum of d2
						-0.26	**Rs**

Table D7. Guayaquil

Point	Distance (km)	Rank dist	Mean pcd	Rank pcd	Difference between ranks (d)	d2	
G1	0.7	18	70.3	1	17	289	
G2	6	17	57.7	3	14	196	
G3	25.7	16	31.5	4	12	144	
G5	42.3	15	21.1	8	7	49	
G6	58.2	14	66.4	2	12	144	
G13	97.9	13	6.55	17	-4	16	
G4	124.1	12	21.6	7	5	25	
G7	153.5	11	29.4	5	6	36	
G9	187.7	10	23.2	6	4	16	
G12	205.3	9	8.37	15	-6	36	
G10	230.2	8	17.3	10	-2	4	
G16	234.2	7	16.4	11	-4	16	
G17	267.8	6	11.2	14	-8	64	
G11	268.7	5	6.34	18	-13	169	
G15	274.5	4	19.2	9	-5	25	
G8	279.5	3	14.2	13	-10	100	
G14	291.4	2	17.2	11	-9	81	
G18	307.7	1	7.96	16	-15	225	
						1635	sum of d2

-0.69 Rs

D6. Spatially distributed changes in FRR

Tables D8 to D13 summarise the findings in Figures 4.15 to 4.20 in Chapter 4.

Table D8. Summary of the changes observed in Figure 4.15 for the Nairobi basin.

Parameter	Summary
Scenario mean (panel a)	Range: 0.025% to 43.77%, median of +3.15%. 91.9% of values are >1 and thus high-risk; 8% are < one, and thus low risk.
Mean difference from baseline (panel b)	Range is -3.94% to +34.8%, median is 0.34%. 25.8% had zero mean difference from the baseline, i.e., no change. 47.1% of cells > zero, showing an increase compared to baseline, 27.1% were < zero, indicating a decrease compared to baseline
Number of scenarios > 10 percent of baseline FRR (panel c)	Most of the basin area is showing increases in flood risk ratios. The basin has fairly even topography, so areas of increase, or lack thereof, are not tending to hillslopes in particular (see Figure C2 below). However, although patchy, the cells of no increase (of more than 10% of baseline) are loosely following the river lines and appear to be not built-up.
NI Storage where more than three scenarios greater than 10 percent of baseline (panel d)	soil storage was the greatest with 60.3% of the eligible cells, followed by canopy, with 33.4%, then floodplains with 6% and wetlands only 0.2%. There was no waterbody storage. Although the soil storage is dispersed through the middle of the basin, the canopy storage is concentrated in the top, north-east part of the basin. Floodplain storage is scattered throughout.
Number of scenarios where high-risk increases (panel e)	31.8% of grid cells have zero cells where high-risk status increases; 62.8% have all six scenarios showing an increase in high-risk cells, followed by 3.16% with 5 scenarios, 0.9% with four scenarios, none have three scenarios, 0.68% with two scenarios, 3.6% with only one scenario where high-risk increases.
NI Storage where more than three scenarios show high-risk increasing (panel f)	soil storage was the greatest with 32.1% of the eligible cells, followed by canopy, with 24%, then floodplains with 0.6% and wetlands only 0.2%. There was no waterbody storage. NAs were 43%.
Number of scenarios where low risk becomes high-risk (panel g)	very few cells, only 22 out of 520, showed low risk in the baseline becoming high-risk in the climate scenario, and this was true for all six scenarios.
NI Storage where more than three scenarios show low risk becoming high-risk (panel h)	only 12 cells fit the criteria of showing LR becoming HR for more than three scenarios. 10 cells were for floodplain NI storage and two were for soil NI storage.

Below are Google Earth images of study basins where high risk flood risk ratios increase by more than 10% of baseline.

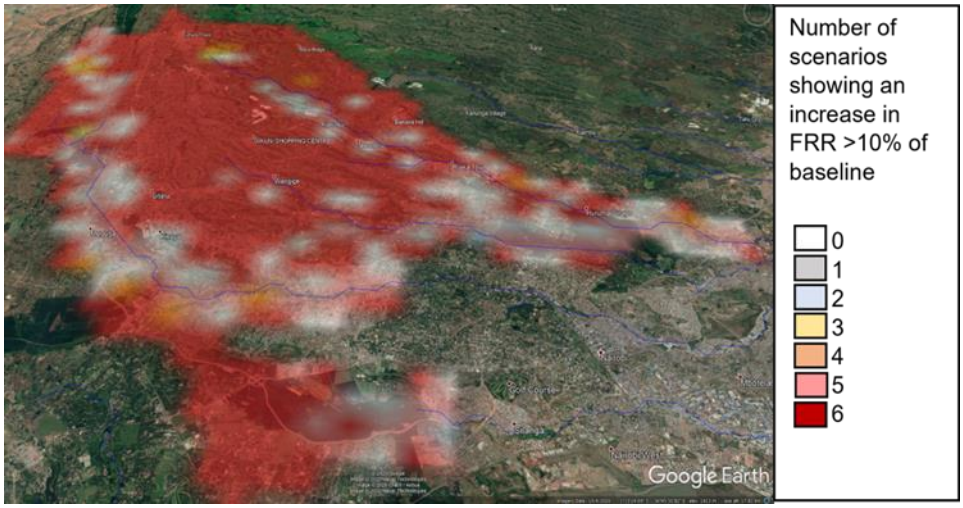


Figure D8. Number of scenarios where high risk FRR increase by more than 10% of baseline in Nairobi basin.

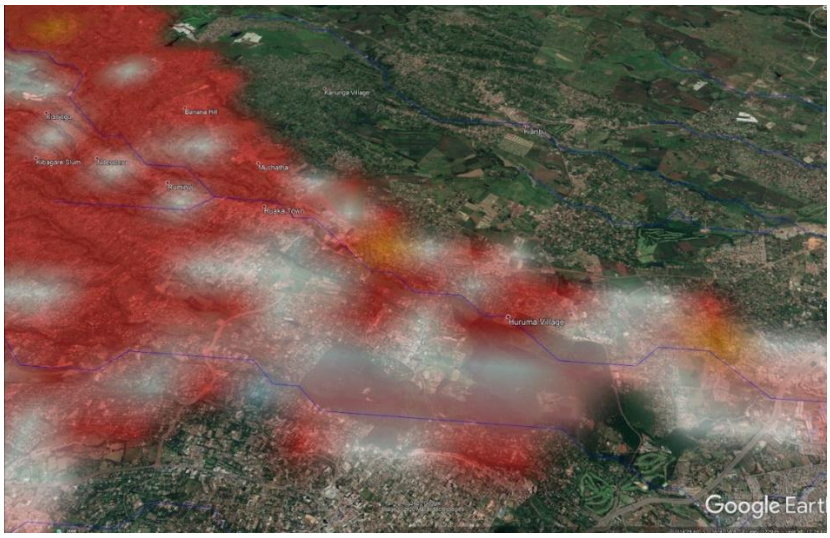


Figure D9. Number of scenarios where high risk FRR increase by more than 10% of baseline in Nairobi basin.

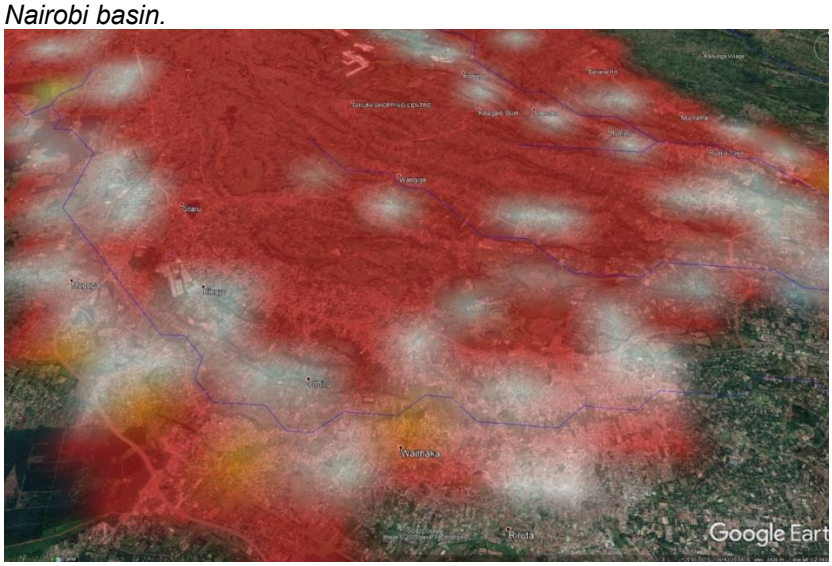


Figure C10. Number of scenarios where high risk FRR increase by more than 10% of baseline in Nairobi basin.

Table D9. Summary of the changes observed in Figure 4.16 for the Chennai basin.

Parameter	Summary
Scenario mean (panel a)	range is from minimum of 0.0006% to maximum of 50% FRR, median of +0.94. 45.5% of values are greater than one (high-risk FRR) and 54.5% are less than one (low risk FRR).
Mean difference from baseline (panel b)	range is from minimum of -0.02% FRR to maximum of +10.9% FRR, median of +0.22. 70.6% of cells had zero mean difference from the baseline, i.e., no change. 26% of cells increased by a value of one; 2.5% increased by values between two and eight; 1.2% of cells increased by a value of between nine and 11. Zero cells had values less than zero, indicating there were no decreases compared to baseline, i.e., all scenarios either stayed the same or increased compared to baseline.
Number of scenarios > 10 percent of baseline FRR (panel c)	74.4% of the grid cells show all six climate scenarios increasing more than 10 percent of the baseline values, 0.27% increase in five scenarios, 0.14% increase in four scenarios, no increase in three scenarios, 8.2% increase in two scenarios, 5.2% increase in one scenario. In this basin, almost all the area shows an increase in flood risk ratios, with small, isolated pockets showing no increase. Looking at these areas overlaid on Google Earth imagery (Fig. C3) shows no discernible pattern to areas of no increase; they occur on both built-up and open land. However, areas showing an increase in all six scenarios certainly follow river lines.
NI Storage where more than three scenarios greater than 10 percent of baseline (panel d)	soil storage is the greatest with 54.2% of the eligible cells, followed by floodplain storage with 38.2%, then canopy with 4.39%, waterbodies 2% and wetlands the least at 1.2%.
Number of scenarios where high-risk increases (panel e)	544 cells out of 1459 (37.2%), excluding NA cells, showed high-risk increases for all six climate scenarios.
NI Storage where more than three scenarios show high-risk increasing (panel f)	soil storage is the greatest with 81.4%, followed by floodplain storage at 9%, canopy at 7.35%, wetlands at 1.3% and waterbodies at 0.9%.
Number of scenarios where low risk becomes high-risk (panel g)	256 cells out of 1459 (17.5%) showed low risk becoming high-risk.
NI Storage where more than three scenarios show low risk becoming high-risk (panel h)	only 85 cells fit the criteria of showing LR becoming HR for more than three scenarios. 48 cells were floodplain NI storage, 35 were soil NI storage, one cell was waterbody storage, and one cell wetland NI storage. Zero cells were canopy storage.

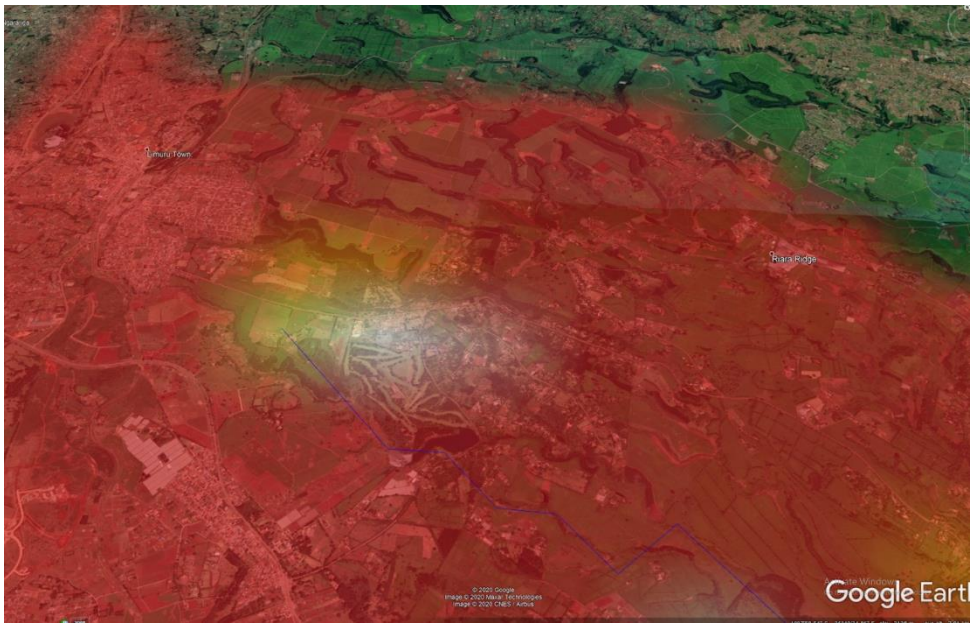


Figure D11. Number of scenarios where high risk FRR increase by more than 10% of baseline in Chennai Basin.

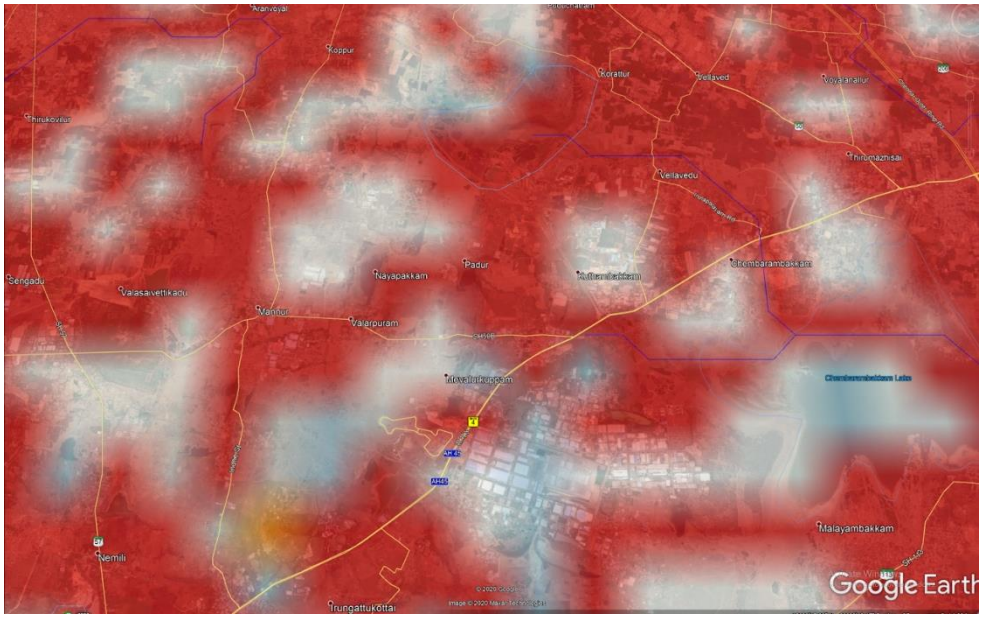


Figure D12. Number of scenarios where high risk FRR increase by more than 10% of baseline in Chennai Basin.

Table D10. Summary of the changes observed in Figure 4.17 for the Jakarta basin.

Parameter	Summary
Scenario mean (panel a)	range is from a minimum of 0.46% FRR to maximum of 120.36% FRR, median of +4.02. 99.2% of values are greater than one, i.e., signifying high-risk flood ratio. 0.8% are less than one, so low risk ratios. Scenario values are mostly/majority high-risk but there is very little change compared to baseline, only 9% decreasing and only 1.7% increasing.
Mean difference from baseline (panel b)	range is from minimum of -6.3 to maximum of +4.2, median of -0.06. Most cells, 89.3%, had zero mean difference from the baseline, i.e., no change. 9% of cells decreased by between one and six. Only 1.7% increased by between one and four compared to baseline.
Number of scenarios > 10 percent of baseline FRR (panel c)	2524 cells out of 2742 (92%), showed zero cells with an increase greater than 10 percent of baseline. 7.95% of cells showed greater than 10 percent increase; 5.5% for one scenario and 2.4% of cells showed greater than 10 percent increase for two to six scenarios. The areas showing increases of more than 10% are in the upland areas at the top of the basin, specifically on the sides of the volcanoes in the south, or small foothills on the east.
NI Storage where more than three scenarios greater than 10 percent of baseline (panel d)	only 50 cells have more than three scenarios greater than 10 percent of baseline. 43 cells (86%) are for canopy NI storage and seven cells (14%) are for soil NI storage. If all six scenarios showing an increase of greater than 10 percent are incorporated, then 218 cells are eligible with 78.4% from canopy NI storage, followed by 19.3% from soil NI storage, 1.4% from floodplain NI storage, 0.9% from wetland storage, and zero for waterbody storage.
Number of scenarios where high-risk increases (panel e)	65% of total cells showed high-risk increasing. Of those, 48.7% have high-risk increasing for only one scenario and 40.7% of cells show high-risk increases in the remaining two to six scenarios (14.3% for all six scenarios). In the Google Earth imagery, it shows that areas where high-risk (FRR >1) increases occur under the most climate scenarios (four to six) in the upland areas, on the slopes and foothills of the volcanoes near the basin boundary. There are also increases for high-risk FRR under four scenarios (orange) in the upper reaches of these upland rivers (see Fig. C_ in Appendix C below).
NI Storage where more than three scenarios show high-risk increasing (panel f)	Of the eligible cells (22.6%), 75.7% are canopy NI storage, 22.1% are soil NI storage, 2% floodplain storage and 0.2% wetland storage. There is no waterbody storage that meets the criteria.
Number of scenarios where low risk becomes high-risk (panel g)	there are no cells where low risk becomes high-risk under any scenario.

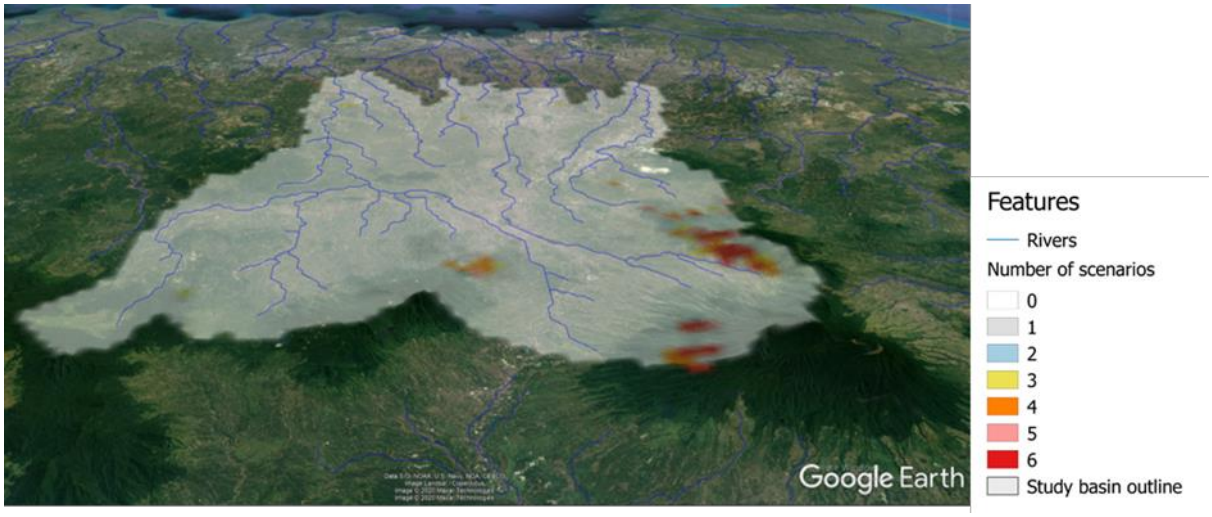


Figure D13. Google Earth image of the upstream basin of Jakarta showing the number of scenarios where high risk FRR increase by more than 10% of baseline.

