Master's Thesis – master Sustainable Development

Assessment of hydrological response on reforestation in the Atlantic Forest of Brazil

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Summary

Atlantic Forest biome is one of the world's biodiversity hotspots (Médail & Myers, 2004; Ribeiro et al., 2009). Over the last five centuries, it went through intense land use change and deforestation, which has left the forest fragmented and decreased to less than 15% of its original size (Ribeiro et al., 2009; INPE, 2019). Forests are crucial in maintaining the water cycle and providing ecosystem services such as water availability and security (Bakker, 2012; Ferreira et al., 2019b). Few studies focus on reforestation and its effects on hydrological response of the area (Salemi et al., 2013)

The objective of this thesis was to quantify the hydrological changes of increasing levels of reforestation and assess the overall impact on the hydrology of Atlantic Forest under feasible scenarios for the expansion of the Atlantic Forest. The hydrological response of reforestation in this thesis is determined by the following parameters: evapotranspiration, groundwater recharge, soil moisture and discharge.

The impacts of reforestation on hydrological response of reforestation were analysed using four scenarios. The scenarios reflecting land-use changes, particularly increase in forest cover were used as an input for the model PCR-GLOBWB (van Beek et al., 2011; Wada et al, 2011b, 2014). This was done in order to compare the effect of different reforestation intensities on the hydrology withing the Atlantic Forest biome.

Increase in forest cover showed marginal changes as increase in evapotranspiration, ground water recharge and a decrease in soil moisture. However, the relationship between soil moisture and forest cover has not been statistically significant. Whereas the hydrological response of reforestation on evapotranspiration and groundwater recharge has been found statistically significant. Overall, discharge has been found to decrease with increase in forest cover

1. Introduction

In Brazil aproximately 26.2 Mha of primary forest has been deforested from 2002 until 2020 (The Nature Conservancy, 2021a). The Atlantic Forest has lost most of its original forest cover due to land-use changes (Brooks et al., 1999; Tabarelli et al., 2004) and it retains only 16.2 percent of its original cover (Calaboni et al., 2018). Through reforestation and restoration projects a slow increase in forest area is noticeable (Crouzeilles et al., 2019).

Forests are crucial in maintaining the water cycle and providing ecosystem services such as water availability and security (Bakker, 2012; Ferreira et al., 2019b). The positive relationship of reforestation and water quality is observed in a reduction of soil erosion and sedimentation, and reduction of pollution (Stolton and Dudley, 2007; Filoso et al., 2017). Besides the reforestation benefits on water quality, forests are crucial in regulating the water flow. Under favourable conditions forests have been found to increase soil infiltration and improve groundwater recharge (Ellison et al., 2017), decrease discharge and run-off (dos Santos et al., 2018), increase evapotranspiration (Loucks et al., 2005) and have a cooling effect on local land surface temperatures (Peng et al., 2014). Previous studies researching hydrological response on afforestation have accentuated decrease in run-off and soil moisture due to increased evapotranspiration demand (Y. Li et al., 2020)

As explained above, forests provide many ecosystem services, but marginal benefits of extra unit of forest are rarely evaluated (Ricketts & Lonsdorf, 2013). Marginal changes are mostly analysed when a land use change from forest to agriculture occurs, rather than other way around. According to Polasky et al. (2011) marginal values provide thorough evaluations of changes in ecosystems, including landscape optimization, dynamic conservation planning and return on investment (Polasky et al., 2011). Depending on the scale and the area's specific characteristics, it is still unknown how will the hydrological cycle change and what its effects would be looking from local and regional scale. Evaluation of marginal changes of an extra unit of forest has also been unclear. Although, some studies touch upon the land-use change impacts on hydrology in Brazil (Ferreira et al., 2019; Montenegro & Ragab, 2012; Siqueira et al., 2021; Viola et al., 2014), but little attention has been given to reforestation and its effects on hydrology (Salemi et al., 2013).Studies on this topic are related to long-term assessment of already reforested areas in other regions in the world (Buttle, 1994; S. Li et al., 2014). The findings from the study of Buttle (1994) show that hydrological response can be seen even with small modification in forest cover, but it largely depends on location of land use change within the area.

The objective of this thesis was to quantify the hydrological changes of increasing levels of reforestation and assess the overall impact on the hydrology of Atlantic Forest under feasible scenarios for the expansion of the Atlantic Forest. The hydrological response of reforestation in this thesis is determined by the following parameters: evapotranspiration, groundwater recharge, soil moisture and discharge. These parameters were chosen because they have been recognized as important relationship indicators of forest change and its influence on hydrology (Bruijnzeel, 2004; Ellison et al., 2017). Based on these the following main research question is formulated:

What are marginal changes of the hydrological response as a result of increased forest cover?

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2. Theory

2.1 Atlantic Forest – importance and land use change

Atlantic Forest biome used to be one of the largest rainforests of South America, originally covering 150 million ha (Myers et al., 2000). It is one of the world's biodiversity hotspots (Médail & Myers, 2004; Ribeiro et al., 2009). The Atlantic Forest has been facing deforestation ever since European settlement in 1500 (Joly et al., 2014). Over the last five centuries, it went through intense land use change and deforestation, which has left the forest fragmented and decreased to less than 15% of its original size (Ribeiro et al., 2009; INPE, 2019). Today it still maintains one of the highest in high amount of species richness and endemism the world. (Laurance, 2009; Médail & Myers, 2004; Myers et al., 2000; Rezende et al., 2018). The Atlantic forest biome is a host to unique and rare ecosystems such as restingas, swamps, inselbergs (isolated rock hills), dry forests, and high-altitude campos (Laurance, 2009). Around 20,000 plant species, 261 mammal species and 688 bird species are endemic to the Atlantic Forest biome. Moreover, 1544 plant species and 380 animal species in the Atlantic Forest biome are endangered Martinelli & Moraes (2013), which is equal to 60 % of the whole list of threatened species for Brazil (Rezende et al., 2018).

Land-use change

Intensive logging of the Pau-Brasil tree *(Caesalpinia echinate*) within the Atlantic Forest biome began in the 16th Century due to its dense red pigment used for dyes that highly prized at that time (Lichtenberg et al., 2019). Nowadays, exploitation continues for use in production of high-quality string instrument bows (Lichtenberg et al., 2022). In 2009 it has been classified as an endangered by IUCN Red List, class EN (IUCN, 2022). This was recognized as a first cycle of Atlantic forest biome exploitation (Sattler et al., 2018).

In the 17th Century, second cycle of economic exploitation started with sugar cane in the northeast of Brazil followed by the third cycle of exploitation of coffee in southeastern Brazil throughout the 18th and 19th Centuries. Fourth cycle occurred during the 19th and 20th Centuries cocoa in the State of Bahia (Joly et al., 2014). More specifically, coffee plantations required fertile soil to grow thus primary forest faced deforestation as exports were increasing. In the State of Rio de Janeiro, after the collapse of the coffee market in the late 19th Century, many coffee plantations were replaced for livestock farming (Nehren et al., 2013). In other states, such as São Paulo and Minas Gerais, soil on coffee plantations due to intensive use became degraded and the land was replaced by cattle ranching. However, the pasturelands did not only expand upon the abandoned coffee plantations, but also upon the forest (Joly et al., 2014). Expansion of pasturelands is thus considered a 5th cycle of Atlantic Forest biome exploitation.

Another anthropogenic cause of deforestation has been urbanization and popularization of cities (Marques & Grelle, 2021). The area of the Atlantic Forest biome includes the Rio de Janeiro–São Paulo megalopolis and 5 state capital cities. Apart from providing ecosystem services, including potable water and climate regulation, to more than 125 million of people (Joly et al., 2014), the Atlantic Forest biome has a crucial agricultural and economic role. Large areas of native cover loss have been replaced for agricultural use that is facing exponential developmental phase and it contributes highly to the Brazilian GDP (Rosa et al., 2021). Thus, reforestation initiatives could be hindered by the economic growth and expansion of agriculture as it is predicted that Brazil will increase exports of food commodities by 2025 (Westcott, 2016).