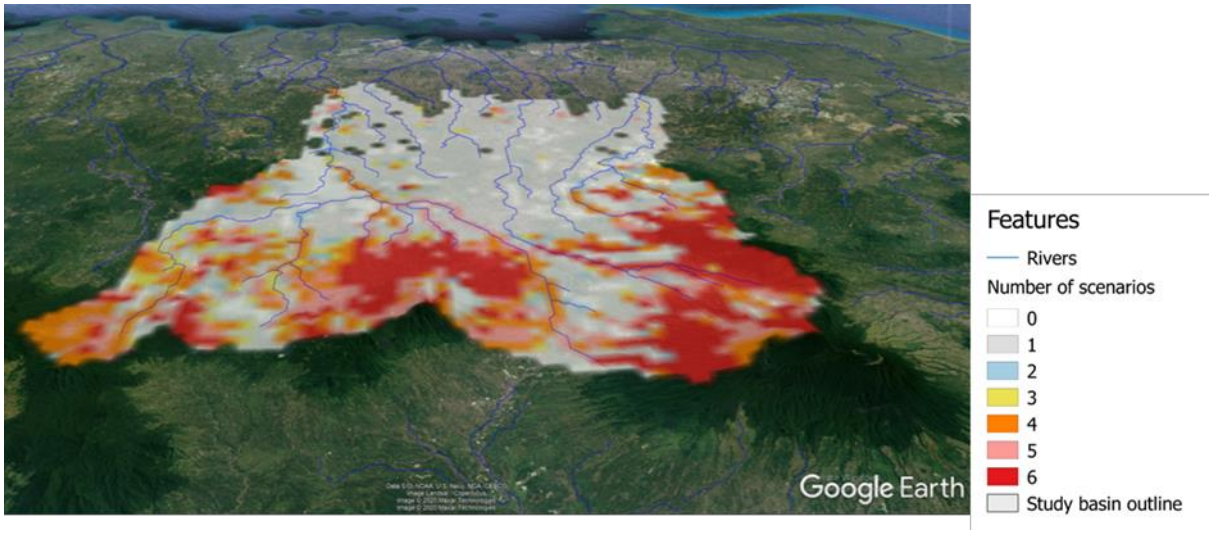


Figure D14. Google Earth image of the upstream basin of Jakarta showing the number of scenarios where high-risk increases.

Table D11. Summary of the changes observed in Figure 4.18 for the Bogotá basin.

Parameter	Summary
Scenario mean (panel a)	range is from a minimum 0.02% to maximum of 12.8% FRR, median of +1.15. 61.8% of values are greater than one (high-risk FRR), 38.2% are less than one (low risk ratios).
Mean difference from baseline (panel b)	range is from min of -4.22 to max of 0.27, median of -0.43. 60.9% of cells had zero mean difference from the baseline, i.e., no change. 39.1% of cells had values less than zero, indicating a decrease compared to baseline. No cells were greater than zero, i.e., there is no mean increase in flood risk ratios.
Number of scenarios > 10 percent of baseline FRR (panel c)	1194 cells out of 2923 (40.8%), excluding NA cells, showed zero cells with an increase greater than 10 percent of baseline FRR. 34.2% of cells showed greater than 10 percent increase in FRR for one scenario and 24.9% of cells showed greater than 10 percent increase in FRR for two to six scenarios. There appear to be discrete pockets or clusters where all six scenarios show an increase of more than 10% FRR relative to baseline. These areas appear to be on hillslopes and elevated areas (see Fig. C5 below).
NI Storage where more than three scenarios greater than 10 percent of baseline (panel d)	92.5% of cells don't meet the criteria or are NA. Of the eligible cells, 65.8% are canopy NI storage, 30% are soil NI storage, with floodplain NI storage 2.2%, waterbody storage 1.7% and wetland NI storage 0.18%.
Number of scenarios where high-risk increases (panel e)	Two scenarios, RCP45 2050s and RCP85 2050s, did not have any cells where high-risk increases. Of the total cells, 29.5% showed high-risk increasing. Of those, 76.7% of cells had high-risk increasing for four scenarios, 3.02% for three scenarios, 1.45% for 2 scenarios and 8% for one scenario. 10.8% for zero.
NI Storage where more than three scenarios show high-risk increasing (panel f)	of the eligible cells, i.e. non-NA, 56.6% are canopy NI storage, 35.7% of cells are soil NI storage, 6.9% are floodplain NI storage, and 0.39% are waterbody and wetland NI storage.
Number of scenarios where low risk becomes high-risk (panel g)	Only 7.8% of all the cells in the basin showed low risk becoming high-risk in the climate scenarios. Of those, 19% showed it for four scenarios, 9.9% for only one scenario, 3.9% for three scenarios and 2.15% for two scenarios. 65% for zero scenarios. In Google Earth, the image combined with the river vectors show that the low risk to high-risk cells are coincident with some of the river lines, particularly the Bogotá river (figure not shown).
NI Storage where more than three scenarios show low risk becoming high-risk (panel h)	Of the eligible cells, 36.7% are floodplain NI storage, 35.8% are canopy NI storage, 25.5% are soil NI storage, and 0.94% are floodplain and wetland NI storage.

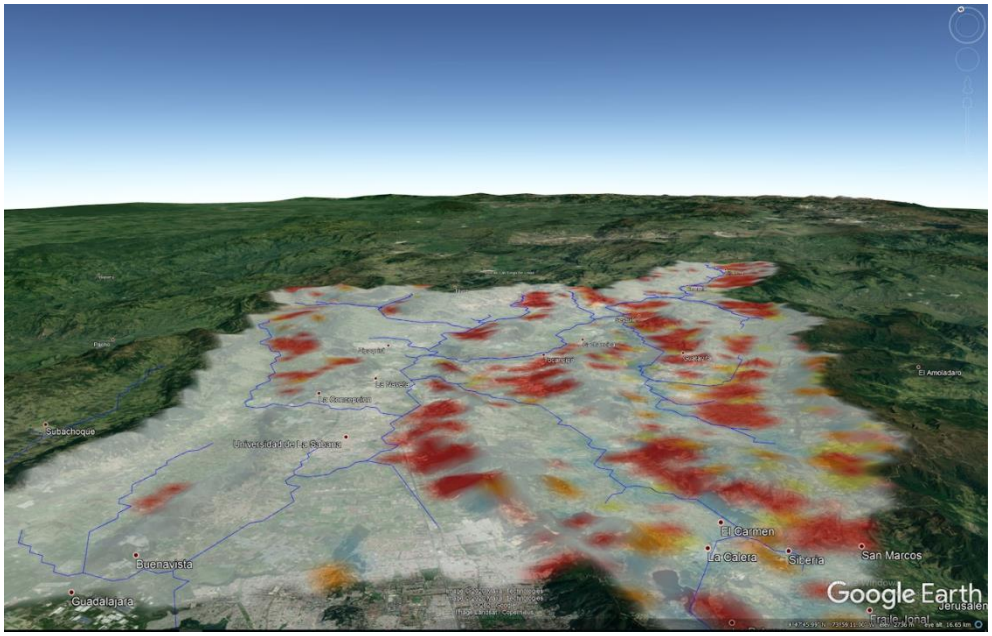


Fig. D15. Number of scenarios where high risk FRR increase by more than 10% of baseline in Bogotá basin.

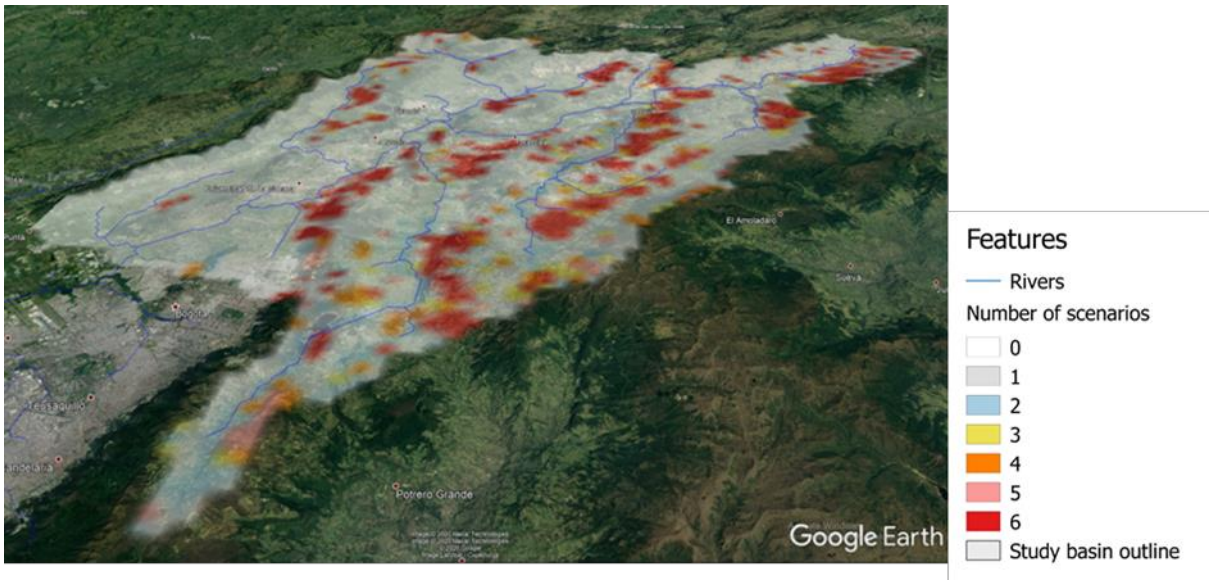


Figure D16. Google Earth image of the Bogotá upstream basin showing the number of scenarios with an increase greater than 10 percent of baseline.

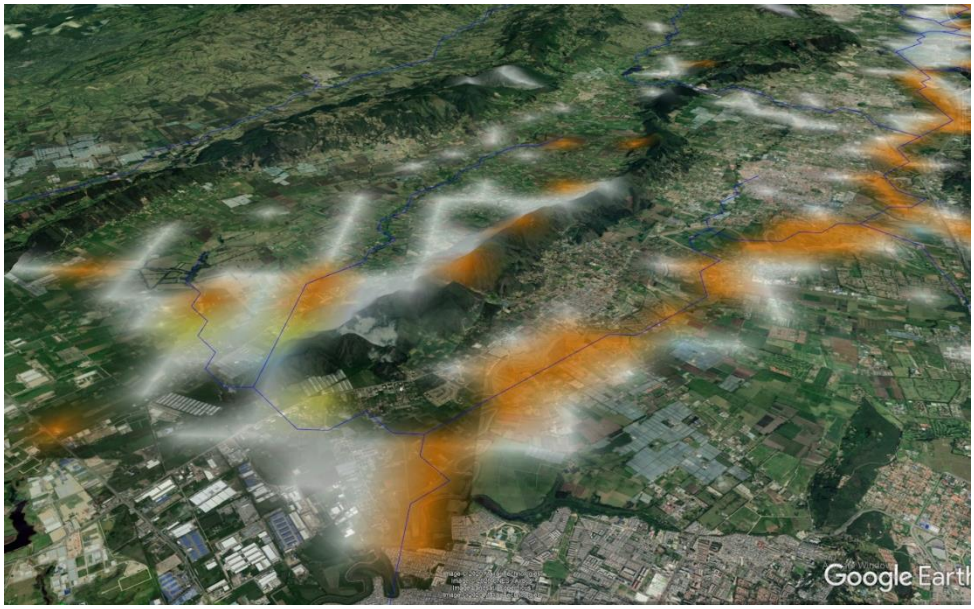


Figure D17. Number of scenarios in Bogotá basin where low risk becomes high risk.

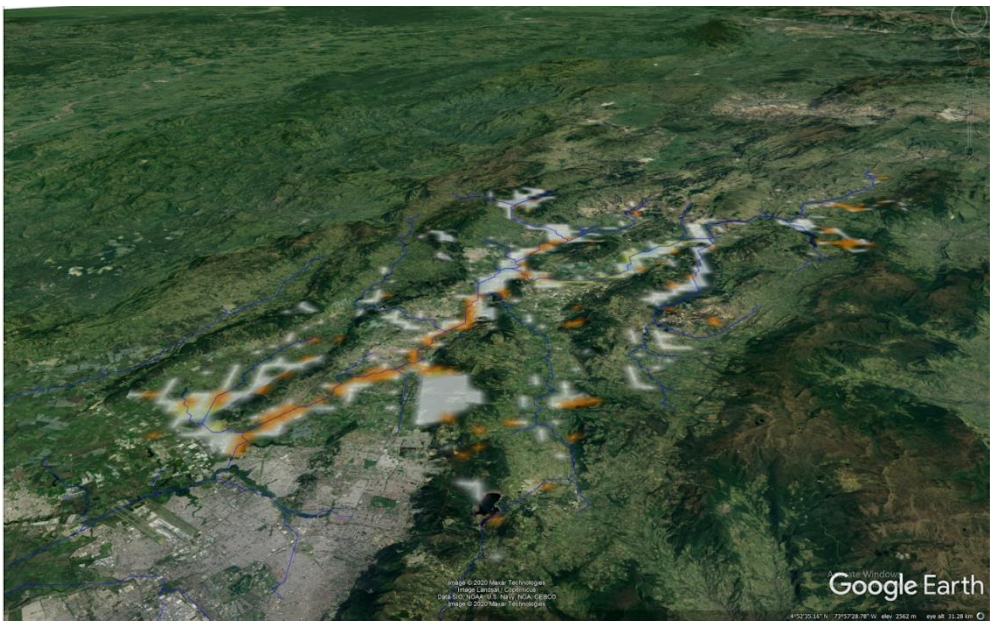


Figure D18. Number of scenarios Bogotá basin where low risk becomes high risk.

Table D12. Summary of the changes observed in Figure 4.19 for the London basin.

Parameter	Summary
Scenario mean (panel a)	range is from min of 0.022 to max of 11.5, median of 0.05. 17.2% of values are greater than one, meaning high-risk flood ratio; 82.8% are less than one, so low risk ratios.
Mean difference from baseline (panel b)	range is from min of -18.6 to max of +7.64, median of -0.28. 62.5% of cells had zero mean difference from the baseline, i.e. no change. Only 3.2% of cells, increased by a value of between one and 8. 34.2% of cells had values less than 0, indicating a decrease compared to baseline.
Number of scenarios > 10 percent of baseline FRR (panel c)	Only one cell had values greater than 10 percent of baseline in five scenarios (all except RCP 45 2050s). This cell is in the town of Luton just off the River Lea.
NI Storage where more than three scenarios greater than 10 percent of baseline (panel d)	The dominant NI storage in that grid cell is soil storage.
Number of scenarios where high-risk increases (panel e)	Only 6.7% of all cells have high-risk increasing in the scenarios. Of those eligible cells, 23.9% had high-risk increasing in all 6 scenarios. 0.9% of eligible cells had high-risk increasing for between one and four scenarios (no increases for five scenarios). 75% of eligible cells had a value of zero (no high-risk increase for any scenarios).
NI Storage where more than three scenarios show high-risk increasing (panel f)	of the eligible cells, i.e., non-NA, 68% are canopy NI storage, 30% of cells are soil NI storage, 0.88% are wetland NI storage. None are floodplain or waterbody NI storage.
Number of scenarios where low risk becomes high-risk (panel g)	Only 1.8% of total cells in the basin showed low risk becoming high-risk. Of those eligible cells, 88% had low risk becoming high-risk in all six scenarios.
NI Storage where more than three scenarios show low risk becoming high-risk (panel h)	Of the eligible cells, 61% are for canopy NI storage, 37.5% are for soil NI storage, 0.84% are wetland NI storage and floodplain NI storage makes up 0.56%. There is no waterbody storage.

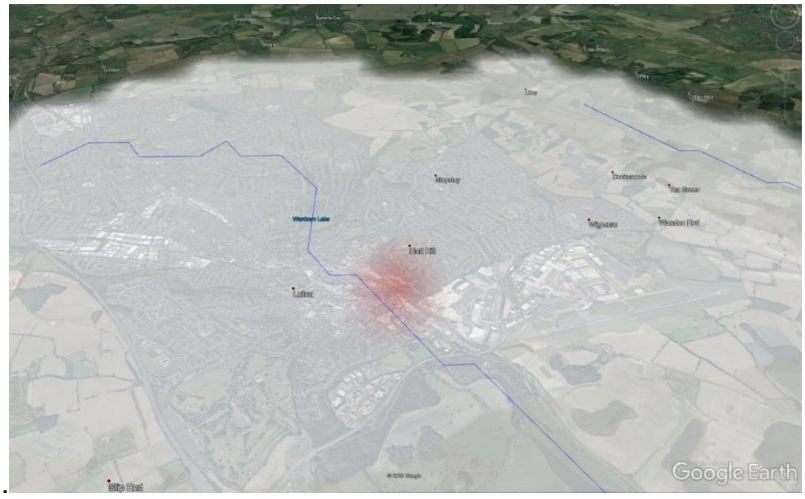


Figure D19. Number of scenarios where high risk FRR increase by more than 10% of baseline in London basin.

Table D13. Summary of the changes observed in Figure 4.20 for the Guayaquil basin.

Parameter	Summary
Scenario mean (panel a)	min +0.12, max +78.2, median +2.3. 95.3% of values range from one to 78, 4.68% are zero.
Mean difference from baseline (panel b)	range is from min of -62.6 to max of 20.5, median of -0.37. 33.7% of cells had zero mean difference from the baseline, i.e., no change. 19.6% of cells increased by a value of between one and 20. 46.7% had values less than zero, indicating a decrease compared to baseline.
Number of scenarios > 10 percent of baseline FRR (panel c)	42% of total cells showed an increase of 10 percent or more compared to baseline. Of those, 47.6% had increases under all six scenarios. 20.5% had increases for only one scenario. The remaining scenarios had increases in 5 - 8% of cells. Overlaying these areas of where high-risk FRR increase by more than 10 percent, onto Google Earth imagery (Fig. 4.21), highlights areas where there are: no increases, i) tracking river networks and, ii) a large N-S area in the Andean foothills and lower slopes; and areas of high-risk increasing by > 10%, i) for all six scenarios at the top of the high mountain areas, ii) for three scenarios tracking river networks.
NI Storage where more than three scenarios greater than 10 percent of baseline (panel d)	of the eligible cells, i.e., excluding NA's, 49.6% are canopy NI Storage, 25.4 % are soil NI storage, 20.5% of cells are floodplain NI storage, 3.1% are waterbody and 1.4% are wetland NI storage.
Number of scenarios where high-risk increases (panel e)	23.5% of total cells show high-risk cells increasing in risk. Of those eligible cells, 79.7% showed high-risk increasing for all 6 scenarios. 12.3% show high-risk increasing for only one scenario. Between 0.04% and 2.9% of cells show high-risk increasing for two to five scenarios.
NI Storage where more than three scenarios show high-risk increasing (panel f)	of the eligible cells, 50.2% are canopy NI storage, 28.5% are soil NI storage and 18.4% are floodplain NI storage. Waterbody NI storage accounts for 1.7% of cells and wetland NI storage accounts for 1.2% of eligible cells.
Number of scenarios where low risk becomes high-risk (panel g)	Only 1.65% of total cells show low risk cells becoming high-risk in the scenarios. Of those eligible cells, 76.9% show low risk becoming high-risk in all six scenarios, with 14.9% for only one scenario. The remaining scenarios account for between 0.9% and 3.4% of eligible cells.
NI Storage where more than three scenarios show low risk becoming high-risk (panel h)	41.4% of eligible cells are canopy NI storage, 41.9% are floodplain NI storage, waterbody and soil NI storage accounts for 6.3% each, and wetland NI storage accounts for 3.6%.

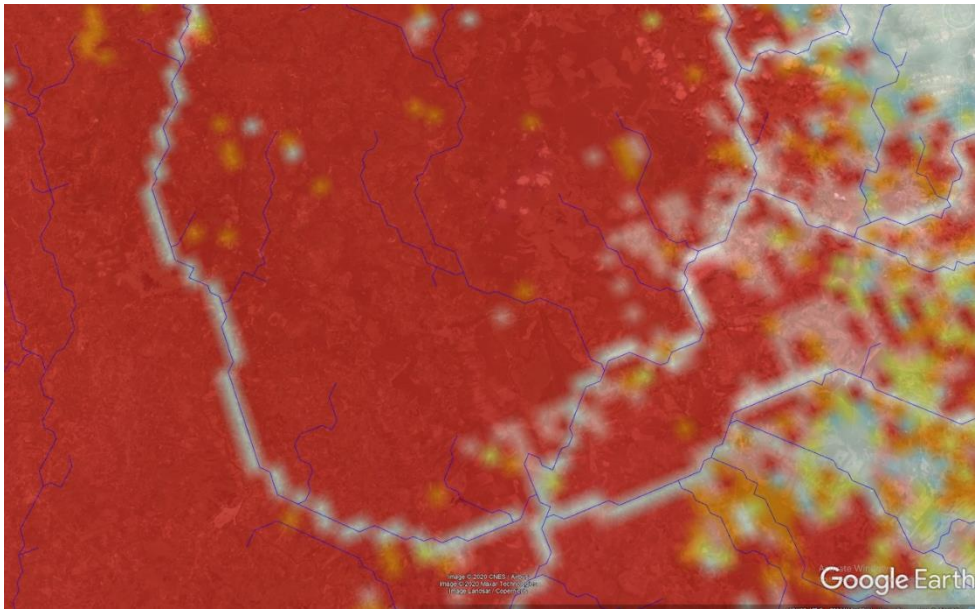


Figure D20. Number of scenarios where high risk FRR increase by more than 10% of baseline in Guayaquil Basin.

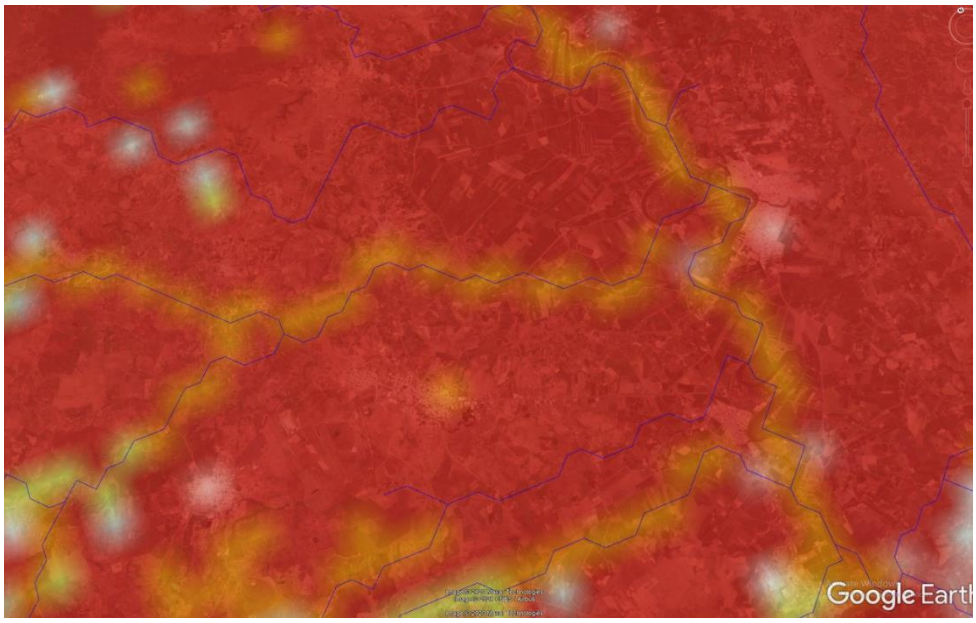


Figure D21 Number of scenarios where high risk FRR increase by more than 10% of baseline in Guayaquil Basin.

D7. Correlations between number of climate scenarios and elevation, slope and tree cover

Below are tables to calculate the Spearman rank correlation coefficient and associated significance between the number of climate scenarios showing a greater than 10% increase compared to baseline, and either elevation, slope or tree cover for the Jakarta, Bogotá and Guayaquil basins.

Table D14. Calculation of Spearman rank correlation coefficient between number of climate scenarios showing a >10% increase and either, elevation (m), slope (degree) or tree cover (%) for the Jakarta basin

diff (cs-elev)	**d2**	**diff(cs-slope)**	**d2**	**diff(cs-tree)**	**d2**
0	**0**	0	**0**	0	**0**
0	**0**	2	**4**	2	**4**
0	**0**	0	**0**	0	**0**
0	**0**	-2	**4**	-2	**4**
0	**0**	1	**1**	0	**0**
0	**0**	-1	**1**	0	**0**
0	**0**	0	**0**	0	**0**
Sum (d2)	**0**		**10**		**8**
(6*sum of d2)	0		60		48
n3-n	336		336		336
Rs=	1.000		0.821		0.857
correlation	very strong		strong		strong
significance	sig		not-sig		sig

Table D15. Calculation of Spearman rank correlation coefficient between number of climate scenarios showing a >10% increase and either, elevation (m), slope (degree) or tree cover (%) for the Bogotá basin.

diff (cs-elev)	**d2**	**diff(cs-slope)**	**d2**	**diff(cs-tree)**	**d2**
2	**4**	3	**9**	1	**1**
-1	**1**	-1	**1**	-1	**1**
1	**1**	-1	**1**	0	**0**
1	**1**	-1	**1**	0	**0**
1	**1**	0	**0**	0	**0**
1	**1**	0	**0**	0	**0**
-5	**25**	0	**0**	0	**0**
Sum (d2)	**34**		**12**		**2**
(6*sum of d2)	204		72		12
n3-n	336		336		336
Rs=	0.393		0.786		0.964
correlation	weak		strong		very strong
significance	not sig		not sig		sig

Table D16. Calculation of Spearman rank correlation coefficient between number of climate scenarios showing a >10% increase and either, elevation (m), slope (degree) or tree cover (%) for the Guayaquil basin.

diff (cs-elev)	**d2**	**diff(cs-slope)**	**d2**	**diff(cs-tree)**	**d2**
5	**25**	6	**36**	6	**36**
1	**1**	3	**9**	4	**16**
4	**16**	3	**9**	2	**4**
-2	**4**	-2	**4**	0	**0**
-4	**16**	-4	**16**	-3	**9**
-1	**1**	-2	**4**	-3	**9**
-3	**9**	-4	**16**	-6	**36**
Sum (d2)	**72**		**94**		**110**
(6*sum of d2)	432		564		660
n3-n	336		336		336
Rs=	-0.286		-0.679		-0.964
correlation	weak		moderate		very strong
significance	not sig		not sig		sig

Discussion

In the Bogotá, Jakarta and Guayaquil upstream basins, there appeared to be a tendency for flood risk increases, under all six scenarios, to occur on hillslopes. The increase in accumulated Storage to Capacity Ratios on slopes may be due to low storage capacity as a result of lack of tree cover and shallow soil. However, comparing the number of scenarios showing an increase of more than 10% against elevation, slope and tree cover did not reveal a clear relationship. For the Jakarta basin, there was a relationship between the number of scenarios showing an increase in flood risk ratios and increasing elevation and slope but also for increased tree cover, not less. In the Bogotá upstream basin, there was a slight linear relationship between steeper slope and more tree cover, not less, but no definitive relationship with regards to elevation. There was no discernible relationship between these variables in the Guayaquil basin, possibly due to the basin's west-east divide between lowlands and highlands. However, a large proportion of the Guayaquil basin lowlands also had a high number of scenarios with a greater than 10% increase. There's also the anomaly of the north-south band in the foothills of the Andes, which show a decrease in flood risk ratios compared to baseline. This could be explained by the mountains causing an enhanced rain shadow under climate scenarios.

A reason for why we may not be seeing the influence of landscape factors could be because accumulated flood risk ratios were used, but the landscape factors (elevation, slope and tree cover) were not accumulated. Accumulated ratios take the influence of upstream areas as well as local, so will not show a strong relationship with local properties. Overall, it may be easier to achieve an increase in flood risk ratios in upstream locations as downstream areas aggregate everything from upstream.

It is important to note that the model does not take into account if soil storage is impacted by poor agricultural practices. The storage calculated is potential storage; some will not be realised.

C8. Regional climate projections: predicted changes in precipitation, streamflow, runoff and extreme events in specific regions

Below are descriptions of projected climate change from the scientific literature for the regions in which the study basins are located. The purpose is to give an indication of whether precipitation and associated flooding is projected to increase or decrease, and to provide a point of comparison with the results from this study. However, the range of models, scenarios, variables, time periods and spatial scales encountered makes comparison very challenging. In addition, for some of the basins, there was very little literature.

Eastern Africa, Kenya, Nairobi

East Africa has a highly variable climate prone to climate and weather extremes; in the past few years it has experienced both significant drought and floods (Kilavi 2018). Future projections for climate in East Africa, using GCMs, shows an increase in the frequency of extreme climate events such as floods, droughts, tropical storms, and heavy rainstorms (Seneviratne et al 2012; Niang et al 2014). Prediction models for the region are difficult to parameterize due to the heterogeneous topography and different synoptic systems that influence the climatic conditions. As such, extreme rainfalls are generally characterised by high spatial and temporal variability (Juma et al 2020 and refs within).

The World Bank's Climate Change Portal for Kenya, using RCP 8.5 ensemble, projects consistent increases in annual rainfall in Kenya. These are expected to be largest in October, November and December (-3 to +49 mm per month), and in March, April and May. Annual precipitation will rise by 42.30mm (-204.93mm to 302.15mm) in 2040-2059 (RCP 8.5, Ensemble)

Gebrechorkos et a.l (2019) applied the Statistical Down-Scaling Model (SDSM) to develop fine-scaled climate projections for East Africa, particularly Ethiopia, Kenya, and Tanzania. They found that precipitation during the long-rain season (MAM) will be lower in large parts of Kenya and Tanzania in the 2020s, 2050s, and 2080s under the RCPs. On the other hand, precipitation during JJAS will increase in Kenya and Tanzania (Gebrechorkos et al 2019).

Focusing specifically on the city of Nairobi, a technical report (not peer reviewed) by the Urban ARK project using 15 GCM's for RCP 8.5, found that annual rainfall totals are projected to remain within the historic range of variability, or to increase slightly in the second half of the century. However, two outlier models diverged, with one projecting a decrease while the other projecting a very significant increase in rainfall into the future. Similar patterns were seen in the projected change in rainfall daily intensity, the frequency of rain days and heavy rain days.

East coast of India, Chennai

Rainfall in India occurs mostly from two monsoons: the southwest summer monsoon and the northeast monsoon. The northeast contributes around 10–20% of annual rainfall in the country. In particular, the southern peninsular India, mainly the Tamil Nadu coast near Chennai, receives about 50% of its annual rainfall from the northeast monsoon (Jyoteeshkumar et al. 2020). Annual maximum precipitation has increased in the majority of India during the period of 1979–2015 (Jyoteeshkumar et al. 2020).

Looking at the whole of India, Kumar Bel et al (2016), using a model at 25 km^2 resolution from the GCM - HadCM3Q for SRES A1B scenarios, found the annual rainfall projections indicated a general increase in rainfall of 15-24%.

Ali et al. (2016) using downscaled and bias-corrected future and historic climate projections from CMIP5 and the Noah-MP model under RCP 2.6 and RCP 8.5 emission scenarios, found that the frequency of single and multi-day extreme precipitation and flood events are projected to increase substantially in the future over the Indian sub-continental river basins, with multi-day precipitation extremes and floods projected to be more frequent than daily extremes. The same was reported by Mukherjee et al (2018), who found that the frequency of precipitation extremes is projected to rise more prominently in southern and central India in the mid and end of the 21st century under RCP 8.5. Also Ramachandran et al (2019), using CMIP5 for RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5, found that the number of extremely heavy rainfall events will be increasing after the mid-century, i.e., 2050, with the projected rainfall intensity becoming nearly double that of the observed rainfall intensity.

The World Bank Climate Portal (ref) for India reports that annual precipitation will rise by 51.56mm (-234.40mm to 370.88mm) in 2040-2059 (RCP 8.5, Ensemble) and that annual Maximum 5-day Rainfall (25-yr RL) will rise by 35.17mm (-89.97mm to 302.90mm) in 2040-2059 (RCP 8.5, Ensemble). However, it also states that considerable uncertainty characterizes projections of local long-term future precipitation trends in India, and that future changes in the seasonality of monthly precipitation at the national level are also highly uncertain under all emissions scenarios. There is greatest agreement on increases in the intensity of extreme precipitation events in south India and in the vicinity of the Himalayas in the north (ref).

Using four GCMs from CMIP5 for RCP 4.5 in the Adyar Basin, Ramachandran et al. (2019) projected that the number of extremely heavy rainfall events will be increasing after the mid-century, i.e., 2050. The projected rainfall intensity becomes nearly double that of the observed rainfall intensity. For the period 2015–2085, they simulated peak discharges of the Adyar river for different return periods according to the future climate scenarios. A comparison of the peak discharges shows a significant increase in the observed and projected GCMs for the 2, 5, 10, 50, and 100-year return periods. The increase in peak discharge ranges from 3.2% to 16.6% for the 2-year return period and from 34.3% to 91.9% for the 100-year return period (Ramachandran et al 2019).

Indonesia, Jakarta

Large uncertainty in the region. Naylor et al. (2007) using downscaled GCMs for IPCC AR4 SRES scenarios found large seasonal variations: total rainfall is expected to increase in AMJ relative to the current pattern, but decrease in JAS. In AMJ, total rainfall is projected to increase by ≈10% in the study regions. In JAS, however, nearly all models project a decline in rainfall. Total rainfall is projected to decline by 10–25% on average and by as much as 50% in West/Central Java and 75% in East Java/Bali at the tail end of the distributions. In East Java/Bali, some models project that total rainfall will drop close to zero for the JAS season.

The World Bank's Climate Change Knowledge Portal (ref) predicts increasing annual precipitation across the majority of the Indonesian islands, except in southern Indonesia where it is projected to decline by up to 15%.

Budiyono et al (2016) simulated the impacts of climate change by combining two scenarios of sea level rise with simulations of changes in 1-day extreme precipitation

totals from five global climate models (GCMs) forced by the four RCPs. The results were highly uncertain; the median change in risk due to climate change alone by 2030 is a decrease by -46 %, but by adding sea level rise combinations they show an increase in risk in some of the sea level rise combinations.

Focusing on the Ciliwung River watershed, Mishra et al (2018) used rainfall IDF curves and extreme precipitation change assessment for the present and future climate scenarios. They found the 1-day maximum precipitation for the 50- and 100-year return periods clearly indicate that extreme precipitation events for all return periods and all durations will be more frequent and intense in the future.

North-western South America, Colombia (Bogotá) and Ecuador (Guayaquil)

South America

The IPCC AR5 (IPCC 2013a, 2013b) suggests both increases and decreases in rainfall for Central and South America by 2100, depending on the region. They project increased precipitation in the southwest and a decrease in the north for the end of the 21st century, although with great uncertainties.

Modelling by Kitoh et al (2011) projects an increase in wet-season precipitation and a decrease in dry-season precipitation over most of South America. In the future, almost all over South America, precipitation intensity will increase. They found a band of increased precipitation in the north of South America, while precipitation in JJA is projected to decrease over most of the Amazon by the end of the century (Kitoh 2011).

Palomino-Lemus et al (2017), using a multi-model SD ensemble mean found that projected changes prove mostly mild (positive) or moderate (negative) for the RCP2.6, covering extensive regions with the same sign, which intensify as the radiative forcing increases. Three broad regions can be distinguished for the three scenarios, with the most pronounced changes for the RCP8.5: a northwest-southeast band extending from northern Mexico to the northeast of Brazil, crossing through northern Colombia, with generally moderate increases in precipitation; substantial decreasing changes over a band extending from eastern Ecuador to southeastern Brazil; and the regions in the south of the area of the study, again with moderate increases (Palomino-Lemus et al 2017).

Colombia

The World Bank Climate Portal for Columbia states that annual precipitation will rise by 18.37mm (-418.06mm to 588.27mm) in 2040-2059 (RCP 8.5, Ensemble). The maximum amount of rain that falls in any 5-day period ─ an indicator of extreme weather – is projected to increase and the maximum period between rainy days is expected to decrease. Recent data suggest that some areas will become wetter while others will become drier (World Bank Climate Portal).

Projected changes in summer precipitation due to climate change were investigated by Palomino-Lemus et al (2015) using a Statistical Downscaling (SD) method on five GCM's for RCPs 2.6, 4.5 and 8.5. Under RCP 8.5 they found a trend of precipitation increase of between 6.16% and 14.76% for the North-Centre Colombia (NCC) region (in which the Bogotá basin is located).

A study focusing on the Upper Bogotá watershed found that water balance changes relative to 2016 show that precipitation will increase as expected under RCP 2.6 but decrease in

RCP 8.5 in the upper Bogotá (Clerici et al. 2019). Actual Evapotranspiration share increases in all future scenarios with 77.3% in the Upper Bogotá watershed.

Ecuador

According to the World Bank's Climate Change Knowledge Portal for Ecuador, mean annual precipitation is expected to increase by 3% in the period 2030-2049 as compared to 1980-1999. December-February and March-May precipitation levels are likely to increase by 3% and 5%. For the June-August period, precipitation levels are likely to decrease by 3%. Increases are projected for the frequency and intensity of extreme rainfall events on the northern coast of Peru and Ecuador in the period of 2071-2100. Annual precipitation will rise by 90.35mm (-312.53mm to 646.34mm) in 2040-2059 (RCP 8.5, Ensemble). Annual Maximum 5-day Rainfall (25-yr RL) will rise by 19.11mm (-57.81mm to 338.59mm) in 2040-2059 (RCP 8.5, Ensemble).

Relative to the other basins, there seems to be comparatively fewer studies focusing on climate change in the Guays basin.

British Isles, London

Watts et al. (2015) review the future prospects for climate and water in the UK. They summarise the UK Climate Projections 2009 (UKCP09) findings as follows: little change in annual average rainfall by the 2080s, with the 10th to 90th percentile range from a 16% reduction to a 14% increase for the medium emissions scenario. Seasonal precipitation changes may be greater. In winter, UKCP09 projects the biggest increases to be along the west coast, with a median change of +33% (10th to 90th percentile range +9 to +70%). In contrast, small decreases are seen in Scotland in winter (10th to 90th percentile range –11 to +7%). In summer, UKCP09's biggest median change of about -40% is in southern England (10th to 90th percentile range -65 to -6%), with little change in northern Scotland (10th to 90th percentile range -8 to +10%).