Although urbanization, industrialization, and intensive farming brought on economic development, it also resulted in a loss of the Atlantic Forest. Very few large patches of old-growth forest remain, and they are surrounded by small edge-affected forest fragments, secondary forest patches emerging from cropland or abandoned pastures, assisted regenerating forest parcels (sensu Chazdon, 2008), *Eucalyptus and Pinus* tree plantations (Fonseca et al., 2009) and agroforestry landscape (Joly et al., 2014). Atlantic forest cover changes from 1990 to 2017 were (Rosa et al., 2021):

i. Native forest cover remained fairly stable (~28Mha)
ii. the area of croplands doubled
iii. the area of monoculture tree plantations quadrupled
iv. the area of planted pasturelands declined by 20% (reduction of ~ 13 Mha)

The spatiotemporal persistence of native forest cover appears to be directly related to the movements of the region's agro-pastoral land use (Rosa et al., 2021). Native forest cover is identified by Rosa et al. (2021) as areas that are larger than 0.5 ha with at least 70 % canopy cover, vegetation older than 4 years and higher than 5 m. It has been argued that the native forest cover has remained almost stable in the last 10 years. It is mainly due to expansion of croplands and monoculture plantations over pasturelands. Although, deforestation of native forests has been camouflaged by planting young forest on agricultural marginal lands (Lapola et al., 2014). Those lands are usually in degraded states (Wright, 2005). Native forest gain was observed to be lower in the area of pasturelands with the exception of riparian buffers protected by the federal legislation known as Areas of Permanent Preservation (APP), on which 291,000 ha of forest was restored (Rosa et al., 2021).

Figure 1 (left) shows percentages of former land use that have been converted into new forest. It is noteworthy to mention that 39% of land converted from native forest had been cut for a minimum of 3 years before reforestation occurred. Land cover use in the Atlantic Forest on deforested area as per year 2017 can be seen from the Figure 2 (right). Overall, historical land use changes from 1985 until 2020 can be seen in the Figure 3. seemingly, forest cover remained stable, that is due old forest being cut and replanted on flatter grounds and on abandoned or marginal agriculture land (Rosa et al., 2021)In general, native forest provide multiple ecosystem services such as climate regulation, water provision and balance, erosion prevention, pollination, and recreation (Marques & Grelle, 2021). Even though newly planted forest can increase certain ecosystem services, it might take decades to overtake the function of native forest cover, particularly in regard to the forest composition, biodiversity and hydrological services (Chazdon, 2008; Molin et al., 2017).

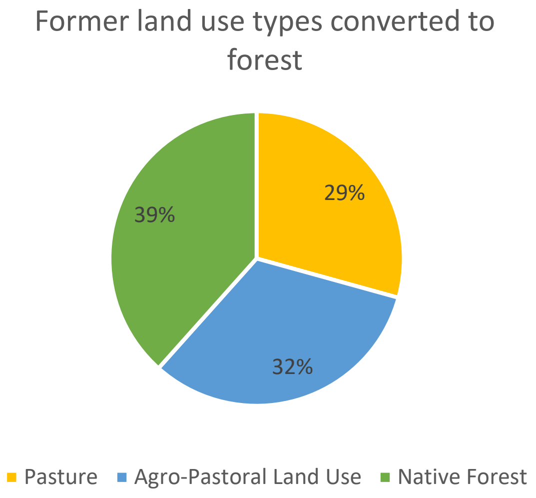


Figure 2: Former land use types converted to young forest, as retrieved by Rosa et al. (2021)

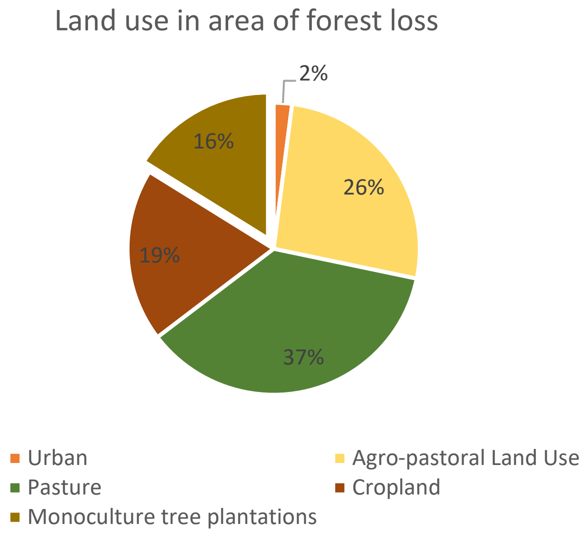


Figure 1: Land use in area of forest loss, as retrieved by Rosa et al. (2021)

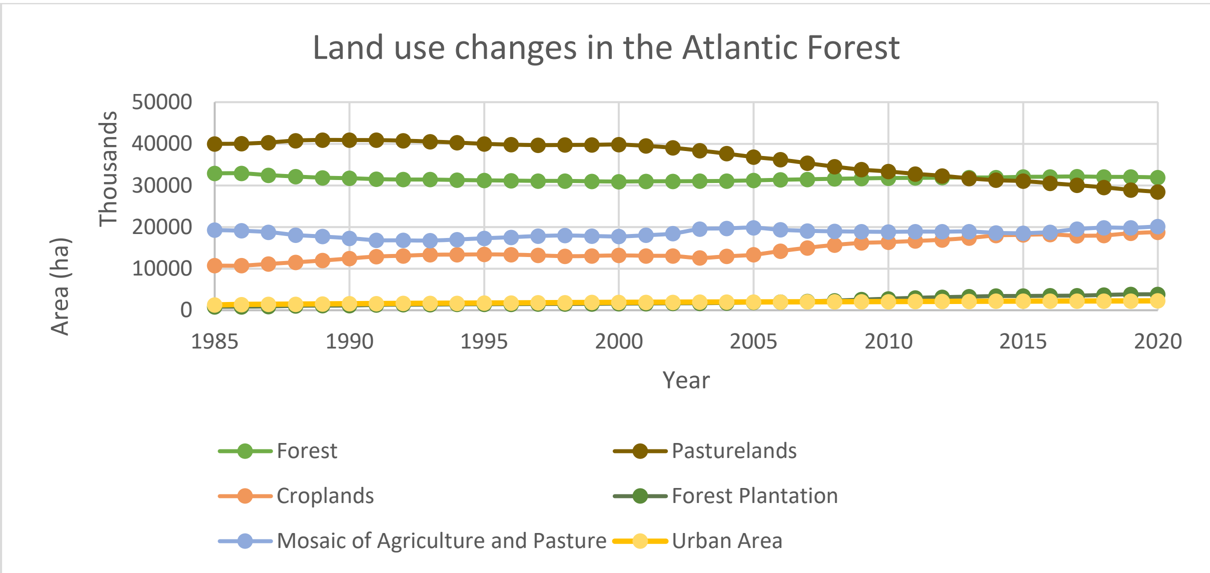


Figure 3: Land use changes in the Atlantic Forest, as per Rosa et al. (2021)

2.2 Relationship between forests and hydrology

Ecohydrological functions of forests

Forests provide important ecosystem services (ES) in a global and local context. Forest related ecosystem services include provision services (wood, timber, biobased products, food), regulating services (climate regulation, air quality, carbon sequestration), supporting services (canopy interception, evapotranspiration, habitat provision), and cultural services such as recreation and tourism that are related to well-being Water-related ecosystem services provide specific ecohydrological functions. For instance, flood protection, low flow conservation, erosion control and landslide regulation. A range of key ES are directly linked to the hydrologic cycle as can be seen from the Table 1:

Table 1: Water-related Forest ecosystem services of forests (adjusted, as per Muys et al., 2014 and Martin-Ortega et al., 2015)

Ecosystem Service Category	Forest Ecosystem Service
Supporting services	Canopy interception, Root uptake, Evapotranspiration
Provisioning services	Drinking water provision
Regulating services	Climate regulation, Atmospheric cooling, Microclimate formation, Erosion control, Flood regulation, Landslide mitigation, Water purification and turbidity regulation
Hydrological services	Low flow conservation, Flood reduction, Improved infiltration and balancing run-off
Cultural services	Recreation, Ecotourism

Hydrologic (water) cycle

Hydrologic cycle happens continuously in nature, and it's considered a water transfer cycle. There are three important stages that drive the hydrologic cycle: evaporation and evapotranspiration, precipitation and run-off. Solar energy initiates the hydrologic cycle by evaporation from open water surfaces. The air saturates with moisture and rises and condenses with cold temperature, resulting in cloud formation. Water then reaches the ground surface as precipitation. Part of the water evaporates back into the atmosphere, another part infiltrates and becomes available as groundwater. The remaining part of water on the ground surface that doesn't infltrate is called a run-off. It occurs when surpluss incoming water is unable to rapidly infiltrate due to soil being fully saturated.

Role of forest in the hydrologic cycle

Forests play a significant role in the water balance by contributing the amount of precipitation that can be reserved as canopy interception, the amount transpired by the trees and the capability of great inflitration. Part of the precipitation that falls on the ground surface is infiltrated into the soil, however part is reduced by the canopy and leaf interception. But also, a portion is evaporated back to the atmosphere from the leaves. A large amount of soil moisture is transpired to the atmosphere by transipation and movement of water through the roots-stem-leaf mechanism(Hadi Pour et al., 2020) . Forests increase the amount organic matter in the soil. Soil organic matter, tree roots and leaf litter (X. Li et al., 2014) increase the infiltration rate and soil moisture holding capacity. The portion of water that infiltrates replenishes underlying aquifers. Combination of this processes, in forested watersheds has been found to decrease overland run-off and water yield when compared to non-forested watersheds (Bosch & Hewlett, 1982b; Zhang et al., 2021).

Precipitation, evapotranspiration, run-off and soil water storage influence and control the hydrological equilibrium of an area (Bonan, 2015). Also, forests have been found essential in regulating the water flow as the portion of blue water infiltrates and becomes available as a baseflow, it lowers the discharge of the watershed area (Neto et al., 2016). In this way, forests have a positive effect on water availiability throughout dry season and periods of low flow. However, if the area is already prone to experiencing droughts, forests can emphasize the effects of drought as the roots take up the water stored below ground. Thus, depending on the conditions forest's effect on low flows during dry periods can be negative, insignificant or positive (Calder, 2012). Furthermore, reforestation in terms of plantations and exotic species can disturb evapotranspiration balance and negatively impact availability of water in that area (Trabucco et al., 2008). Reforestation with monoplantations has been found to further reduce water availability when taking into consideration climate change and consequential increase in temperature and decrease in precipitation (Ferreira et al., 2019b). In a study done on small and large watersheds, there was no statistically significant difference between reforestation and run-off in small watersheds. Nontheless, in larger watersheds a negative link has been noted, concluding that the increase in forest cover can lead to a reduction in annual run-off (Pires et al., 2017).

Evapotranspiration

Apart from regulating the surface and base flow, forests aid in precipitation and climate regulation. Flow of atmospheric moisture and precipitation patterns are regulated by forests. Water vapor volatilize from the Earth's surface (land and oceans) into the atmospere. When there is land covered with forest, the process is encouraged by evapotranspiration. Evapotranspiration (ET) is a process that consists of evaporation of water from soil and plants and transpiration of water molecules by plants (Fu et al., 2009) . Term „recycled“ is used to describe evapotranspired water that contributes to the local rainfall.

Thus, by evapotranspiration forests replenish atmospheric moisture by „recycling“ precipitation into clouds influencing wind and weather patterns. In such manner, biotic pumps are created. atmospheric pressure reduces when the rates of evaporation are high over a certain area (Makarieva and Gorshkov, year). This resulting low pressure pulls additional moist air from the zones of lower evaporation, creating a net transfer of atmospheric mositure towards the zones that already have high evapotration rates(Makarieva & Gorshkov, 2007). Moreover, in the same study they developed a possible explanation why in tropic climates rain falls after midday. The precipitation is generated when saturation of accumulated condensed mositure occurs and the humid air created bouyancy that is low enough. It was observed that when plants and trees close their stomata, which frequently happens in the later portion of the day to relieve moisture stress, evaporation then decreases. Hence, this decrease may provide light on why majority of tropical rainstorms occur after noon in many terrestrial ecosystems, aside from marine ones (Nesbitt and Zipser 2003). This is particularly important for Serra do Mar region in Brazil where forests have been found to regulate rainfall and soil stability (Rosado et al., 2012) & (Joly et al., 2014). Plant species such as Hyeronima alchorneoides Allemão (Phyllanthaceae) found in lowland areas of the Atlantic Forest are able to transpire more than 350 liters per day throughout the dry season and 525 liters per day during the wet season (Rosado et al., 2012).

Groundwater recharge is a process of replenishing groundwater resources. It is a hydrologic process where the infiltrated water moves in a downward direction from surface to groundwater table. Forests partly control ground water recharge due to water uptake through the roots, but also by increased water holding capacity. Forest soils have large water-holding capacity due to higher organic matter content. In turn, sufficient saturation of soil with water is beneficial for biomass production and thus supporting the organic matter composition. Soil moisture refers to the water content of the soil, and it depends on soil properties and organic matter content. Furthermore, substantial amount of soil moisture is transpired to the atmosphere by transpiration and movement of water upwards through the roots, stem and leaves. Thus, evapotranspiration is dependent on available soil moisture, but is controlled by temperature and humidity.

Zhang et al. (2021) states that the hydrological equilibrium of an area is controlled by precipitation, evapotranspiration (ET), runoff, and soil moisture storage. The chosen parameters are relevant for answering research questions because they help to understand how the main components of the hydrological balance are being affected and when the forest cover is increasing.

2.3 Legal requirements and initiatives for reforestation

Restoration of deforested or degraded ecosystems can be done through ecological regeneration which can be either active or passive. Active regeneration is done through human initiatives and planting seedlings whereas passive is when forest naturally goes through the process of regeneration (Chazdon, 2013). Passive reforestation takes more time, as seeds produced by the trees or sprouts from stumps or roots need an extended amount of time to reach a full-grown tree (Meli et al., 2017). Although, it has been a controversial question whether secondary forests provide ecosystem services and support biodiversity as equal as old-growth forests, their importance is evident when it comes to increasing species connectivity by providing suitable habitat (Chazdon, 2008). Water quality and stability of soil is also improved by the growth of young trees when compared to non-forest areas (Ditt et al., 2010). Moreover, secondary forests may restore nutrient cycling (Finzi et al., 2011) and by sequestering carbon, aid in climate change mitigation (Finegan et al., 2015). Thus, in order to minimize impacts of fragmentation, species loss and climate change at the landscape scale, it is important to increase the amount of regenerating forest (Strassburg et al., 2016).

In some of the tropical areas, large-scale restoration and secondary forest regeneration has occurred actively by planting of new forest and passively as a consequence of agricultural abandonment due to migration from rural to urban areas (Chazdon et al., 2009; Norden et al., 2009; Sánchez-Cuervo et al., 2012). In the Atlantic Forest, passive regrowth on pastureland and sugarcane plantations near the rivers was observed, as well as on steeper slopes with enough precipitation (Molin et al., 2017). In addition, active reforestation is taking place under the initiation of different reforestation programs described in more detail below.

Forest Code

The Forest Code, also known as Native Vegetation Protection act or Law n° 12,651, is a legislation on a Brazilian national level that establishes a region-specific percentage of area that must be protected on privately owned property (Brancalion et al., 2016a). The Forest Code was first established in 1934 with a motivation to regulate logging activities In 1965 was revised, but only in 1990 rules for forest protection were imposed and enforced throughout the country, evolving the law to be of a conservationist nature (Azevedo et al., 2017). Moreover, the law includes all native biomes and land cover such as grasslands, shrublands and savannas.

Two legally binding natural protection instruments act as a keystone of the Forest Code, namely Permanent Preservation Areas and the Legal Forest Reserve.

- Permanent Preservation Areas (APP) – define natural areas that must be protected and left intact as they have been recognized of a vital importance to the maintenance of essential ecological services. It refers to the marginal strips of the waterbodies, but also springs, lakes, mangroves, wetland (*vereda*), hilltops, steep slopes and sandbanks (Chiavari & Lopes, 2015). The size of APP depends on the size of the water body (the larger water body, the bigger APP).
- Legal Forest Reserve – Since the Forest Code of 1934, LR have been established as a legal requirement to conserve natural vegetation on private property (Metzger et al., 2019). It has a defined standard percentage set for protection in proportion of the property, but it varies from 80% for Amazon to 35% for the transitory area between Amazon and Cerrado and 20% in other regions including Atlantic Forest.

As a part of the national level law, another law exists specifically focused on Atlantic Forest. Law No. 11.428 on the use and protection of Atlantic Forest Biome regulates maintenance and recovery of biodiversity, vegetation cover, water services and fauna (Miola et al., 2019).