The UK's Met Office's new suite of climate projections, UK Climate Projections 2018 (UKCP18), show general climate change trends projected over UK land for the 21st century are broadly consistent with earlier projections (UKCP09) showing an increased chance of warmer, wetter winters and hotter, drier summers along with an increase in the frequency and intensity of extremes (Met Office, 2019).

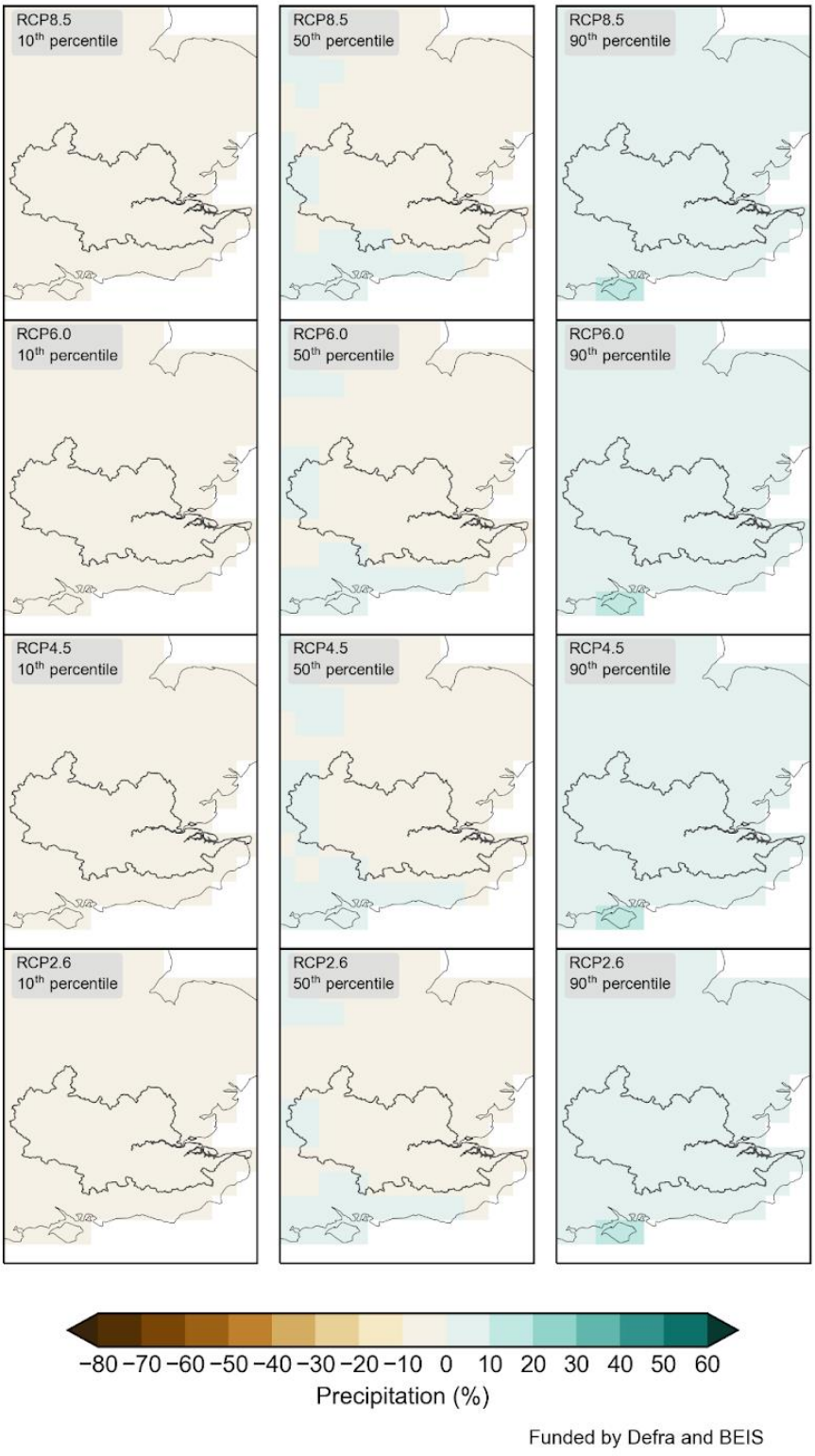
London and Thames basin

For the London area, the UK Climate Projections (UKCP09) estimated for the same emissions scenario and future time period, a 50% probability of winter rainfall increasing by 19% and summer rainfall decreasing by 22% (Jenkins et al., 2009; Bell et al 2012).

The UKCP09 projections suggest that for the Thames River Basin District8 in the 2050's "Under medium emissions, the central estimate of change in annual mean precipitation is 0 per cent chance; it is very unlikely to be less than –4 per cent and is very unlikely to be more than 5 per cent. Under medium emissions, the central estimate of change in winter mean precipitation is 15 per cent; it is very unlikely to be less than 2 per cent and is very unlikely to be more than 33 per cent. Under medium emissions, the central estimate of change in summer mean precipitation is –18 per cent; it is very unlikely to be less than –39 per cent and is very unlikely to be more than 7 per cent. (Environment Agency, 2009)

Met Office
Hadley Centre

Annual precipitation anomaly in Thames
for 2060-2079 minus 1981-2000



Funded by Defra and BEIS

Summary of climate impacts by country

The range of models, scenarios, time periods and variables used for these regions in the literature makes it extraordinarily difficult to summarise and compare results between regions. However, the Climate Change Knowledge Portal (CCKP; https://climateknowledgeportal.worldbank.org) created by the World Bank, provides an online platform for access to comprehensive global, regional, and country data related to climate change and development. As it provides information for every country, region and major watershed using the CMIP5 models, I have used it to summarise climate change impacts for temperature and precipitation variables under RCP 8.5 in Table C17.

Table C17. Climate change impacts for RCP 8.5 under CMIP5 models, for 2040-2059, using multi-model ensembles, summarised from Climate Change Knowledge Portal (World Bank Group).

Country	Mean annual temperature	Mean annual precipitation	Annual Maximum 5-day Rainfall (25-yr RL)
Kenya	Increase by 1.68°C (1.19°C to 2.42°C)	Increase by 42.30mm (-204.93mm to 302.15mm)	Increase by 12.22mm (-30.10mm to 121.21mm)
India	Increase by 1.89°C (1.11°C to 2.84°C)	Increase by 51.56mm (-234.40mm to 370.88mm)	Increase by 35.17mm (-89.97mm to 302.90mm)
Colombia	Increase by 1.88°C (1.37°C to 3.08°C)	Increase by 18.37mm (-418.06mm to 588.27mm)	Increase by 10.72mm (-76.77mm to 249.30mm)
Indonesia	Increase by 1.42°C (1.17°C to 2.12°C)	Increase by 82.94mm (-607.44mm to 751.55mm)	Increase by 22.26mm (-64.84mm to 415.97mm)
UK	Increase by 1.51°C (0.36°C to 2.65°C)	Increase by 37.96mm (-150.51mm to 249.59mm)	Increase by 8.19mm (-7.23mm to 26.04mm)
Ecuador	Increase by 1.72°C (1.34°C to 2.74°C)	Increase by 90.35mm (-312.53mm to 646.34mm)	Increase by 19.11mm (-57.81mm to 338.59mm)

The problem with summarising by country is that the range in values can be quite large due to heterogeneous landscapes over large scales and the mean value may not be representative of the basins focused on in this chapter. For instance, in Indonesia the value range for mean annual precipitation is from -607 mm to +751 mm indicating areas that will have large declines in mean annual precipitation as well as areas that are projected to have large increases. Another issue is that reporting for only RCP 8.5 is problematic in that it is the extreme or worse-case scenario.

Appendix E - Forests as mitigation

E1. Random points

To determine how a change in tree cover relates with the flood risk ratio at each point, the upstream average of change in tree cover was calculated and plotted against the change in accumulated flood risk ratio for each POI. Looking at a change in accumulated ratio at a point reflects what's happening upstream and allows us to ask " Do big changes in tree cover lead to big changes in flood risk?"

Approximately, 1,000 points in the basin were randomly selected. The change in FRR at these points for the 50%, 25% and 10% scenario was compared, and the downstream average of change in tree cover against change in FRR for the three scenarios was calculated and shown in Figures D1-6. The steps to do this in *WaterWorld* are: Run the scenario, then go to prepare data > list alternative workspace data> list of workspace data > cover of tree-covered ground change map> geobrowse > calculation > hydrological > downstream averaging >stats for all active POI sets. Downstream averaging calculates the average of this variable (percentage of tree covered ground) down flow networks. In this case, it cumulates the tree cover values and divides by the number of cells.

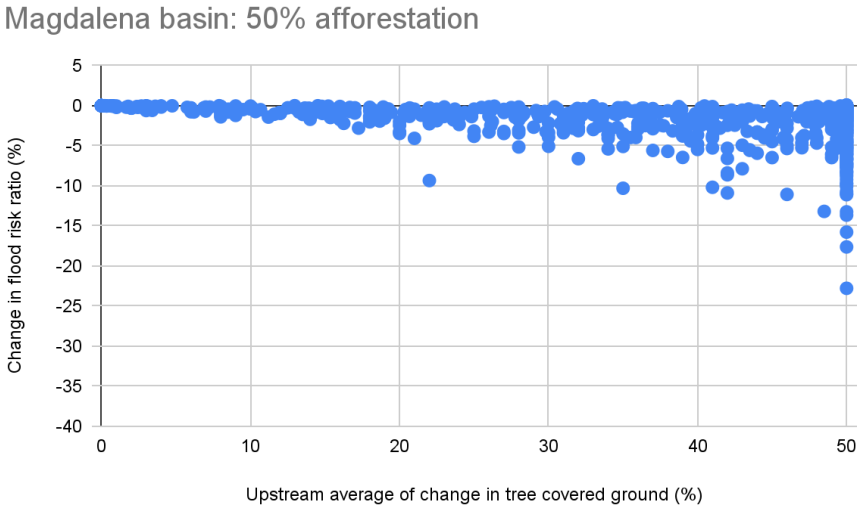


Figure E1. The change in flood risk under a 50% forestation scenario is compared to the upstream average of change in tree covered ground for the Magdalena hydro basin (n=1029).

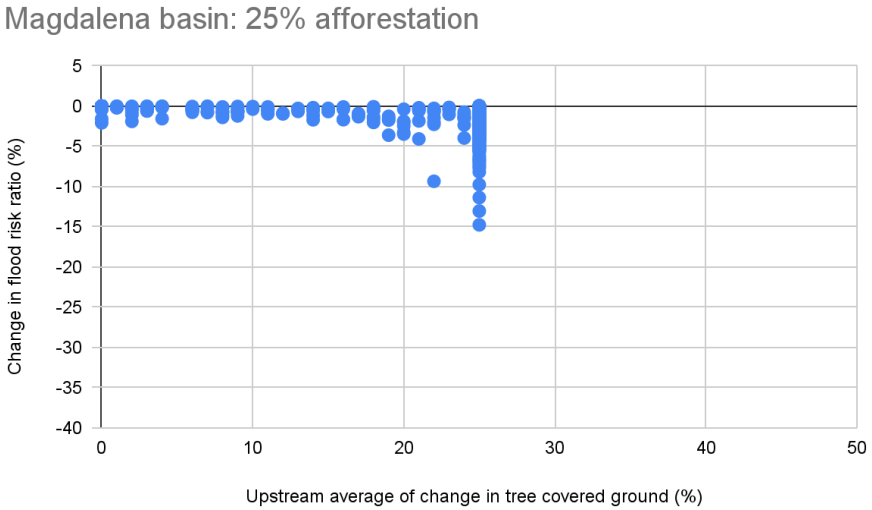


Figure E2. The change in flood risk under a 25% forestation scenario is compared to the upstream average of change in tree covered ground for the Magdalena hydro basin.

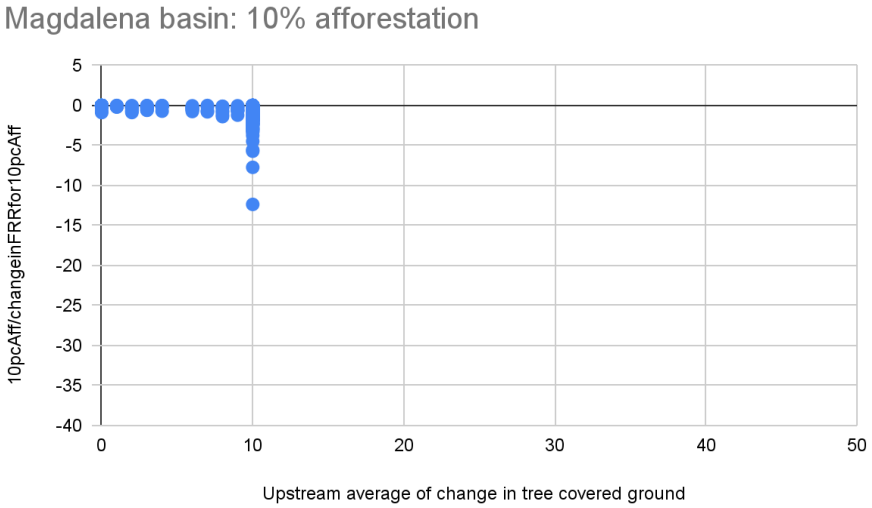


Figure E3. The change in flood risk under a 10% forestation scenario is compared to the upstream average of change in tree covered ground for the Magdalena hydro basin.

Figures E4-6 shows that the bigger changes in tree cover do result in big(ger) changes in flood risk ratio but there is variability. The number of points changes with the degree of forestation; each drop in forestation rate results in a larger proportion of points clustered at the change point. The cluster of points at the change point shows every pixel that had a change in that % forestation.

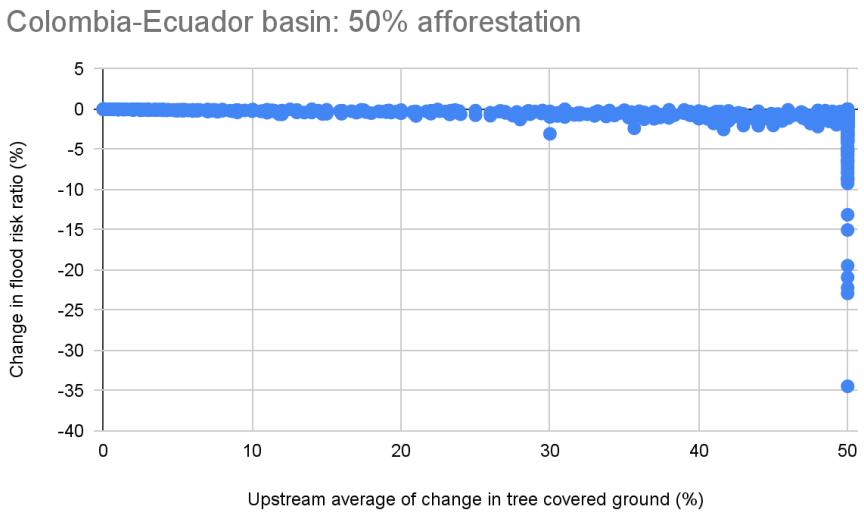


Figure E4. The change in flood risk under a 50% forestation scenario is compared to the upstream average of change in tree covered ground for the Colombia-Ecuador major hydro basin.

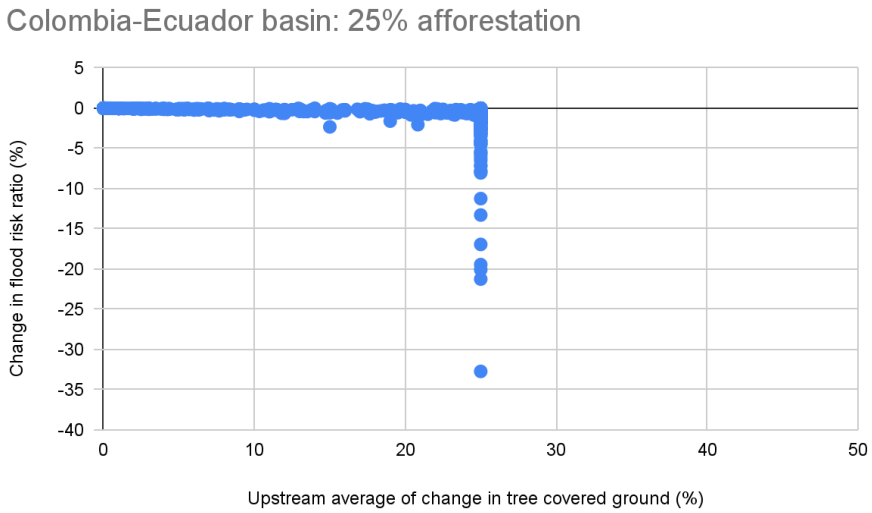


Figure E5. The change in flood risk under a 25% forestation scenario is compared to the upstream average of change in tree covered ground for the Colombia-Ecuador major hydro basin.

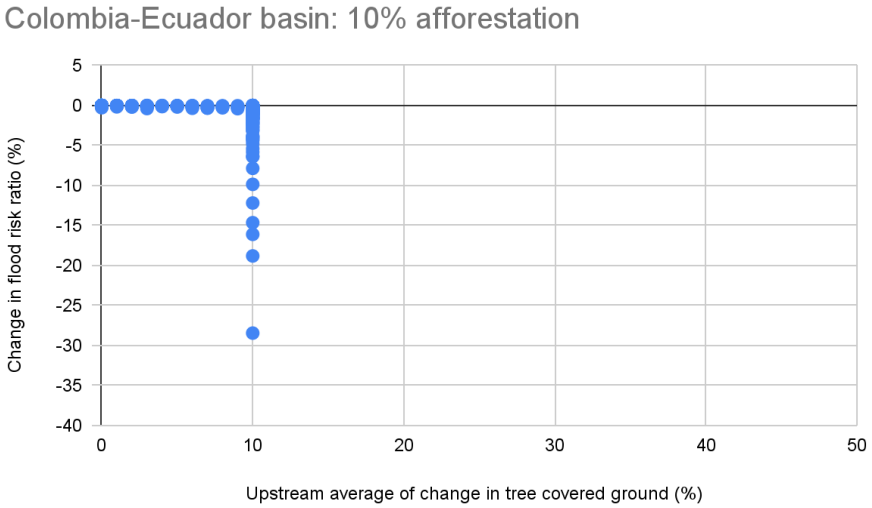


Figure E6. The change in flood risk under a 10% forestation scenario is compared to the upstream average of change in tree covered ground for the Colombia-Ecuador major hydro basin.

In comparison to the Magdalena basin, the pattern of Flood Risk Ratio (FRR) reduction for the Colombia-Ecuador basin is less variable (Figs. D6-8). Most points showed very little change in FRR, and are concentrated in the 0 to -5% band. The exception being those that experienced the target amount of forestation increase.