Atlantic Forest Restoration Pact

The Atlantic Forest Restoration Pact (AFRP) is a multi-stakeholder partnership created in 2009 as a movement aiming to restore 15 million ha of degraded land within the Atlantic Forest biome by 2050. (NWO, 2012). It's first aim in the Bonn Challenge pledge was to restore 1 Mha by 2020. Bonn Challenge is a global reforestation program aiming to restore biodiversity and mitigate climate change through restoration of degraded landscapes. In the Atlantic Forest, from 2011 to 2015, around 673,510–740,555 ha of native forests has been reforested (Crouzeilles et al., 2019). The total amount of forest restored from 2011 till 2020 exceeded the commitments of the Bonn Challenge, reaching 1.35-1.48 Mha. Achieving the restoration targets of 15 Mha has the potential to bring a wide variety of benefits such as food security, reduction in poverty, biodiversity protection and carbon sequestration (Wentink, 2015).

Protected areas

Only 30% of Brazil's total vegetation cover is protected (Rezende et al., 2018). Out of that, only 9% is under strict protection and 21% is classified for sustainable use (Gonçalves-Souza et al., 2021). The remaining 70% is under the Brazilian Law suitable for that region which might allow interference and deforestation in particular situations (Rezende et al., 2018). Regarding the Atlantic Forest, currently less than 2% of is protected (The Nature Conservancy, 2021b).

Reforestation gap

Despite the current efforts for regeneration and reforestation, a considerable amount of forest has been and still is being degraded – creating a reforestation gap. A reforestation gap is a term used to describe all areas that must have vegetation cover according to the Forest Code, but currently don't have. The underlying reasons for the reforestation gap, or 'legal deficit', are related to the complexity and issue of compliance to the legal requirement for environmental protection. The Forest Code has been revised many times especially the part about Legal Reserves (LR). Despite its importance for maintaining biodiversity in agricultural landscapes and protection of several ecosystem services such as water, energy, food and climate mitigation, this legal requirement received criticism(Metzger, 2009). Criticism came from the agribusiness sector and its delegates in the Brazilian Congress as most of the Congress is influenced by the rural lobby (Vieira et al., 2018; Wilson Fernandes et al., 2016). The Legal Reserve requirement was denounced as limiting and to hinder the expansion of agribusiness. Hence, it is seen as an obstacle for the country's development. Recently, the Brazilian Senate received a proposal to completely discard LR from the law (Metzger et al., 2019). Without legal protection of LR, Atlantic Forest could lose 12.2 Mha of forest (Metzger et al., 2019), which would lead to a significant loss of ecosystems services that may affect the water cycle (Silvério et al., 2015)

The revision of the Forest Code in 2012 has led to a reduction of total 41 Mha out of which 36,5 Mha in LR and 4,5 Mha (Guidotti et al., 2017). After the revision, those areas were no longer required to reforest since the updated version ignores illegal deforestation in riparian areas (APP) and LR that occurred before to 2008 (Soares-Filho et al., 2014). To put it in other words, previous deficit that would have been required to restore, covers 41 Mha and to this day it is only required to reforest 11 Mha (Metzger et al., 2019). Moreover, Environmental Reserve Quota was introduced in the 2012's version of the Forest Code, allowing deficit debt from one property to be offset if another property within the same biome has a vegetation surplus (Brancalion et al., 2016b; Vieira et al., 2018)

In the Atlantic Forest, Rezende et al. (2018) reported a legal vegetation debt of riparian areas that is 1.3 – 3.7 times greater than existing estimates (Guidotti et al., 2017; Soares-Filho et al., 2014). At least 5.2 Mha out of 7.2 Mha of riparian areas must be restored before 2038 by the property owners in order to comply with the APP law. Restoring the vegetation debt of riparian areas would increase the cover of native vegetation in the Atlantic Forest up to 35% (Rezende et al., 2018). The APP vegetation debt corelates to around 40 to 50% of the Brazil’s commitment in the Paris Agreement that it would restore 12 Mha. Moreover, the ambitious target of Atlantic Forest Reforestation Pact to restore 15 Mha by 2050, as well corresponds to the areas that should have been and must be reforested in accordance with the current Forest Code (Melo et al., 2013).

3. Method

3.1 General approach

The impacts of reforestation on hydrological response of reforestation were analysed using four scenarios. The hydrological response in this thesis has been quantified by four hydrological indicators: evapotranspiration, groundwater recharge, soil moisture and discharge. The rationale behind the selection of indicators and scenario development is explained in the following paragraphs.

The scenarios reflecting land-use changes, particularly increase in forest cover were used as an input for the model PCR-GLOBWB (van Beek et al., 2011; Wada et al, 2011b, 2014). This was done in order to compare the effect of different reforestation intensities on the hydrology withing the Atlantic Forest biome. Evapotranspiration, soil moisture, groundwater recharge and discharge output maps were used to calculate marginal change. These four indicators were compared between 4 scenarios in order to assess the answers to research question.

Based on meteorological data and land-cover specifications, PCR-GLOBWB computes water flows and retention across soil layers, the groundwater storage layer, surface water and the atmosphere. Hydrological studies often apply computer modelling as it is a useful tool that reflects how hydrological parameters of an area are behaving (dos Santos et al., 2018; Loucks et al., 2005). Models have been used for estimation of discharge, evapotranspiration and other hydrological parameters over time (Hosseini & Ashraf, 2015). Moreover, hydrological models in research have been recognized as a means to comprehend the impacts of land-use changes more clearly and to provide a foundation for decision-making associated with water and forest resource management and sustainable development (Dwarakish & Ganasri, 2015). Schematic overview of the methods can be seen in Figure 4.

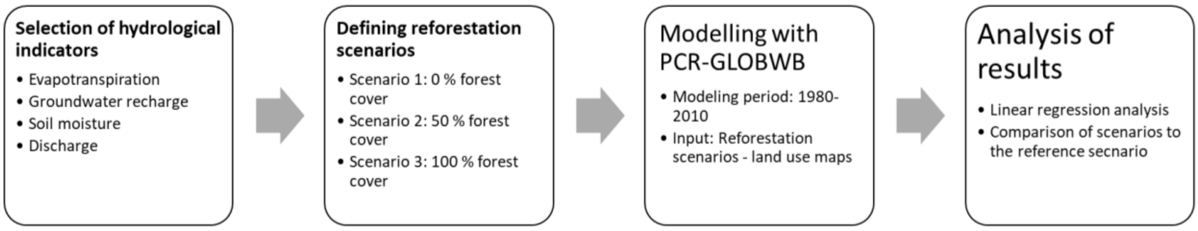


Figure 4: Schematic overview of the method

3.1.1 Study Area

The study area constitutes the Atlantic Forest biome and hydrological catchment areas situated within its borders. The Atlantic Forest biome is situated along the Atlantic coast of Brazil from the Rio Grande do Norte state in the southeast to Rio Grande do Sul in the south. Differences between the north and the south of the biome are reflected in heterogeneous rainfall patterns, climate classification variety and vegetation distribution (Oliveira-Filho & Fontes, 2000). Land use can be seen in Figure 5. The mountain chain of the Serra do Mar spreads along the Atlantic coast and the Atlantic Forest covers the majority of the low and medium elevations of the eastern slopes (Morellato et al., 2000). Within the Atlantic Forest biome, forest composition changes from the north, where tropical evergreen rainforest is present, to inland areas with tropical semideciduous and deciduous forests, to a subtropical rainforest in the south (Oliveira-Filho & Fontes, 2000).

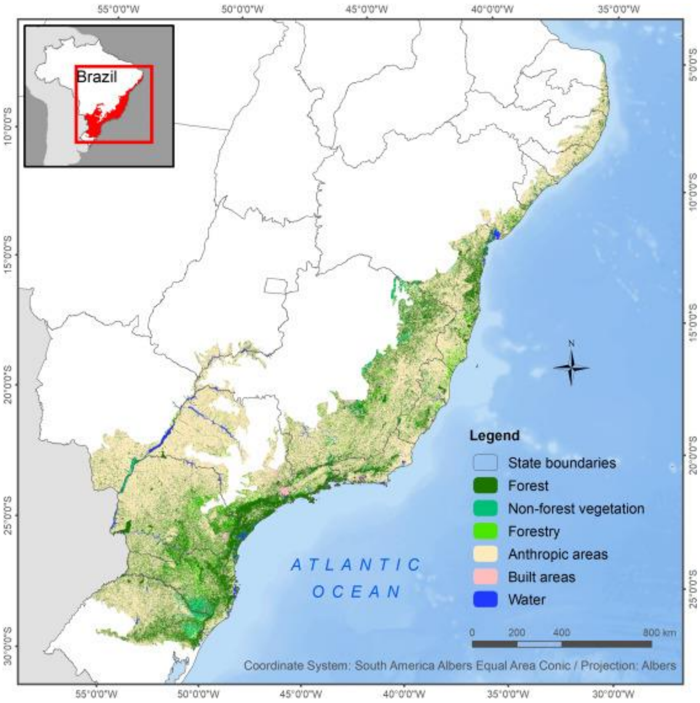


Figure 5: Land use within Atlantic Forest (Morellato et al., 2000).