E2. Change in tree cover as a result of the different 'selective targeting' scenarios

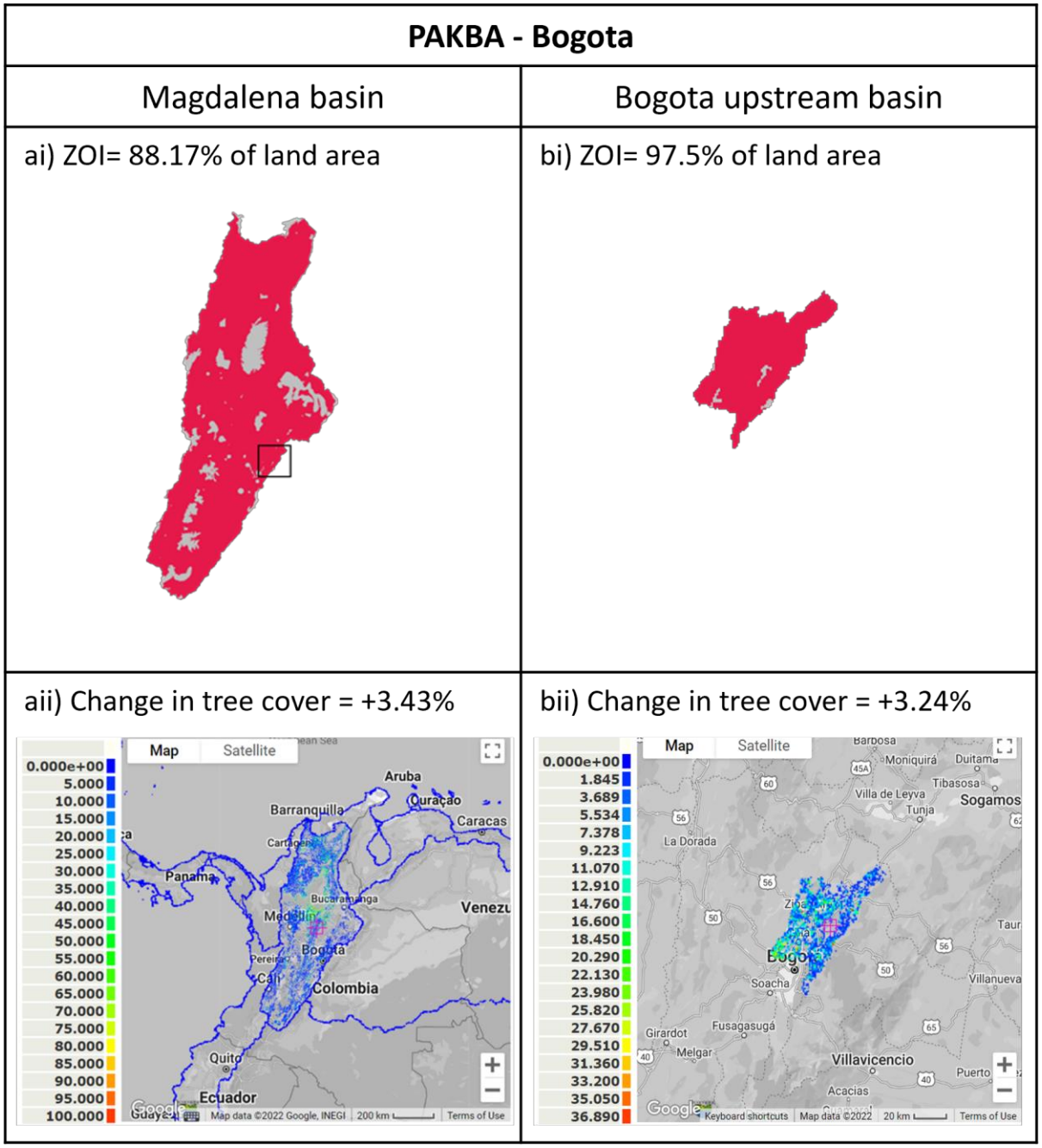


Figure E7. Maps of the Magdalena hydrological basin (a) and the Bogotá basin (b), showing the spatial distribution of the i) PAKBA ZOI (avoiding PAs and KBAs) and ii) the resultant change in tree cover. Grey areas are excluded from the ZOI and red areas are included in the ZOI. Black square represents the geographical location of the Bogotá basin within the Magdalena basin.

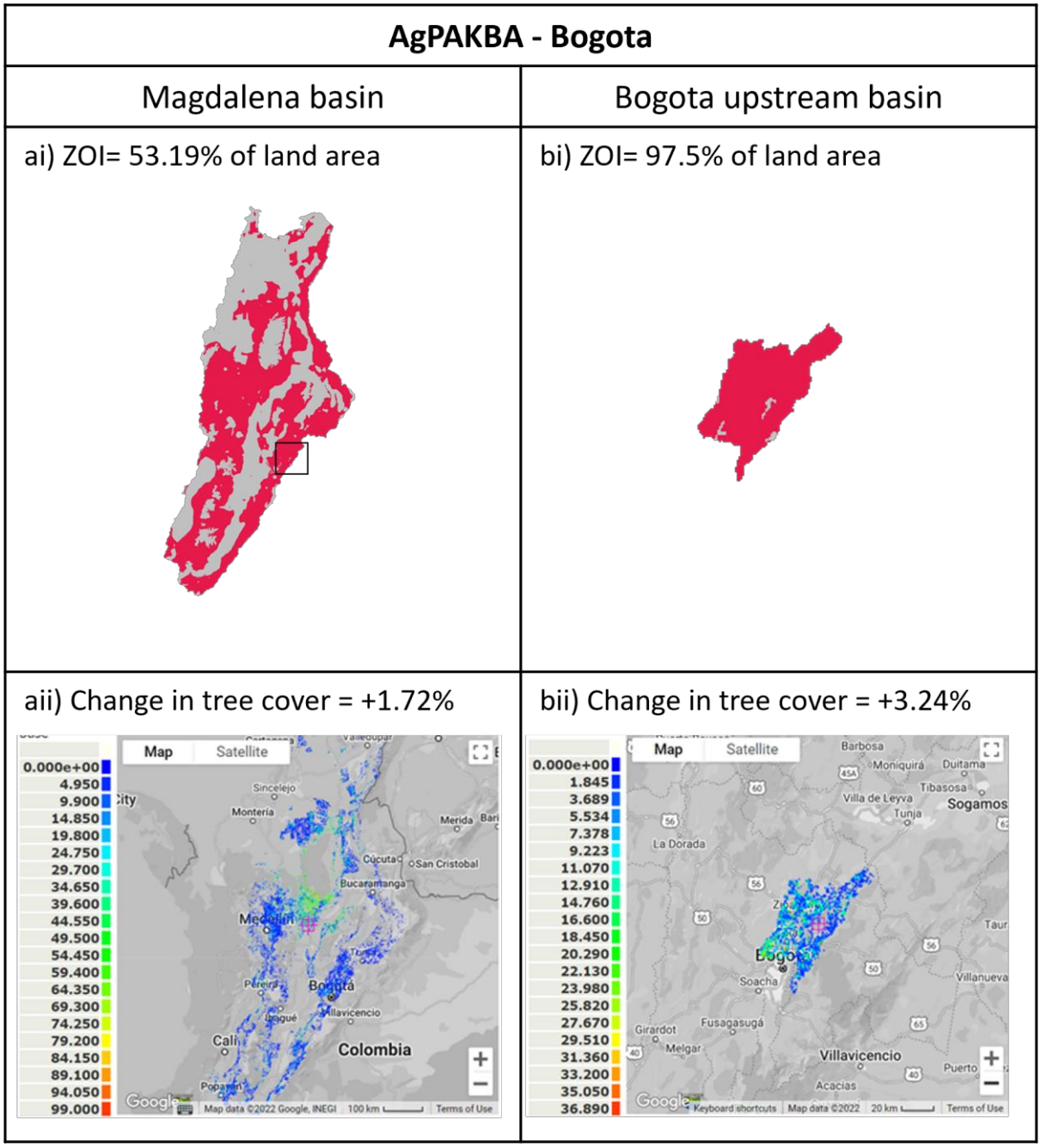


Figure E8. Maps of the Magdalena hydrological basin (a) and the Bogotá basin (b), showing the spatial distribution of the i) AgPAKBA ZOI (avoiding PAs and KBAs; targeting least suitable agricultural land) and ii) the resultant change in tree cover. Grey areas are excluded from the ZOI and red areas are included in the ZOI. Black square represents the geographical location of the Bogotá basin within the Magdalena basin.

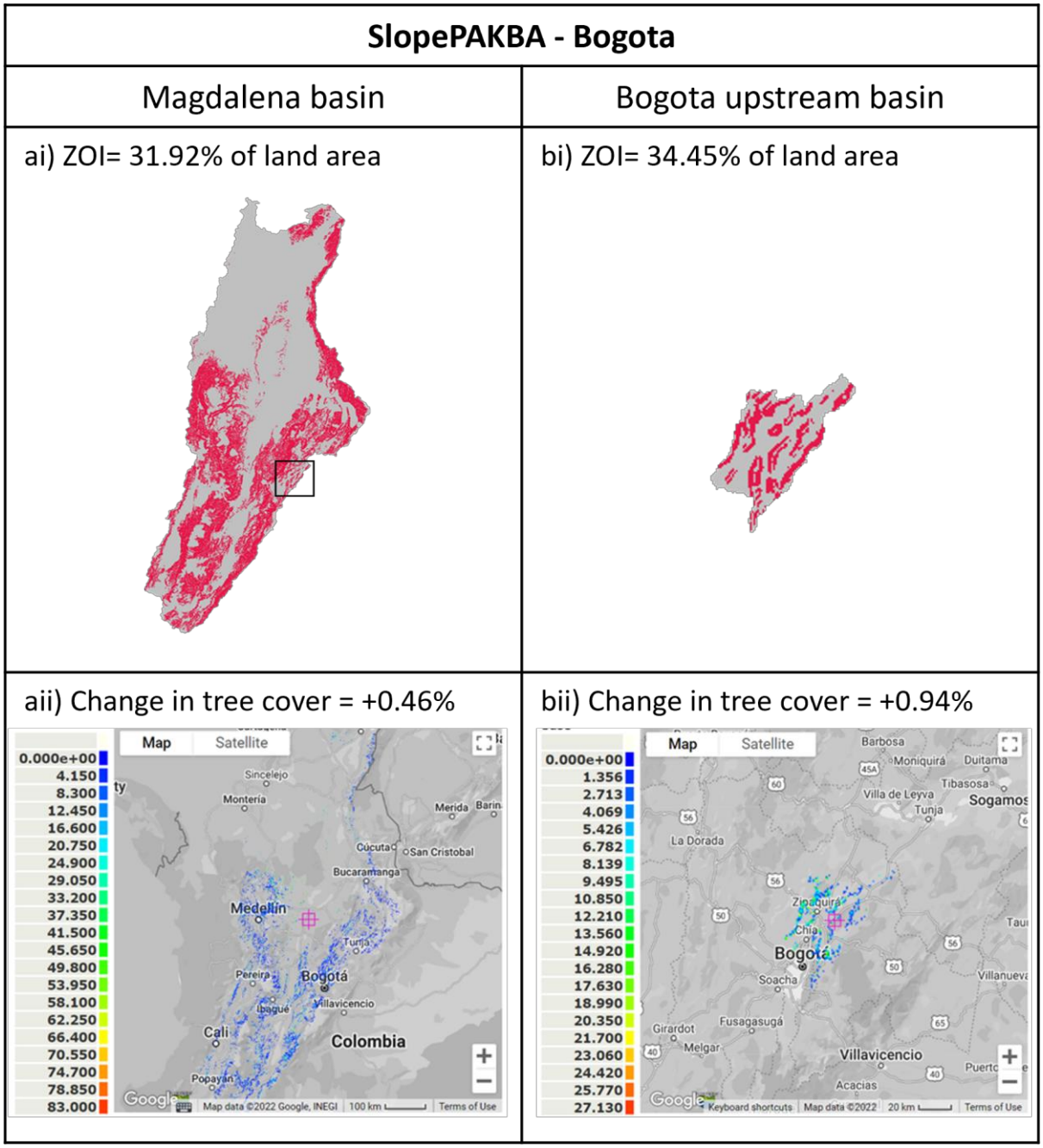


Figure E9. Maps of the Magdalena hydrological basin (a) and the Bogotá basin (b), showing the spatial distribution of the i) SlopePAKBA ZOI (avoiding PAs and KBAs; targeting land over 5 degrees in slope) and ii) the resultant change in tree cover. Grey areas are excluded from the ZOI and red areas are included in the ZOI. Black square represents the geographical location of the Bogotá basin within the Magdalena basin.

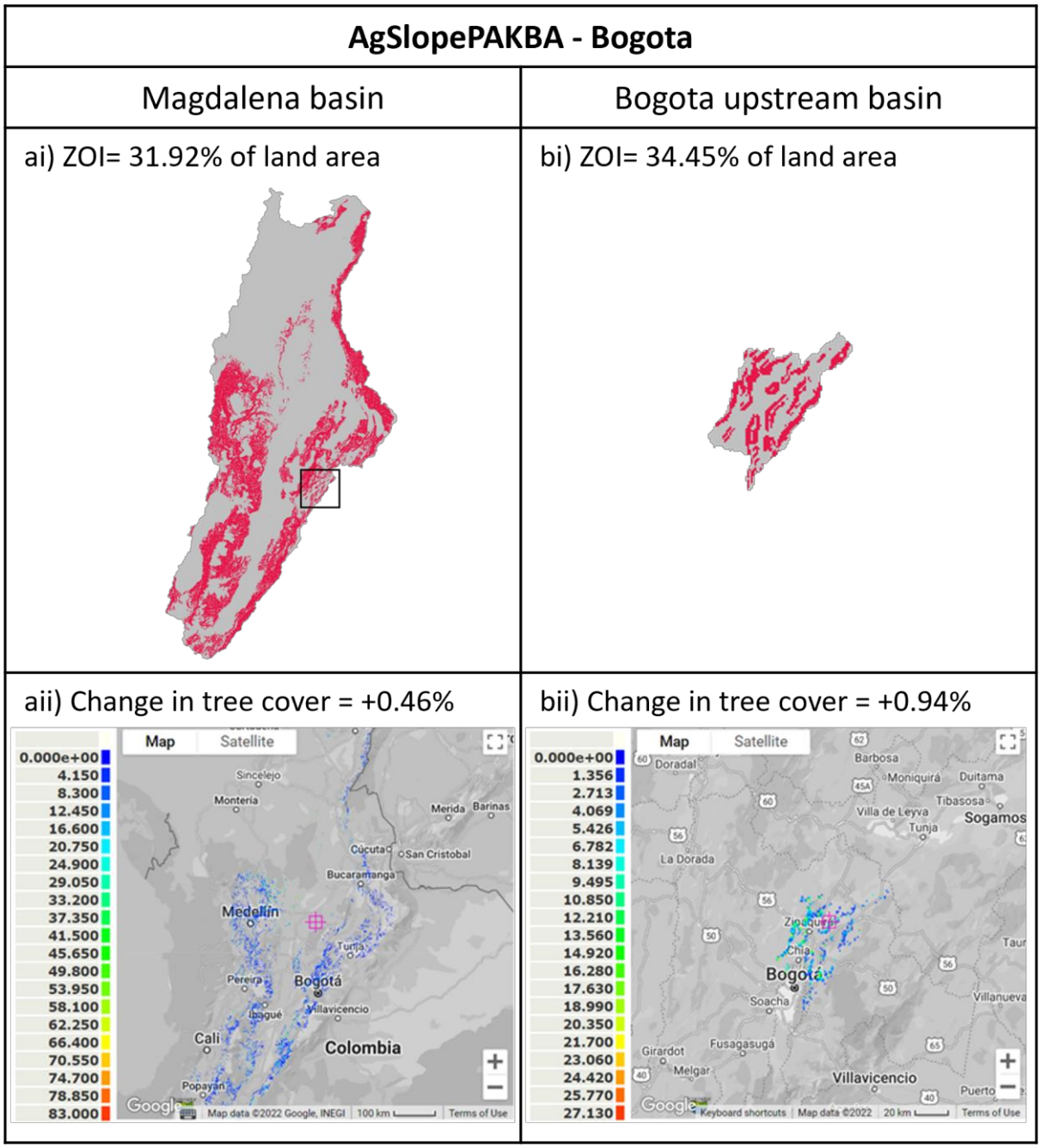


Figure E10. Maps of the Magdalena hydrological basin (a) and the Bogotá basin (b), showing the spatial distribution of the i) AgSlopePAKBA ZOI (avoiding PAs and KBAs; targeting land over 5 degrees in slope) and ii) the resultant change in tree cover. Grey areas are excluded from the ZOI and red areas are included in the ZOI. Black square represents the geographical location of the Bogotá basin within the Magdalena basin.

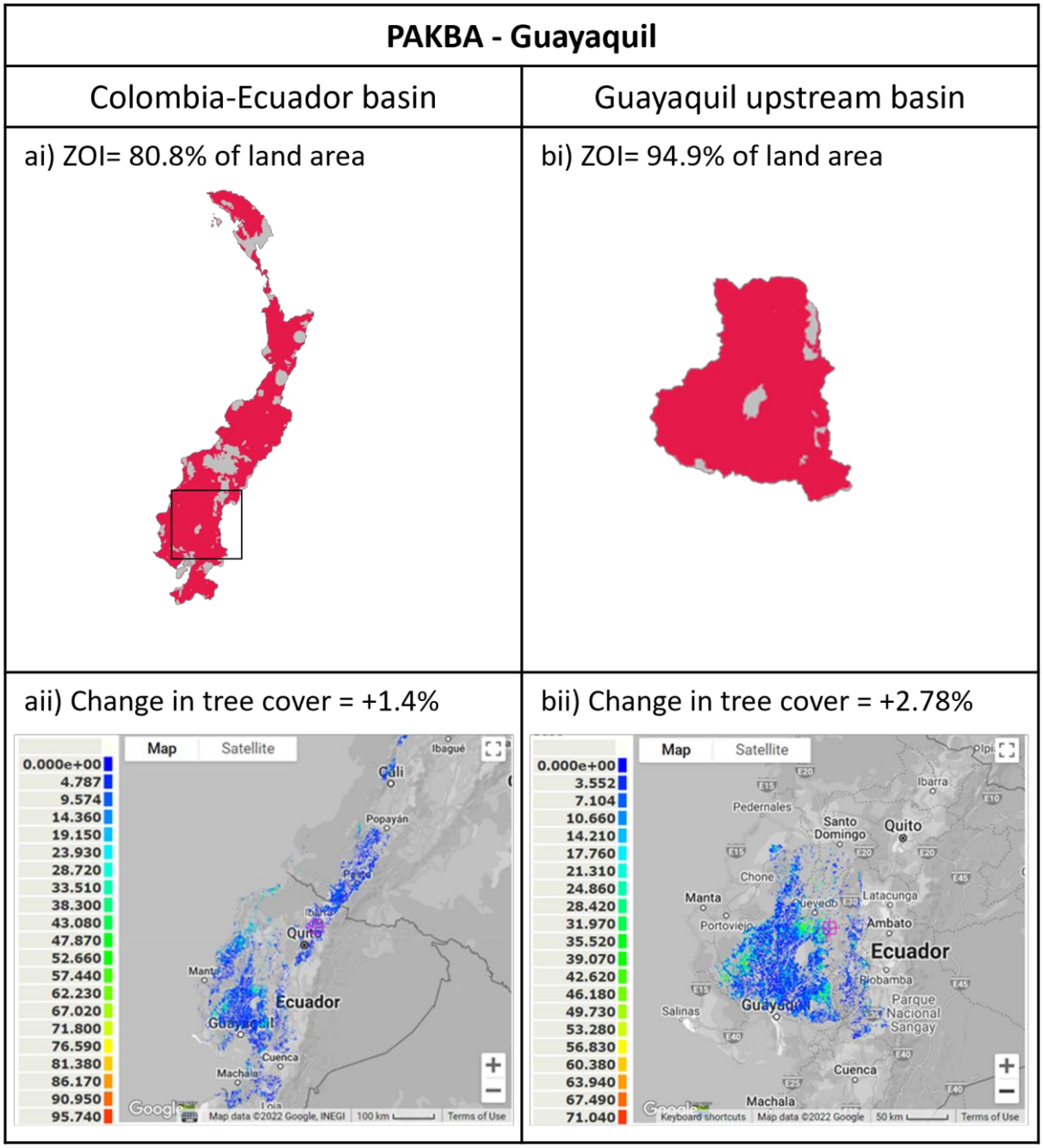


Figure E11. Maps of the Colombia-Ecuador major hydrological basin (a) and the Guayaquil basin (b), showing the spatial distribution of the i) PAKBA ZOI (avoiding PAs and KBAs) and, ii) the resultant change in tree cover. Grey areas are excluded from the ZOI and red areas are included in the ZOI. Black square represents the geographical location of the Guayaquil basin within the Colombia-Ecuador basin.

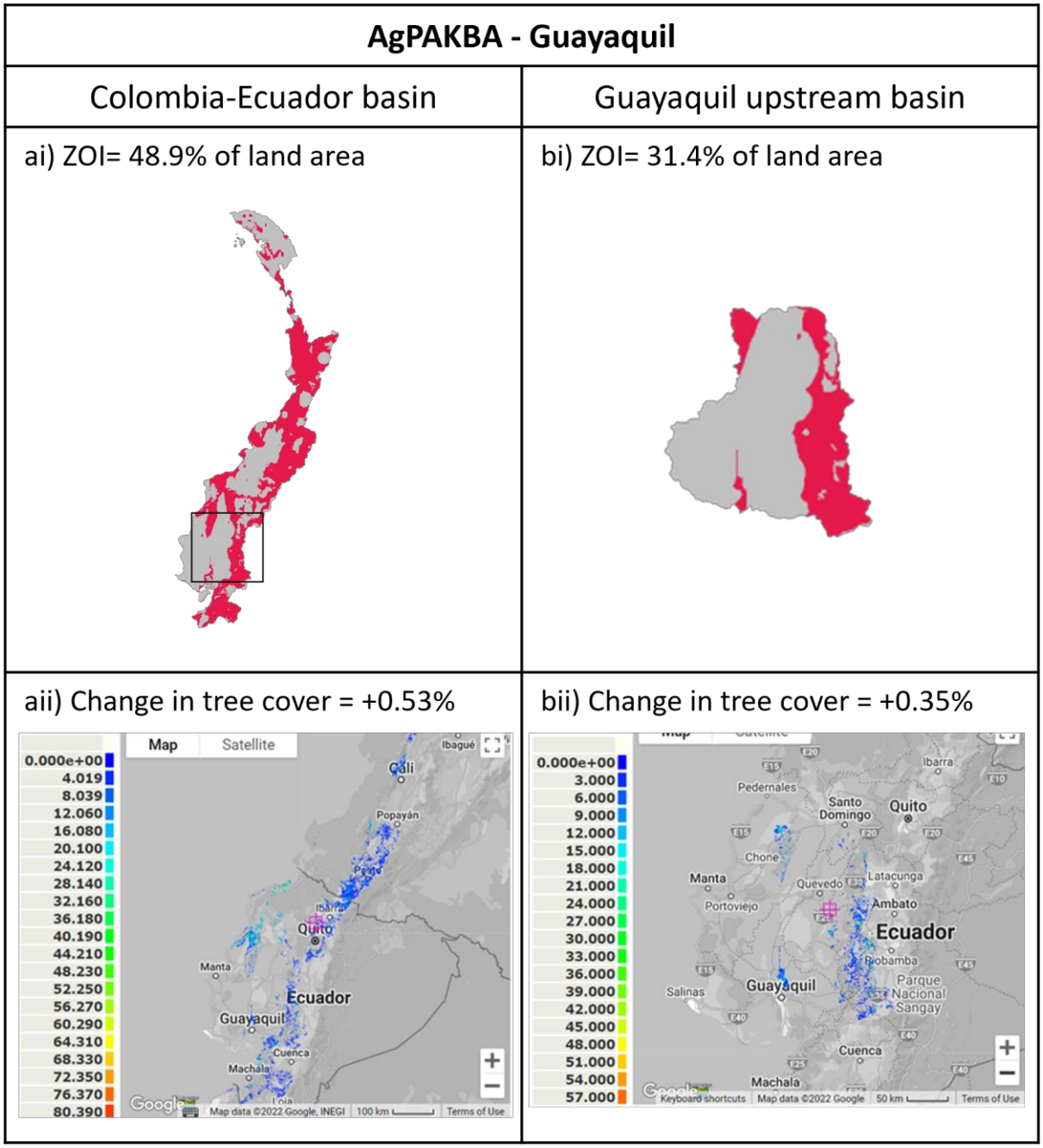


Figure E12. Maps of the Colombia-Ecuador major hydrological basin (a) and the Guayaquil basin (b), showing the spatial distribution of the i) AgPAKBA ZOI (avoiding PAs and KBAs, and targeting low suitable agricultural land) and, ii) the resultant change in tree cover. Grey areas are excluded from the ZOI and red areas are included in the ZOI. Black square represents the geographical location of the Guayaquil basin within the Colombia-Ecuador basin.

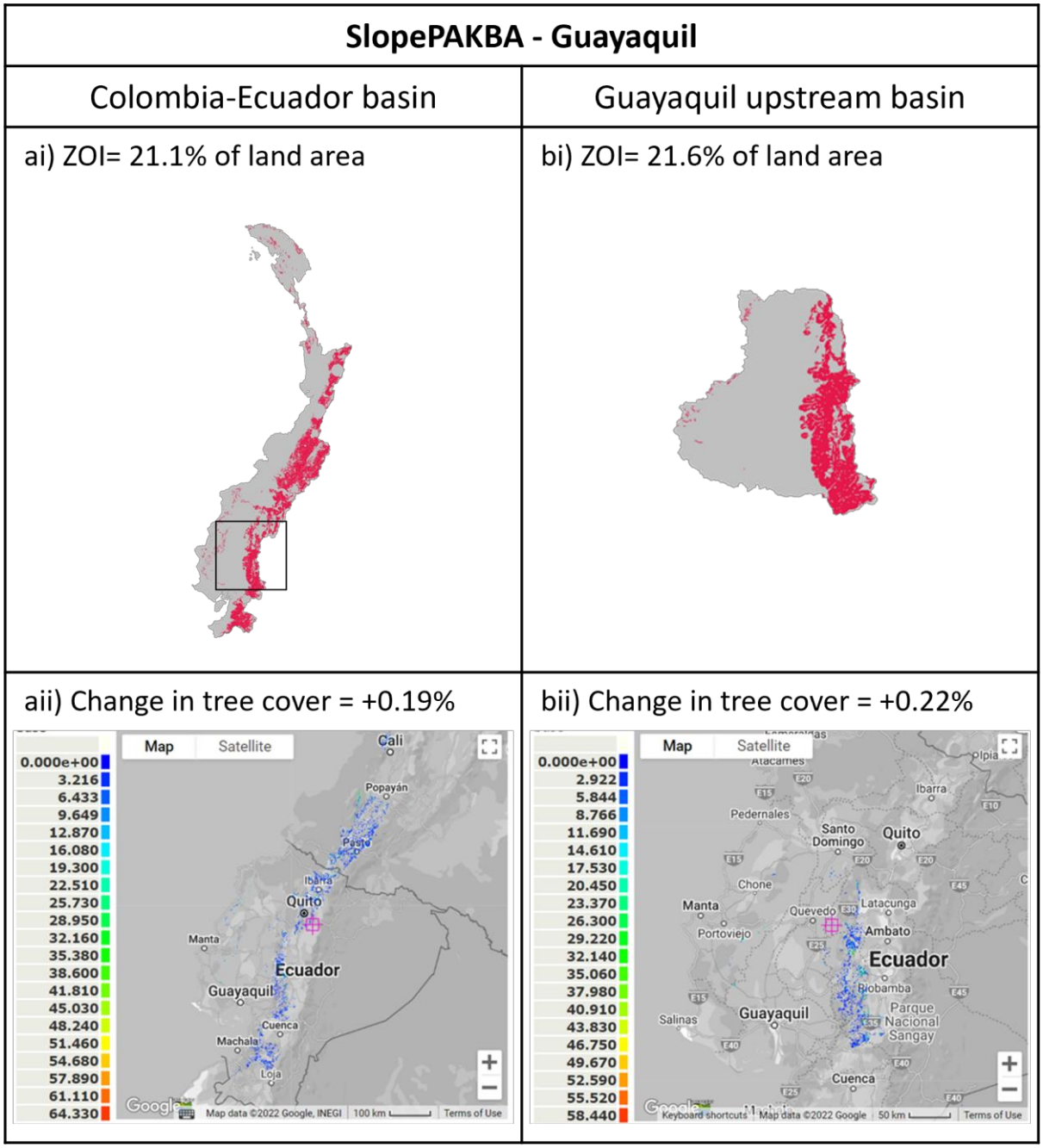


Figure E13. Maps of the Colombia-Ecuador major hydrological basin (a) and the Guayaquil basin (b), showing the spatial distribution of the i) SlopePAKBA ZOI (avoiding PAs and KBAs, and targeting slopes over 5 degrees) and, ii) the resultant change in tree cover. Grey areas are excluded from the ZOI and red areas are included in the ZOI. Black square represents the geographical location of the Guayaquil basin within the Colombia-Ecuador basin.

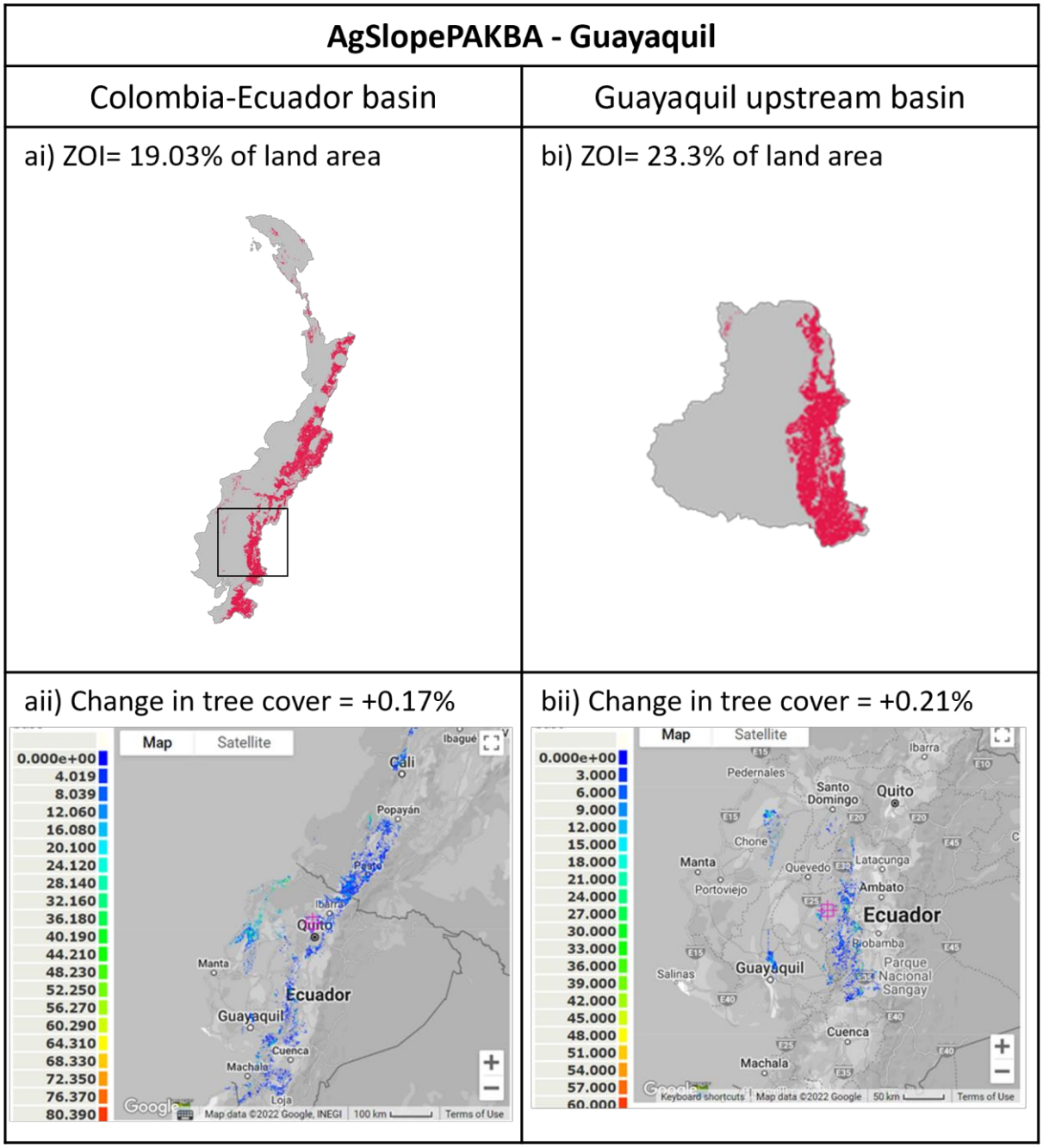


Figure E14. Maps of the Colombia-Ecuador major hydrological basin (a) and the Guayaquil basin (b), showing the spatial distribution of the i) AgSlopePAKBA ZOI (avoiding PAs and KBAs, and targeting low suitable agricultural land and slopes over 5 degrees) and, ii) the resultant change in tree cover. Grey areas are excluded from the ZOI and red areas are included in the ZOI. Black square represents the geographical location of the Guayaquil basin within the Colombia-Ecuador basin.

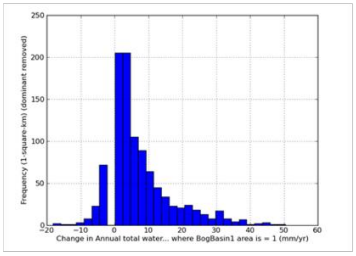
E3. Change in hydrological variable contribution

Figure E15 shows the change in hydrological variables that make up the FRR change in the Bogotá basin. For the PAKBA scenario in the Bogotá basin, water balance shows both increases and decreases but more values in the 'increase' classes than 'decrease' classes (Fig. E15a). Looking at this in combination with Figure 5.18, we see that total water balance increased by +0.28% compared to baseline. The increase is explained by the increase in fog inputs (more tree canopy means more ability to capture water vapour which condenses as fog under the canopy). Evapotranspiration showed only increases, which is expected with increased tree cover (Fig. D15aii). Runoff showed both increases and decreases (Fig. E.15aiv). The slight overall increase at the basin scale (+0.22%, Fig. 5.18) is a result of the increase in water balance.

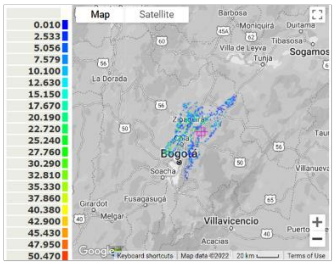
Under the SlopePAKBA scenario for the Bogotá basin, the patterns are similar but dampened (Fig. E15b). Water balance once again has negatives and positive values but increases by only +0.11% (Fig. E1bi), more than half that of the PAKBA scenario, with the input from fog reduced, +1.69%, compared to +4.89% in the PAKBA scenario (Fig. D15biii). It is notable that under both forestation scenarios, all the variables show an increase overall at the basin scale, compared to baseline conditions.