3.2 PCR-GLOBWB 2.0 model

3.2.1 Model description

The PCR-GLOBWB 2.0 model was used to assess the hydrological response on reforestation. It (Sutanudjaja et al., 2018; van Beek et al., 2011; van Beek & Bierkens, 2009)was developed at the Department of Physical Geography, Faculty of Geosciences at Utrecht University, in the Netherlands.

PCR-GLOBWB 2.0 is a grid-based hydrological model that calculates water balance for 0.5°×0.5° grid cell at the monthly time step (Van Beek & Bierkens, 2009). The model uses process-based equations to calculate moisture storage in the two uprights soil layers (S1 and S2 in Figure 6), while also taking into account the exchange process between the soil layers; the underlying groundwater storage (S3); surface water and the atmosphere. Precipitation and evaporation from open water sources and soil as well as plant transpiration are all considered an atmosphere's exchange processes. Lateral as well as vertical water flows are calculated and simulated based on input maps from land-use and meteorological data. The model is divided into 5 hydrological modules (Figure 6):

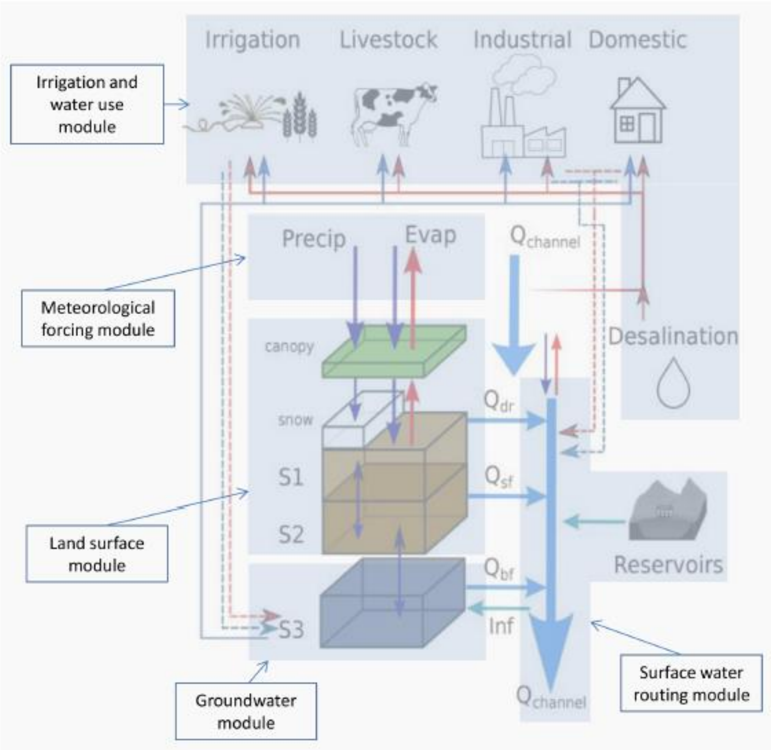


Figure 6: PCR-GLOBWB 2- schematic overview representation of the modules and its states and flows (Sutanudjaja et al., 2018)

- Meteorological forcing module
- Land surface module
- Groundwater module
- Surface water routing module
- Irrigation and water use module

3.2.2 Application of PCR-GLOBWB 2.0 for this study

Modelling protocol

Meteorological and land cover data are required as an input to PCR-GLOBWB model. Meteorological forcing was used from the global climate data set of the Climate Research Unit (University of East Anglia). In particular, data set used was CRU-TS3.21 (Harris et al., 2014). It consists of monthly gridded data with high resolution (5 arcmin) over the period of 1901-2012. The chosen cell resolution for this thesis was 0.5-degree scale. Modelling at the high resolution allows for a better level of precision and detail. Large amount of data included in the standard version of the model is in the same resolution, thus no conversion and re-scaling needed to be done.

Initial conditions were used to define starting hydrological input data. Setting initial conditions is important for the stability and indication of water amount and position. In other words, in what cell is the water present and how much water is present in groundwater and other soil layers. Initial hydrological conditions for this thesis were taken from the year 1999, followed by a spin-up of 10 years. Spin-up time is the time that model needs to reach a statistical equilibrium of its climatology after being run using a new set-up of initial conditions. The reason behind including a spin-up lies in its importance for the model to reach a dynamic steady state. Hence, this enabled the model to start in a balanced state. In order to appropriately account for the changes in land cover the model has been run from 1980-2010 with a spin-up of 10 years. Justification behind choosing a 30-year timeframe to model is that hydrological response might lag behind and some effects take more time to show which would result in incomplete hydrological response. Land cover changes have been implied from the starting year, assuming that the study area immediately has forest coverage as indicated in scenarios. In reality, reforestation would occur gradually and not all individual tree species would grow or reach the climax stage at the same time. Modelling 30 years with spin-up was done in order to allow sufficient time for the hydrological processes to stabilize.

First soil layer has water input from precipitation of non-intercepted part. Evaporation is induced as water extraction from the vegetation in the first soil storage layer that includes short vegetation and the second soil storage layer from tall vegetation. Therefore, it is dependent and constrained by soil moisture content and its availability in the top two soil layers (van Beek and Bierkens, 2009). Only in the portion of the cell that is unsaturated with water transpiration can occur. Determined by a vegetation cover fraction, model distinguishes evaporation from the plants, but also if there is no vegetation, evaporation from the bare soil.

Parametrization

it is possible to include various land cover types in a single cell. Every land cover type can be defined by a separate set of parameter values that characterize it. In this thesis, four land cover types are used: natural tall vegetation, natural short vegetation, non-paddy irrigated crops and paddy irrigated crops. By default, pastureland and rain-fed crops were included in the short natural vegetation type and forest was classified as “tall natural vegetation”. Since PCR-GLOBWB allows for the inclusion of different land cover types within one land use class, under tall natural vegetation other than natural forests, different types of tall vegetation such as savannas, Brazilian Cerrado and some agricultural plantations are also considered as forest. Atlantic Forest has over 6 different types of forest (Oliveira-Filho & Fontes, 2000) within four land cover types, there are more vegetation types present.

In order for adequate hydrological modelling, PCR-GLOBWB requires precise representation of land cover parameters, such as the vegetation fraction for each cell, leaf area index, interception capacity, rooting depth (maximum, minimum and total), root fraction, crop calendar and crop coefficient. There is spatial and temporal variation present within the parameterisation of the land use types and they may vary in order to resemble natural and accurate vegetation features of that vegetation type. Besides varying per land cover type, natural vegetation parameters might also differ from cell to cell (Sutanudjaja et al, 2018). Temporal variation is related to vegetation's growing season.

Parametrization for land cover was based on Olson classification (Olson, 1994) of the Global Land Cover Characterization (GLCC) and the parameter set by Hagemann et al., (1999). It is of a particular importance to determine land cover vegetation parameters due to their influence on evapotranspiration, moisture stability and overall hydrologic cycle (Hagemann et al 1999). The unique land cover parameter adjusted for the purpose of this research was vegetation fraction. Other parameters such as aquifer transmissivity, soil thickness and the specific vegetation parameters mentioned above were unchanged and used values given in the model as defined in van Beek and Bierkens (2009).

Scenario development

In order to evaluate and understand the influence of reforestation in the Atlantic Forest, four scenarios have been chosen for analysis. Scenario development as a methodology was previously applied by Viola et al., (2014) and de Oliveira et al., (2018) analysing the effects of land-use changes on the hydrology of four subbasins in Upper Grande River, situated in the South-eastern Brazil. Based on conclusion from similar studies, it is a validated method. Developing scenarios with different amounts of forest cover is essential for this thesis in order to compare the hydrological effect of different proportions of forest in the Atlantic Forest. For the purpose of evaluating marginal changes in evapotranspiration, groundwater discharge, soil moisture and discharge when forest cover is increasing.