PAKBA - Bogota

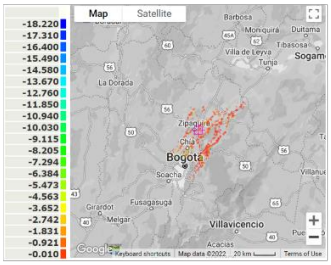
ai) change in total water balance



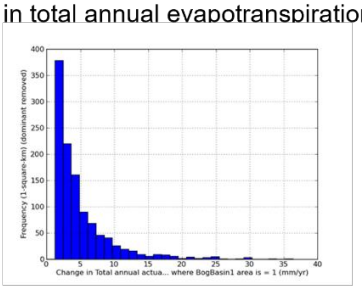
Positives



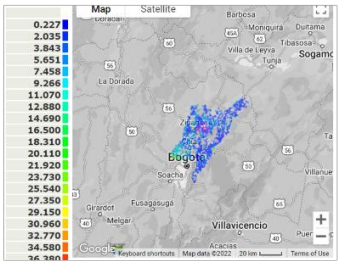
Negatives



aii) change in total annual evapotranspiration

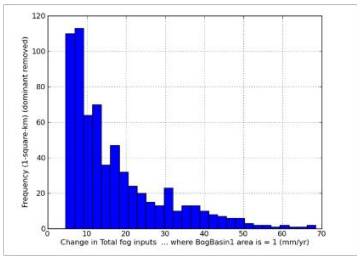


Positives

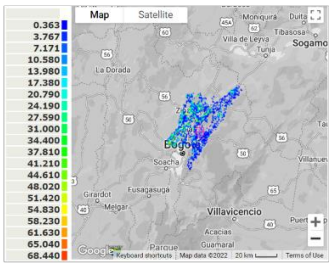


Negatives
n/a

aiii) change in total annual fog inputs

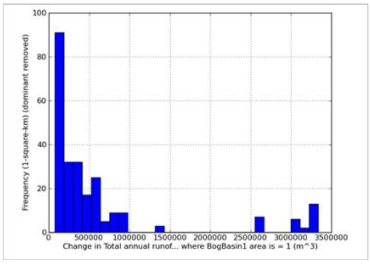


Positives

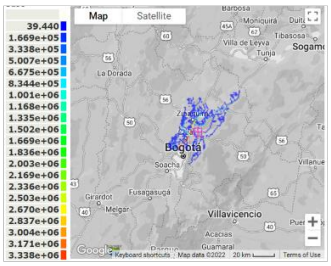


Negatives
n/a

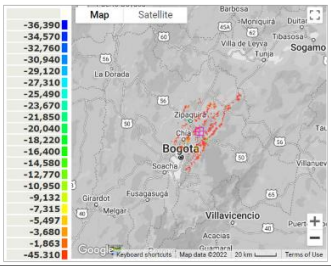
aiv) change in total annual runoff



Positives



Negatives



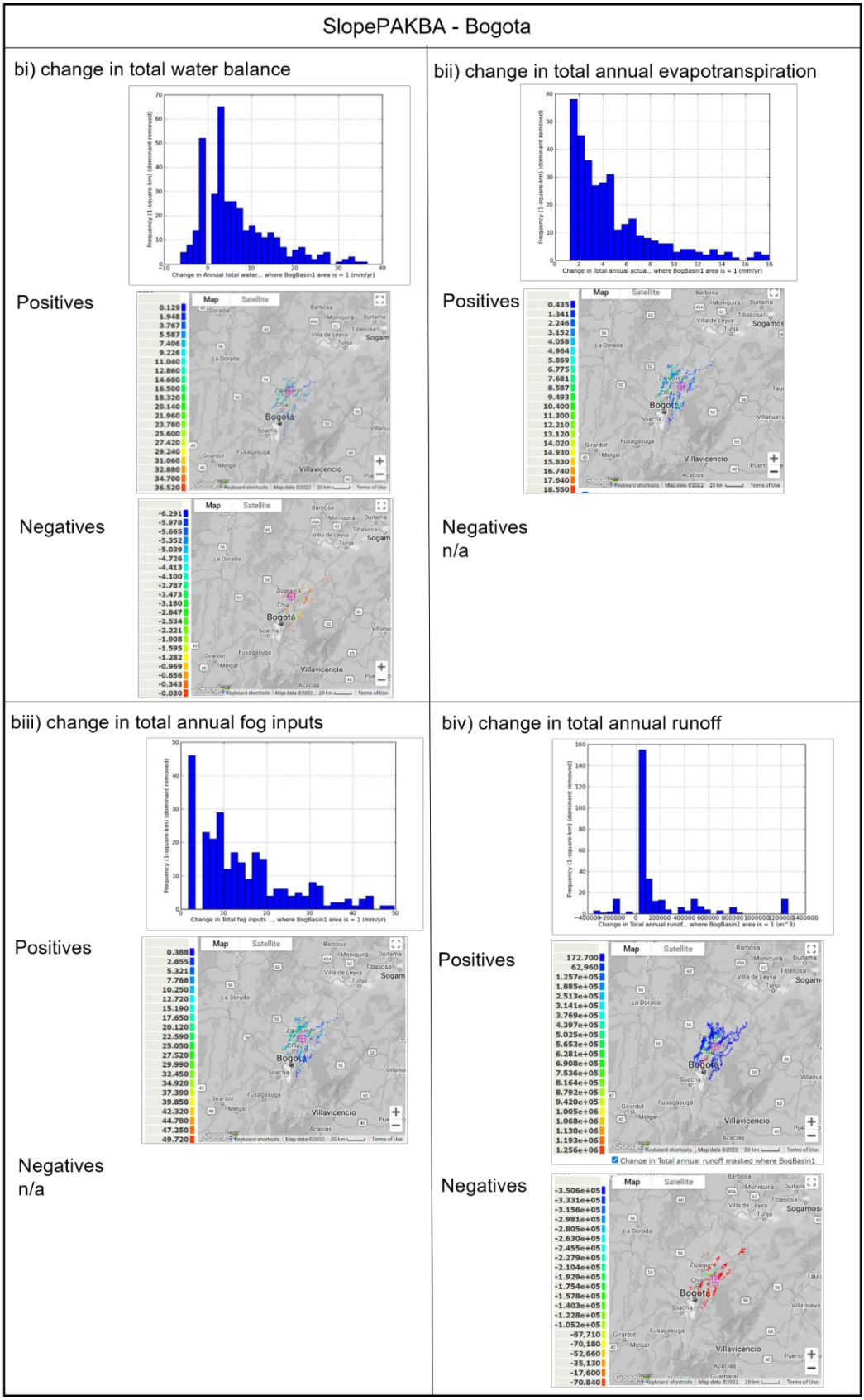


Figure E15 Comparing influence of hydrological variables in the Bogotá basin, for scenarios: a) PAKBA, and b) SlopePAKBA for i) change in total annual water balance, ii) change in total annual evapotranspiration, iii) change in total fog inputs and iv) change in total annual runoff.

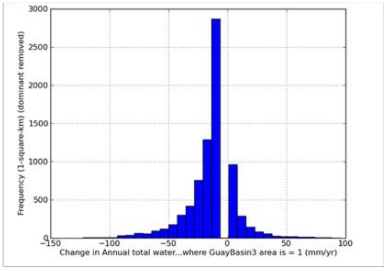
Figure D16 show the change in hydrological variables that make up the FRR change in the Guayaquil basin. Under the PAKBA scenario, water balance shows more values in the 'decrease' class than the 'increase' class (Fig. E16ai). The percentage decrease is -0.25% (Fig. 5.20b). This is different to the PAKBA scenario for the Bogotá basin, which had overall increases in water balance. Spatially, the decreases in water balance in the Guayaquil basin are in the western part of the basin (low elevation) while the increases are in the eastern (high elevation) regions. Evapotranspiration is primarily all positive numbers with a few scattered areas of decreases (Fig. E16aii). Fog inputs only display increases but there are areas in the central plain and eastern mountains where there is no change from baseline (Fig. 5.19aiii). Total runoff increases and decreases but with more values in the decrease class and spatially concentrated on the western part of the basin Fig. E16aiv).

Under the AgPAKBA scenario for the Guayaquil basin, water balance has more values that increase than decrease (Fig. E16bi) but with the negative values occurring in both the western and eastern edges of the basin. Evapotranspiration has all positive values but the change is much lower than under the PAKBA scenario (+0.08 compared to +1.1%, Fig. 5.20). Fog inputs are all positive values (Fig. D16biii). Runoff has both positive and negative values but more positive than negative (Fig. D16biv) with runoff increasing slightly at the basin scale compared to baseline (Fig. 5.20).

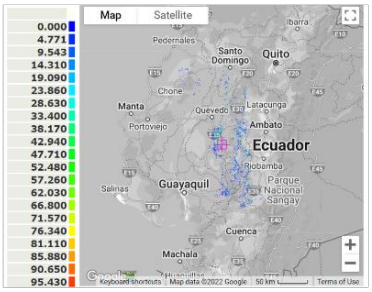
Under the SlopePAKBA scenario for the Guayaquil basin, there are very few negative values for water balance (Fig. E16ci) with water balance increasing only marginally (+0.02%) at the basin scale compared to baseline. Evapotranspiration has only positive values; these are concentrated in the eastern part of the basin (Fig. E16cii), likewise with fog inputs (Fig. E16ciii). For runoff, the map shows negative values that are not shown in the frequency distribution (Fig. E16civ). This may be because the range is high and the negative values are few and small, so they do not show, given the range of the frequency distribution.

PAKBA - Guayaquil

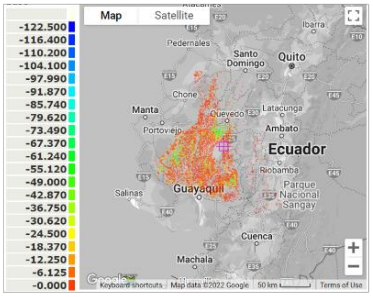
ai) change in total water balance



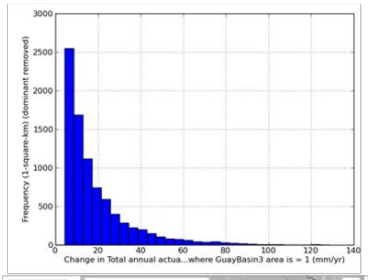
Positives



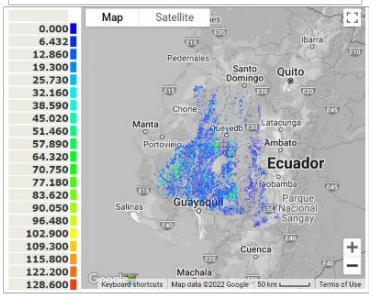
Negatives



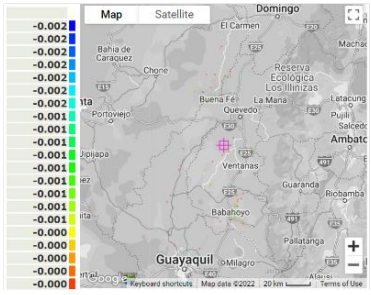
aii) change in total annual evapotranspiration



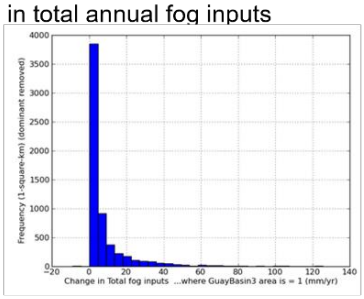
Positives



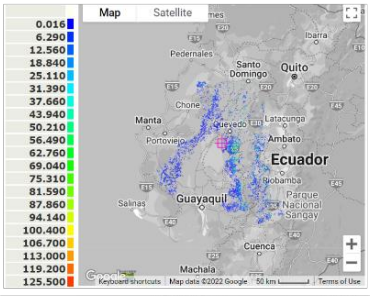
Negatives



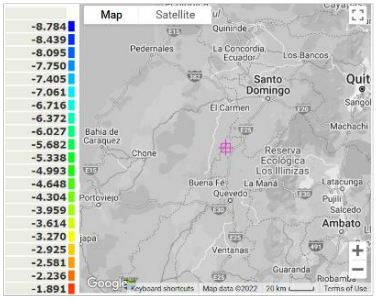
aiii) change in total annual fog inputs



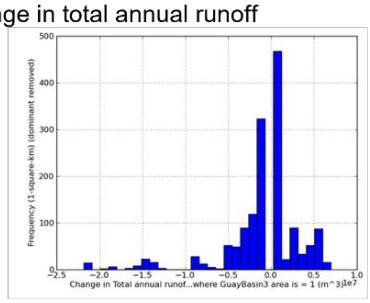
Positives



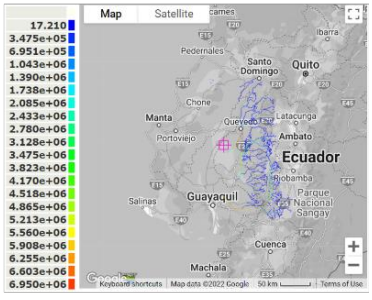
Negatives



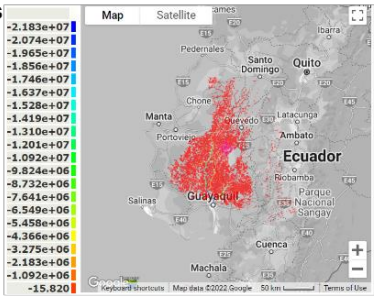
aiv) change in total annual runoff



Positives

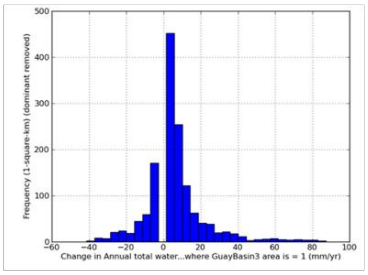


Negatives

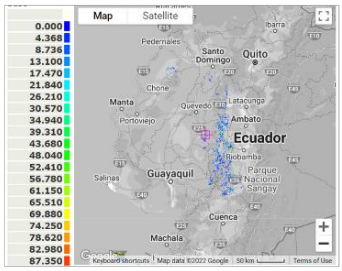


AgPAKBA - Guayaquil

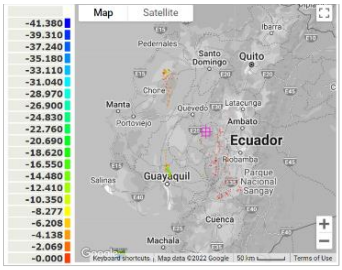
bi) change in total water balance



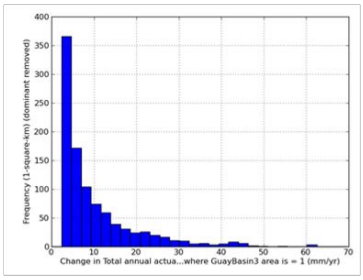
Positives



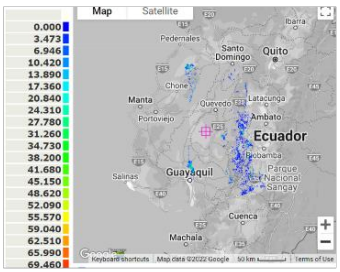
Negatives



bii) change in total annual evapotranspiration

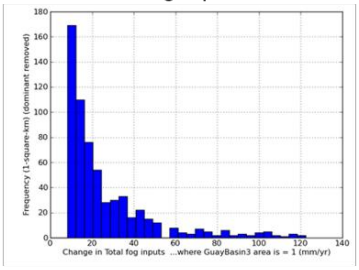


Positives

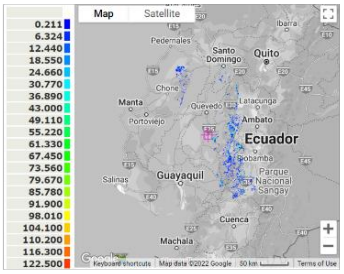


Negatives
n/a

biii) change in total annual fog inputs

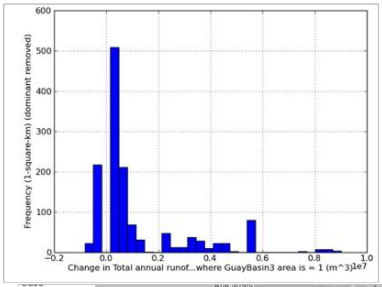


Positives

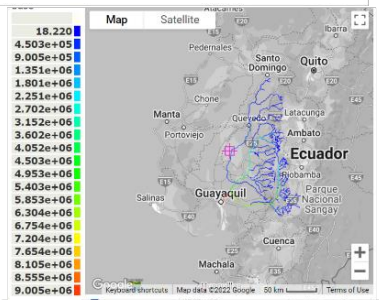


Negatives
n/a

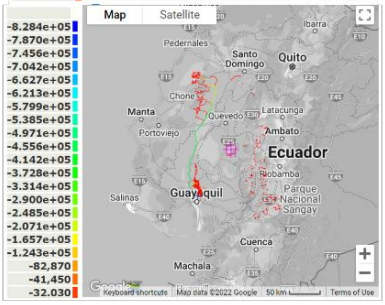
biv) change in total annual runoff



Positives



Negatives



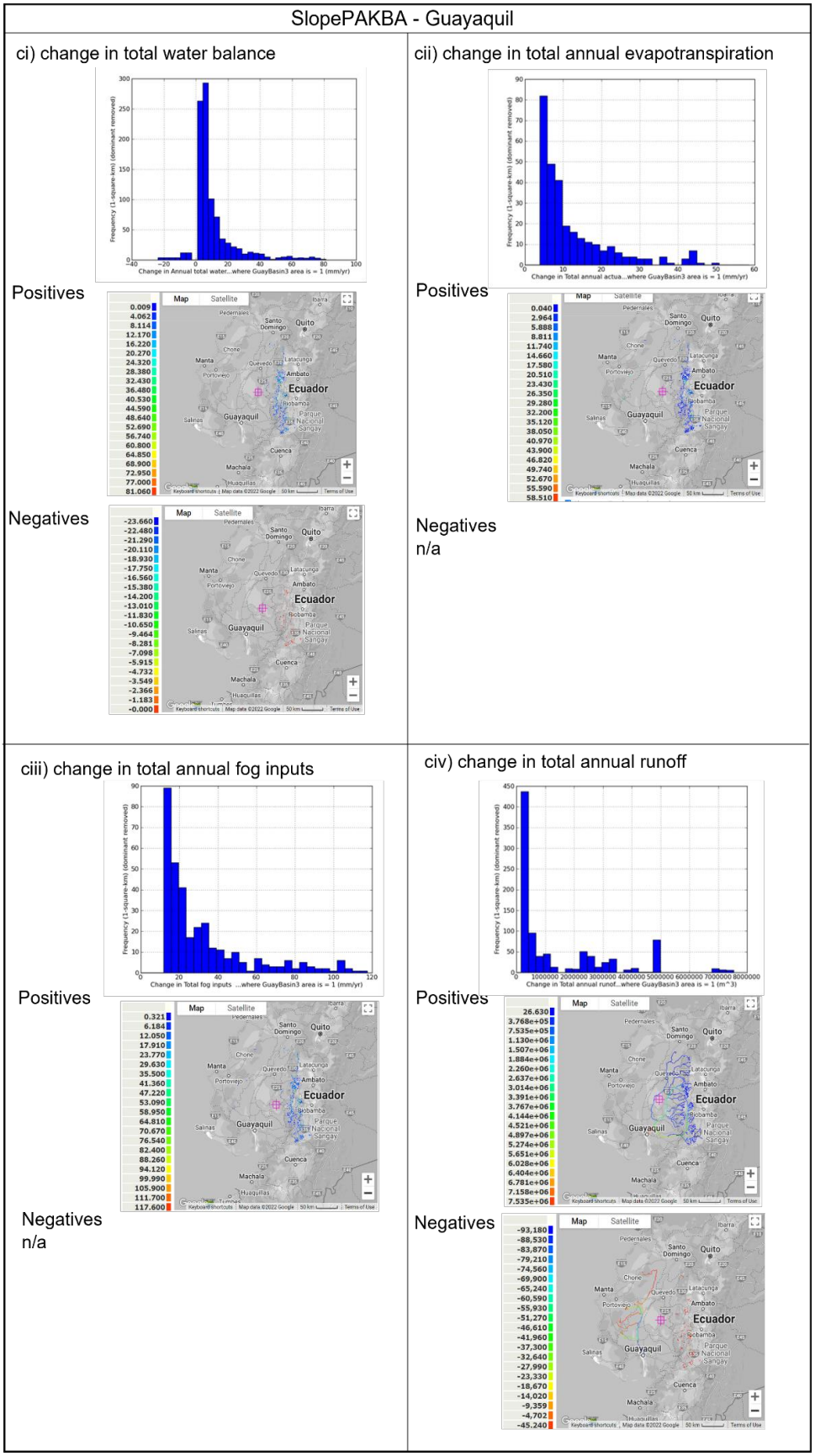


Figure E16. Comparing influence of hydrological variables in the Guayaquil basin, for scenarios: a) PAKBA, b) AgPAKBA, and c) SlopePAKBA for i) change in total annual water balance, ii) change in total annual evapotranspiration, iii) change in total fog inputs and iv) change in total annual runoff.

E4. Flood Risk Trajectories of the Restoration scenarios on Google Earth Imagery

Flood risk trajectory maps from the forest restoration LUC scenarios are overlaid onto Google Earth imagery (Fig. E17 and E18). Green is high-risk decreasing, yellow is low risk decreasing, purple is high-risk becoming low risk.