The scenarios were motivated by reforestation initiatives such as The Atlantic Forest Restoration Pact (AFRP). There is increasing number of reforestation initiatives and it is still unknown what impact increase in forest cover will have on the hydrological response in the Atlantic Forest biome. Chosen scenarios are hypothetical in order to show extremity of the hydrological response. Therefore, scenario 1 (S1) does not have any forest cover; scenario 2 (S2) and scenario 3 (S3) have 50% and 100 % forest cover, respectively. The scenarios were developed based on the forest fraction per cell.

In order to run PCR-GLOBWB according to the scenarios, vegetation fraction were used as an input Forest fraction were in different scenarios were computed as explained in next paragraph. A reference scenario has been included in order to assess changes relative to baseline forest cover. Reference scenario represents unchanged forest cover as forest fractions were not modifies from the original land cover input map that has been used as a standard default in PCR-GLOBWB. Scenarios correlate to the following forest amount (see table 2).

Table 2: Scenarios and forest areas

Name of the scenario (abbreviation)	Forest cover (%)	Forested area
Reference scenario (S0)	81	89 343 709 Mha
Scenario 1 (S1)	0	0 Mha
Scenario 2 (S2)	50	56 163 398 Mha
Scenario 3 (S3)	100	110 383 812 Mha

Computing forest fractions

Forest fractions were to be computed in order to create land cover input maps for the scenarios. PCR-GLOBWB uses land cover input maps that contain different number of vegetation fractions for each land cover type determined in a cell. In particular, forest and other land cover types (short vegetation, paddy and non-paddy). PCR-GLOBWB updates the cells depending on the forest fraction that each cell initially has, and it updates it by adding the new fraction. By using this method, the spatial distribution of the forest within a cell may vary, with some cells having more forest and others having less. Because not all cells initially have equal amount of forest fraction. Other land cover types are distributed in accordance with their original fraction of land cover inside a model cell.

In detail, "tall natural" has been chosen as the target vegetation type to modify, and the new fraction has been specified (in this case: 0, 0.50 and 1). The update of the vegetation fraction was therefore initialized after reading the original land cover fractions. The maximum value of fractions is 1 meaning that cells then become fully forested. PCR-GLOBWB computes the ratio which is calculated from the total area (original forest fractions) and divided by the total assigned area (new forest fractions) in order to change the values. The fraction in a cell cannot exceed the maximum value. Furthermore, final land cover fraction values are the sum of all fractions which should reach unity. If the fraction decreases, PCR- GLOBWB does not need to verify that the maximum has not been exceeded, whereas an increase requires this verification to be done. If the forest fraction increases, the update of cells is limited by the maximum value and the iterations stop after the area meets the cover fraction and the new fraction converge with a tolerance of 100.10^{-6}. After which the total area assigned is updated and the new land cover fractions are made. Although cells may have different amounts of forest fractions, when the average forest fraction for the entire area is summed, it equals the new forest fraction.

3.3 Analysis of results

Output contains yearly data per indicator at 0.5° resolution between 1980-2010. As the output from the model calculated value per cell, this means that the result is from each cell that is within the Atlantic Forest. It has been averaged across the years for easier interpretation of results. In order to extract data from the model output evapotranspiration, soil moisture and groundwater recharge data were extracted using QGIS. By selecting the regular points in an output data map and sampling raster values to extract the data. Further analysis was done in Microsoft Excel.

Marginal change was assessed by statistical analysis of the average cell results from the model output data (evapotranspiration, ground water recharge, soil moisture and discharge). The analysis compares scenarios to the reference scenario. Moreover, yearly averaged discharge data was used for creating flow duration curves that show percentage of time that discharge was exceeded. But also, enabling identification of high and low flows that indicate how discharge is behaving under different scenarios.

3.3.1 Marginal change

Output from PCR-GLOBWB 2.0 is stored as multiple NetCDF files. The files contain a value for each cell and every time step. Marginal change has been defined as an increase or decrease per hydrological indicator as forest cover increases. Marginal change was analysed by evaluating the effect on hydrological response of the average cell result for the chosen indicators. Average cell result means that the yearly average from obtained data for each year of the running period (1980-2010) was summed and averaged. Marginal change was analysed by performing linear regression analysis for evapotranspiration, groundwater recharge, discharge and soil moisture in Microsoft Excel. Linear regression was chosen as it can provide statistical significance and explain the relationship of the dependant variable (or response variable) on the independent variable (or predictor). It assumes a linear relationship between the variables. Linear regression has the following equation below where x is the dependant variable (in this case hydrological indicator, eg. Evapotranspiration) and Y is the dependant variable (forest cover). The slope is b and the intercept is a.

$$Y = \ a + bX$$

Linear regression was run on standardized values. Values were standardized in order for making comparison of independent and dependant variables scalable because the input variables have different units. Standardization allowed to compare the magnitude of effects directly. Standardized beta coefficient was used to determine how strong is a relationship between the two variables.

Calculating standardized beta coefficient was calculated by taking the standard deviation of the independent variable and dividing it by the standard deviation of independent variable and multiplying it by the regression coefficient, as per this equation:

$$b' = b\frac{s_x}{s_y}$$

Soil moisture in this thesis has been calculated from the model output as a saturation degree in the first and second soil layer.

3.3.2 Discharge

Outlet points were identified in the local drainage direction map and averaged per watershed in order to extract the values of discharge per outlet. It was essential to identify outlet points in order to extract the discharge value for the watersheds at the outlet. Because all the incoming water is drained at the outlet, calculating discharge at the outlet points gives the best presentation of the changes in discharge that might result from the increase forest cover. The outlet points were identified in QGIS, this resulted in over 100 points across several catchment areas in the Northeast Region of Brazil. Using the QGIS raster tool function watersheds within the Atlantic Forest border were selected and outlets pinpointed in order extract the outlet value points per watershed. Figure 7 shows watersheds within the Atlantic Forest. Number of outlet points corresponding to its watershed within the Atlantic Forest can be seen in table 3.

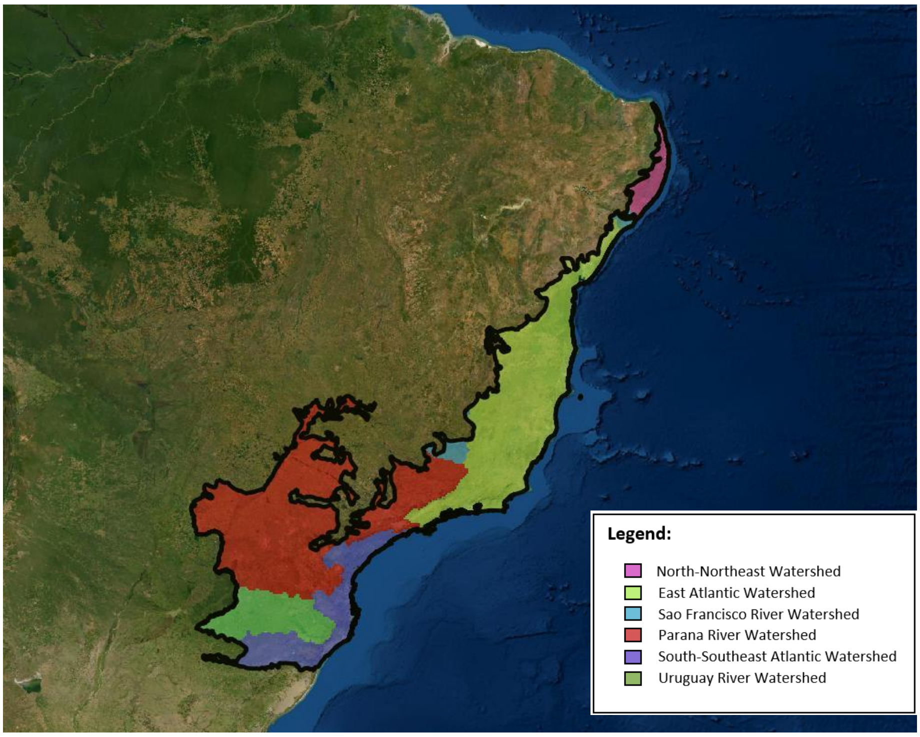


Figure 7: Watersheds within the Atlantic Forest

Table 3: Number of outlet points per watershed

Watershed	Number of outlet points within the Atlantic Forest
1. North-Northeast	16
2. East Atlantic	59
3. South-Southeast	20
4. Sao Francisco	1
5. Parana	1

Corresponding to each watershed a flow duration curve was made. Flow duration curve combines the flow characteristics over the whole range of discharge without regard to the order of occurrence and it combines it into a single curve. It is thus possible, by creating a flow duration curve, to calculate the percentage of time that any particular flow exceeded a given value. Flow curve shows high, mid and low flows. The percentage of highest flow moments are represented on the graph between 0-10% and lowest flow moments between 90-100% on the x-axis. The flow moments between the scenarios do not occur at the same time frame. Instead, wettest moments from scenarios and driest moments are compared using the “flow-order”. Flow duration curve was chosen because it is clear way to compare and identify in what part of the curve the greatest difference of discharge occurs instead of chronologically comparing discharge flows for each scenario.

Marginal change was calculated by extracting the median cell value of each watershed. Unlike for the other indicators where an average value was taken. Median was chosen as it represents the "middle" value for discharge. Per each watershed and for the whole area of the Atlantic Forest marginal change was calculated using linear regression.

4. Results

As described in the methodology chapter, four scenarios were modelled with PCR-GLOBWB to assess hydrological response of increased forest cover. Hydrological response in this study is defined as a change in evapotranspiration, discharge, ground water recharge and soil moisture (represented by upper and lower soil layer saturation). By modifying the values of forest cover fraction in the model, according to scenarios (S1, S2 and S3), the following results were obtained. The first subchapter paragraph shows the forest fraction maps followed by the second paragraph and results of marginal changes. Next, answer to RQ2, calculated discharge at the outlet point of several watersheds in the Atlantic Forest can be found.

4.1 Scenarios

Scenario 1 and 3 are straightforward, having no forest or full forest coverage. Resulting in all the cells to have the same forest fraction. However, reference scenario and S2 have 81 % forest cover (0.81 fraction of forest) and 50 % (0.50) on average over the whole area, respectively.

Forest fractions vary per cell despite the average over the whole area having exact percentage of forest cover as it was given from the input data. Because of PCR-GLOBWB way of updating the cells depending on the forest fraction that each cell initially has and adding the new fraction, resulting fractions differ per cell. That is explained due not all cells initially having equal amount of initial forest fraction which is based on the parametrization of the vegetation types within the cell. As explained in the method section various vegetation types are considered as forest such as savannas and shrubs thus the parametrization difference. Forest fraction for the scenarios can be seen in the figure 8. Parts in blue show low values of forest fraction whereas high ones are in green. Average forest fraction can be seen in the table 4.

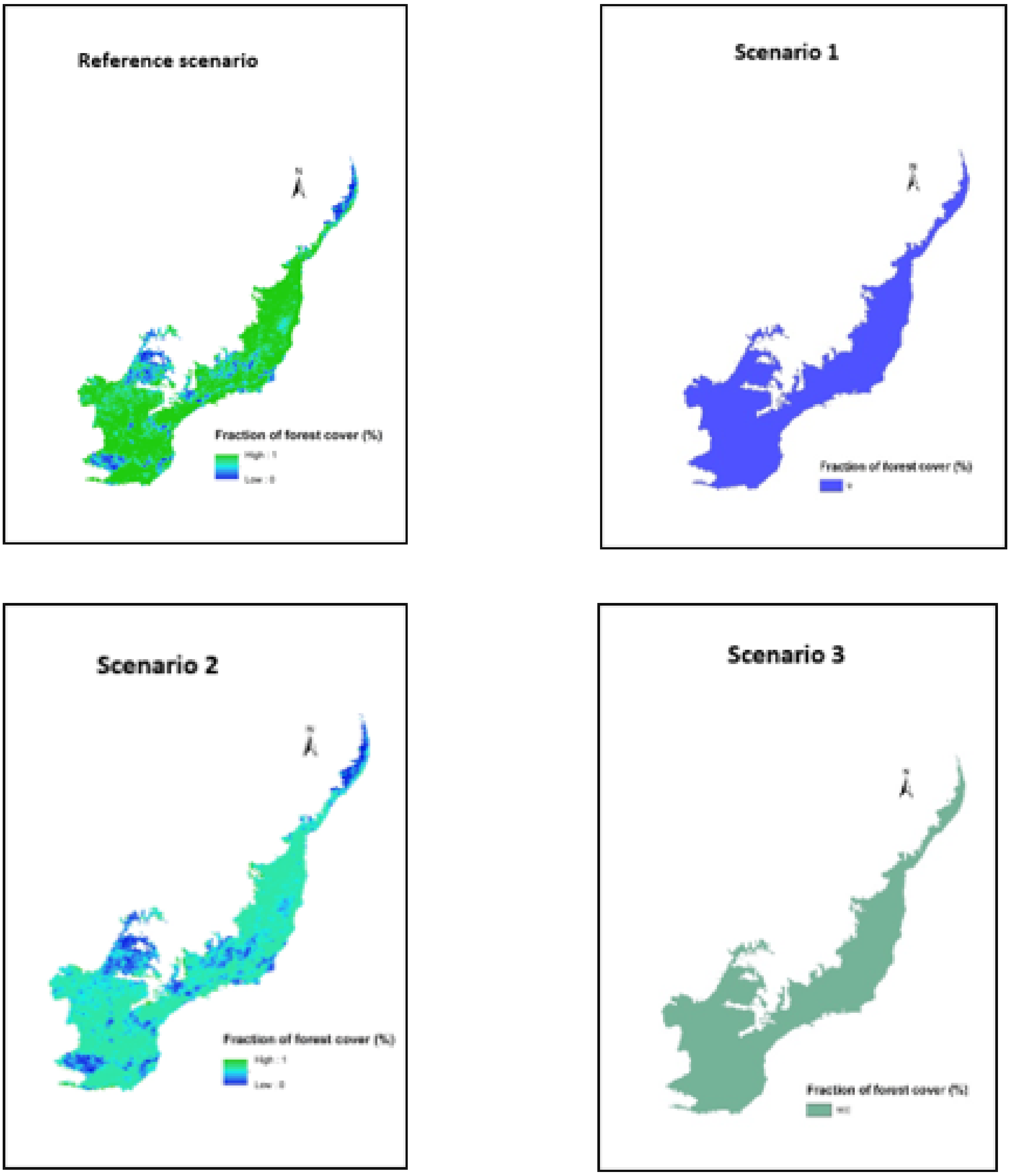


Figure 8: Forest fraction maps

Table 4: Foresr fraction per scenario

Scenario	Forest fraction	Forest percentage
Reference Scenario	0. 814219	81 %
Scenario 1	0	0 %
Scenario 2	0.505552	50 %
Scenario 3	100	%

Reference scenario resulted in 81% of forest cover which was unexpectedly high. In the reference scenario model cell on average has 0.81 mean fraction of forest, 0.18 mean fraction of short vegetation and very small fractions of paddy (0.001) and non-paddy (0.006). The input parametrization and forest fractions were used from standard default input and were therefore not changed. The model does not account for deforestation or expansion of agricultural areas. Values for paddy, non-paddy areas and shrublands are small and possibly unrealistic considering the fact that cropland doubled, and monoculture plantations quadrupled in the past 30 years (Rosa et al. 2021). However, due to parametrization these vegetation types were included tall vegetation thus explaining high fraction of forest in the reference scenario.

The table 5 include fractions of other land cover types. The fractions are given as the mean value of all cells in the area, and they vary per watershed. For North-Northeast, mean value all the cells for forest is 0.2 it resulted in expansion of short vegetation rather than paddy and non-paddy. In the East Atlantic and Sao Francisco there is more irrigated cropland observed, compared to other watersheds. Parana watershed has higher short vegetation fraction than forest meaning there is not a lot of forest coverage in the watershed. Total value represents all watersheds combined across Atlantic Forest. For instance, in scenario 2 a cell consists of 0.50 forest fraction, 0.36 short vegetation, 0.01 paddy and 0.11 non-paddy fraction. Detailed table including watersheds can be found below, for other scenarios corresponding fractions per watershed can be found in Appendix I.