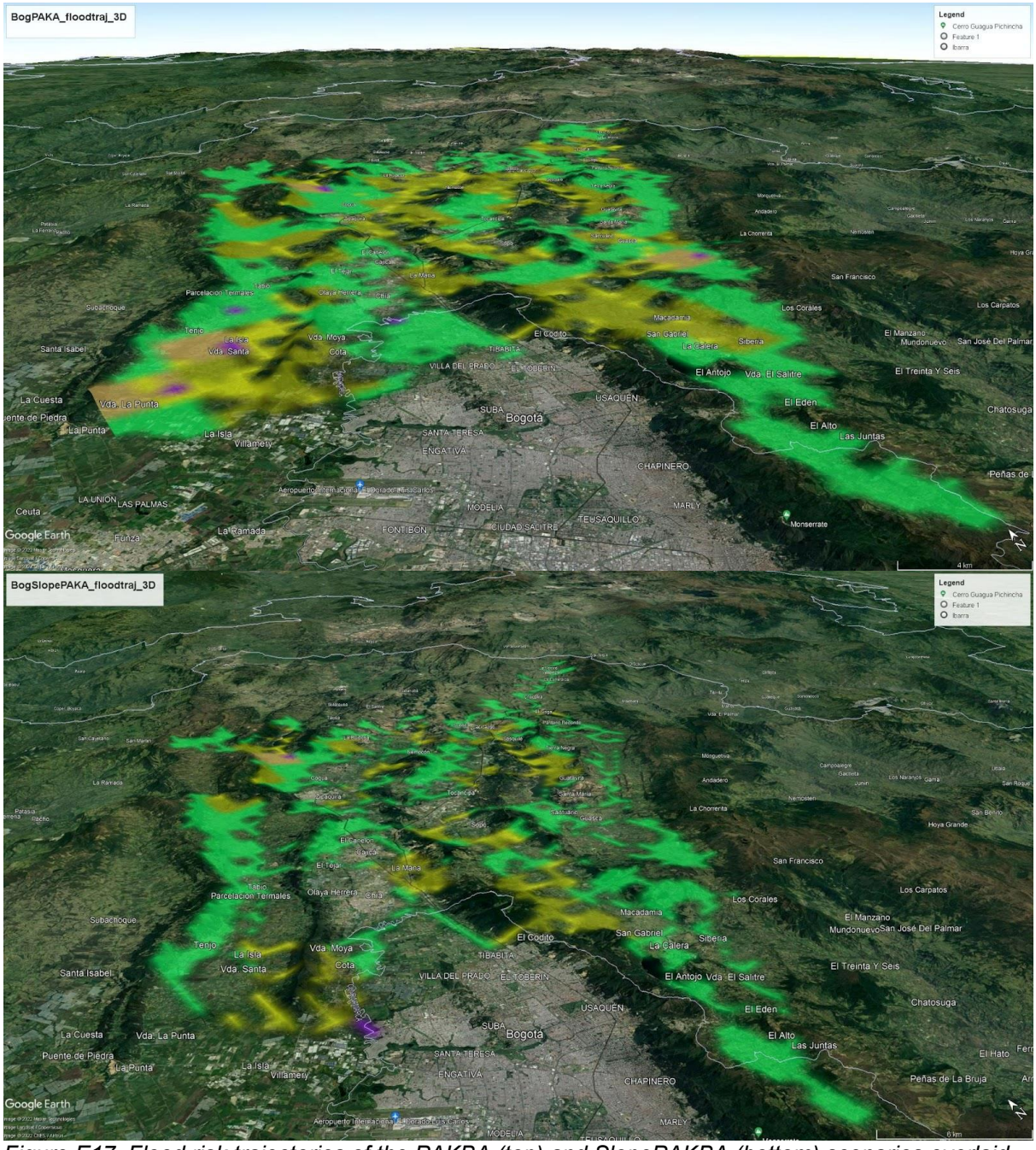


Figure E17. Flood risk trajectories of the PAKBA (top) and SlopePAKBA (bottom) scenarios overlaid onto Google Earth imagery for the Bogotá basin. Green is the 'high-risk decreasing' class, yellow id 'low-risk decreasing' class and purple is 'high-risk becomes low-risk'.

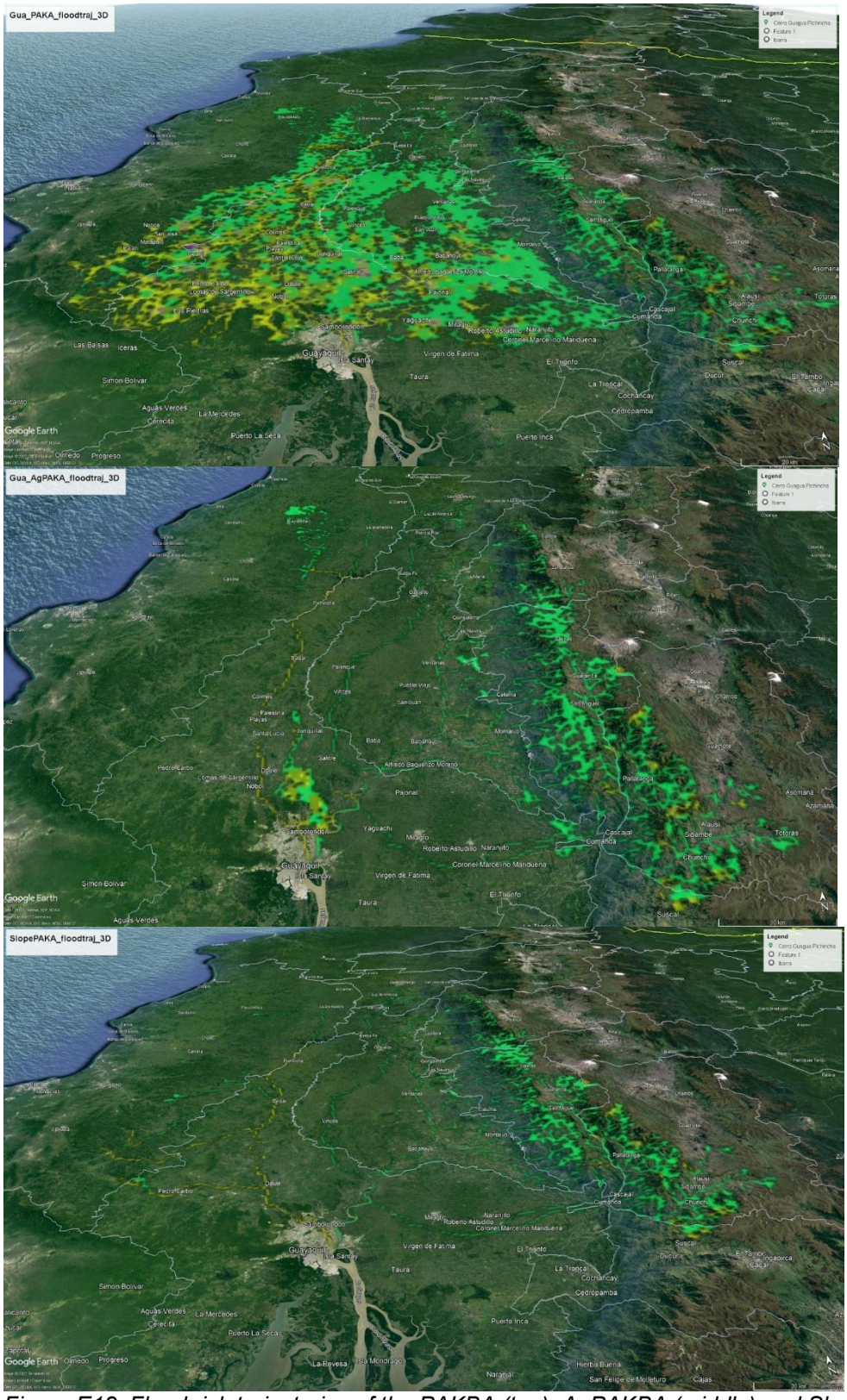


Figure E18. Flood risk trajectories of the PAKBA (top), AgPAKBA (middle) and SlopePAKBA (bottom) scenarios overlaid onto Google Earth imagery for the Bogotá basin. Green is the 'high-risk decreasing' class, yellow id 'low-risk decreasing' class and purple is 'high-risk becomes low-risk'.

E5. Exploring the characteristics of areas of 'overlap' of forest induced FRR reduction and climate induced FRR increase

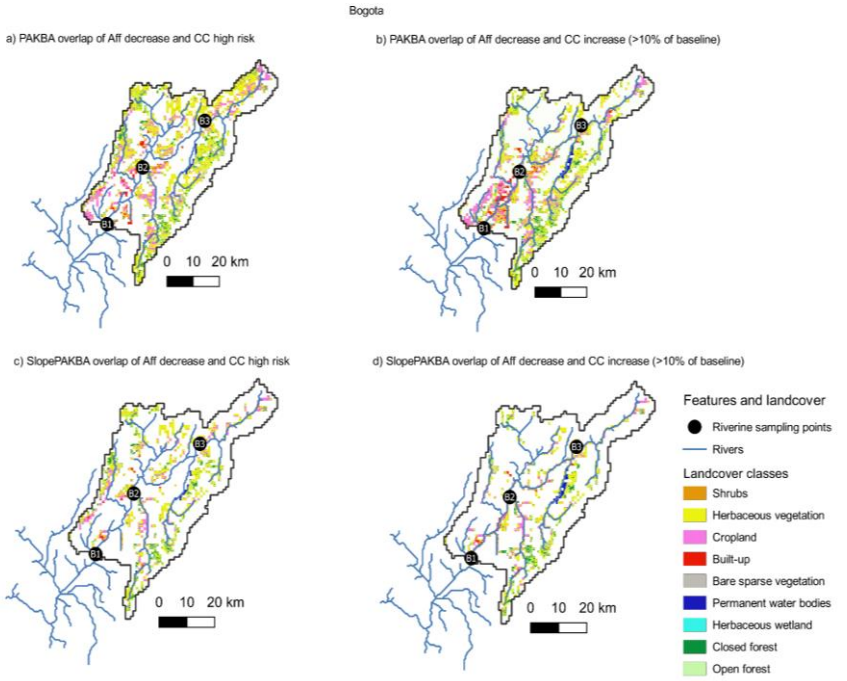


Figure E19. Land cover map (Copernicus, 2019) masked by areas of overlap (i.e., areas where the FRR decreases under forestation scenarios coincide with where the FRR increases under climate scenarios) for the Bogotá basin.

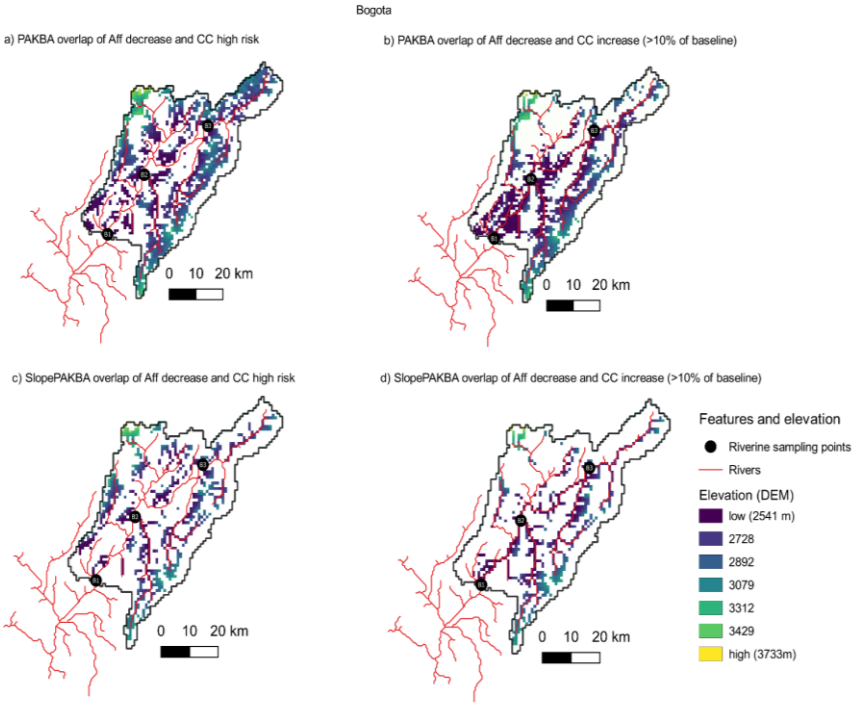


Figure E20. Digital Elevation Model (DEM; STRM60) masked by areas of overlap (i.e., areas where the FRR decreases under forestation scenarios coincide with where the FRR increases under climate scenarios) for the Bogotá basin.

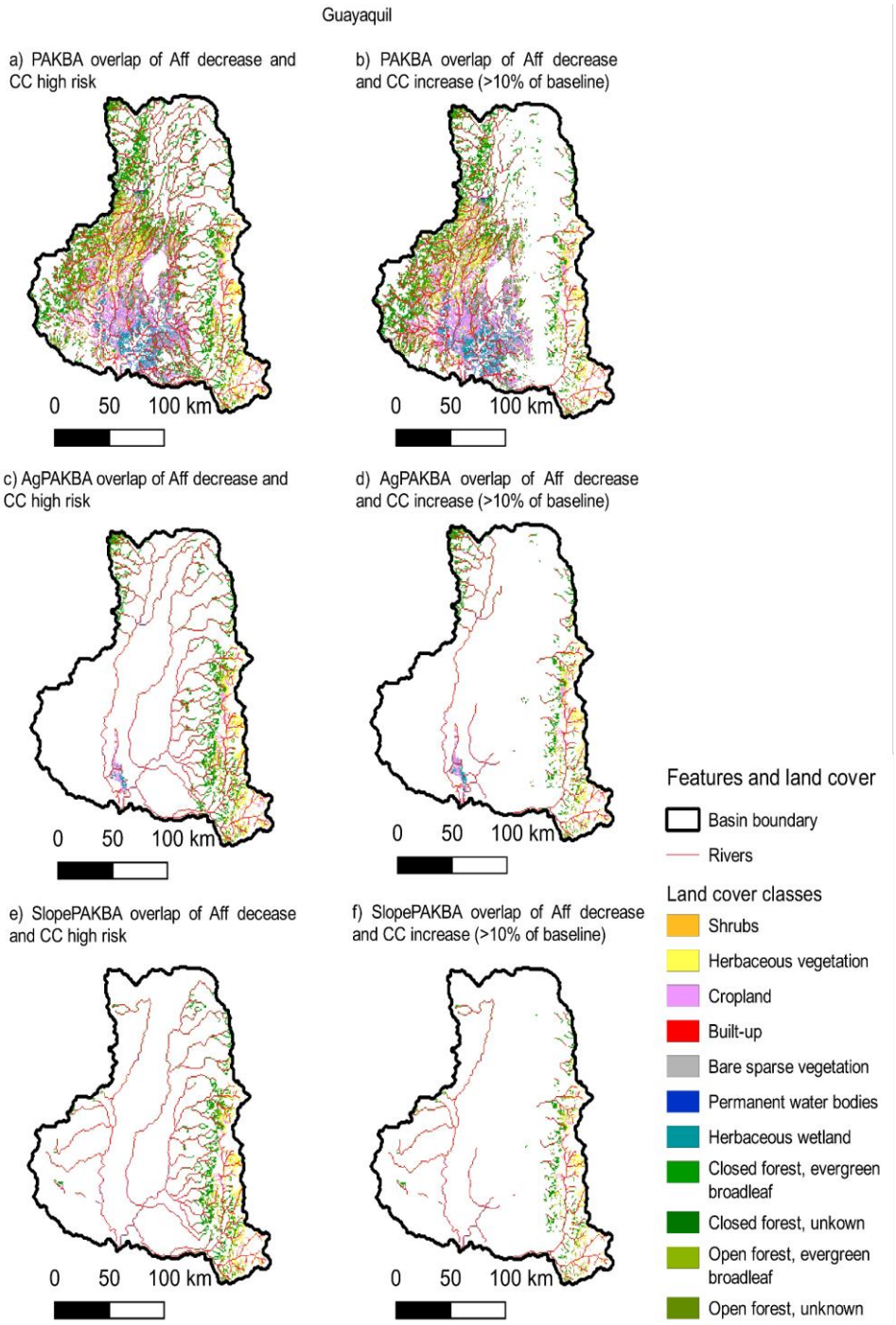


Figure E21. Land cover map (Copernicus 2019) masked by areas of overlap (i.e., areas where the FRR decreases under forestation scenarios coincide with where the FRR increases under climate scenarios) for the Guayaquil basin.

In the Guayaquil basin, the overlap areas on land-cover, show different patterns based on the scenario (Fig. E21). For the PAKBA scenario, the overlap areas are dispersed across the whole basin with a high concentration on the western and middle part, coinciding with cropland, herbaceous vegetation and forested land cover (Fig. E21a, b). For the AgPAKBA scenario, the overlap areas are concentrated on the western boundary of the basin, the top north-west corner and the southern middle area, above Guayaquil (Fig E21c, d). The land cover in these areas is mostly herbaceous vegetation and some forest. The overlap areas also follow the main river networks. For the SlopePAKBA scenario, the overlap areas are mostly along the eastern boundary and some of the western river networks (Fig. E21e, f).

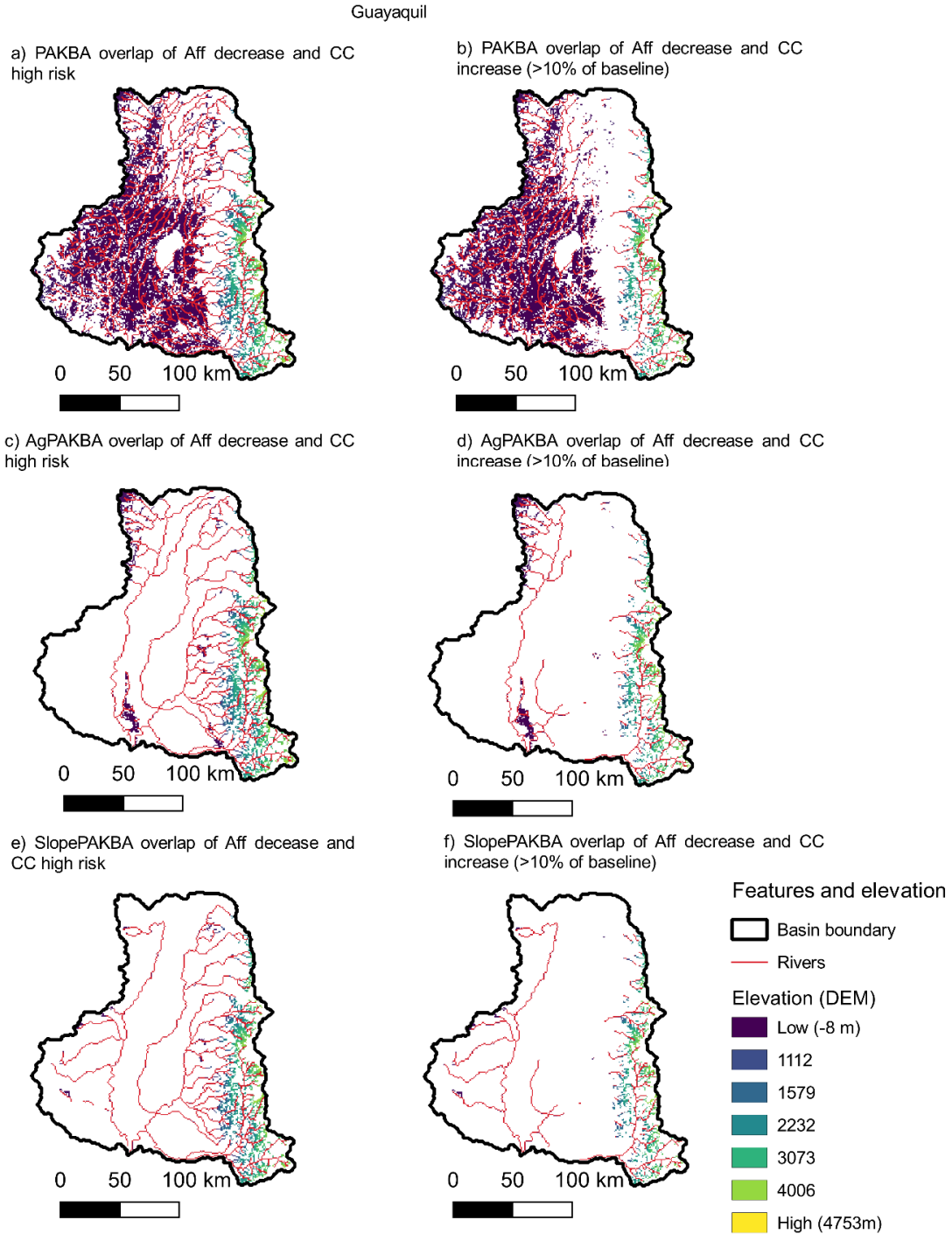


Figure E22. Digital Elevation Model (DEM; STRM60) masked by areas of overlap (i.e., areas where the FRR decreases under forestation scenarios coincide with where the FRR increases under climate scenarios) for the Guayaquil basin.

Ends