Table 5: Scenario 2- Forest reactions per watershed

nr	Watershed	Mean forest fraction	Mean short vegetation fraction	Mean paddy fraction	Mean fraction non-paddy
1	North-Northeast	0.221	0.725	0.000	0.052
2	Sao Francisco	0.374	0.289	0.001	0.155
3	East Atlantic	0.553	0.238	0.060	0.149
4	Parana	0.482	0.605	0.001	0.018
5	South-Southeast	0.550	0.427	0.00	0.080
6	Uruguay	0.484	0.372	0.035	0.107
	Total	**0.505**	**0.364**	**0.0149**	**0.114**

4.2 Marginal change

The model output was used to assess marginal changes in evapotranspiration, groundwater recharge, soil moisture and discharge. Marginal changes were calculated using linear regression analysis and plotted as percentage of change against the reference scenario.

4.2.1 Evapotranspiration

A linear regression was calculated to assess response of evapotranspiration based on forest cover. A significant relationship was found (F (1, 2) = 827.6129, $p<0.02$) R^2 =0.99, (β) =0.965. This means that evapotranspiration increased for 0.965 standard deviation for each standard deviation increase in forest cover. The relationship between the forest cover and evapotranspiration has proven to be positive and linear. Graph below shows unstandardized averaged values over 30 years in which an increase in evapotranspiration is seen (Figure 9). The results are aligned to literature reviewed that reported increase in evapotranspiration with increase in forest cover (Cristiano et al., 2015; Hadi Pour et al., 2020; Pereira da Silva et al., 2021).

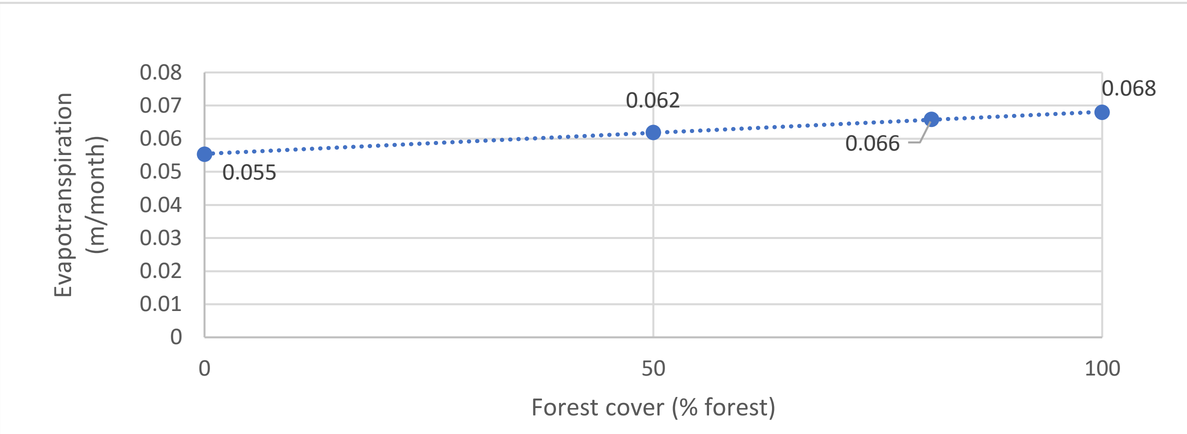


Figure 9: Evapotranspiration response

Moreover, change in evapotranspiration for scenarios (S1, S2 and S3) was compared to the reference scenario (S0). The unstandardized results show increase of 3 % for S3 and decrease in 6 % and 16 % for S2 and S1, respectively. Visual representation can be seen in Figure 10.

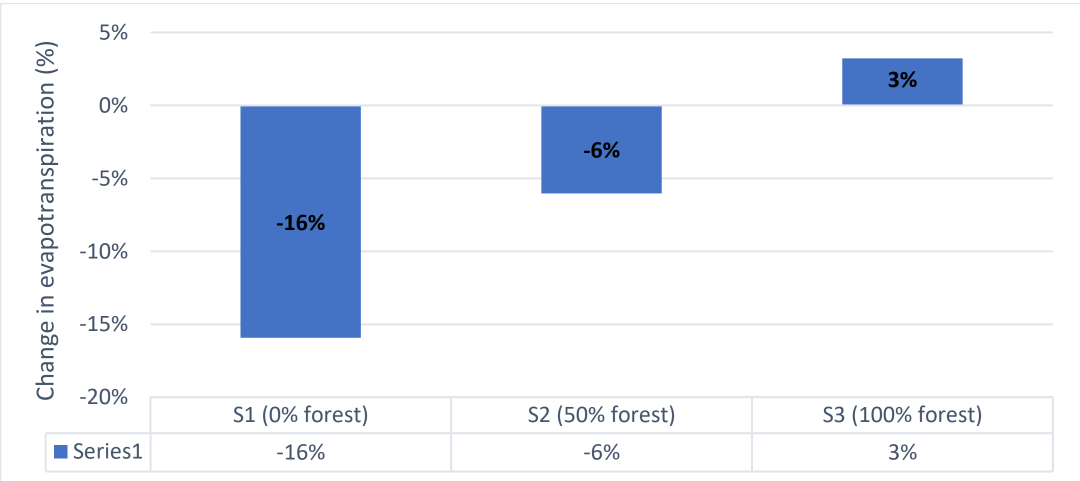


Figure 10:Percentage of change compared to reference scenario

This shows percentage of change in average cell result in evapotranspiration response across the Atlantic forest biome over 30 years. Increase in 3% for S3 means that if the Atlantic Forest biome would become fully covered in forest in would result in 3 % more evapotranspiration compared to reference scenario. If forest cover decreases, the evapotranspiration across the whole biome would decrease as well. This relationship is supported by the linear regression shown above that shows statistically significant relationship of evapotranspiration and forest cover increase. Marginal change of evapotranspiration has been found to have positive linear relationship with forest cover resulting in increase of 0.965 standard deviation for each standard deviation increase in forest cover.

4.2.2 Groundwater recharge

The graph below shows unstandardized average yearly values over 30 years. Scenario 1 with 0% forest resulted in groundwater recharge value of 0.03 m/month. Scenario S2 showed a slight decline of the averaged groundwater recharge resulting in 0.023 m/month. Followed by the Reference scenario with 0.020 m/month. The scenario with 100% forest (S3) has the lowest groundwater recharge; 0.187 m/month. The regression analysis was found to be significant (F (1,2) =5916.3, *p*=0.008) with R^2 of 099. The standardized beta correlation coefficient (β) was -0.8620. This means that ground water recharge decreased for 0.8620 standard deviation for each standard deviation increase in forest cover. The relationship between the forest cover and groundwater recharge was found to be negative (Figure 11). A Negative relationship means that as forest cover increases (independent variable), groundwater recharge (dependant variable) decreases.

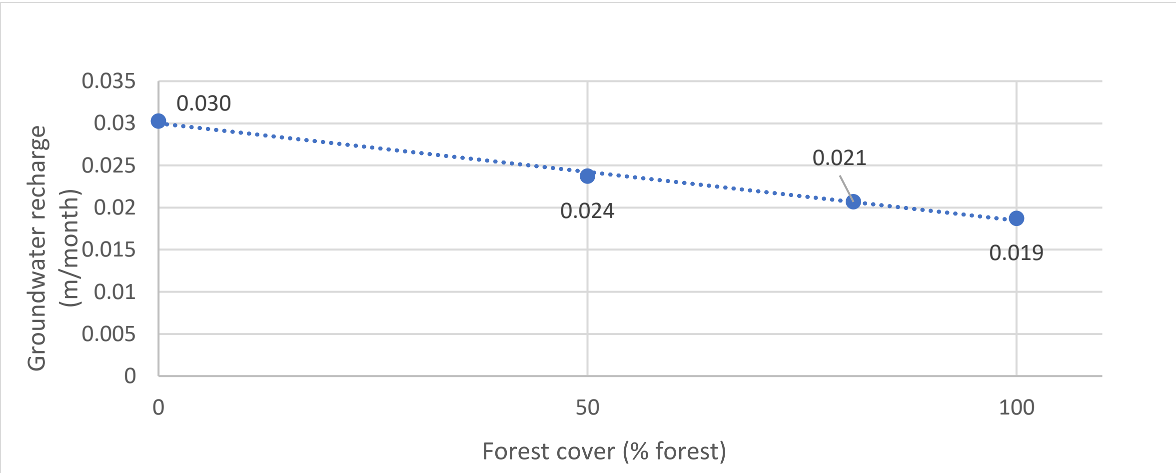
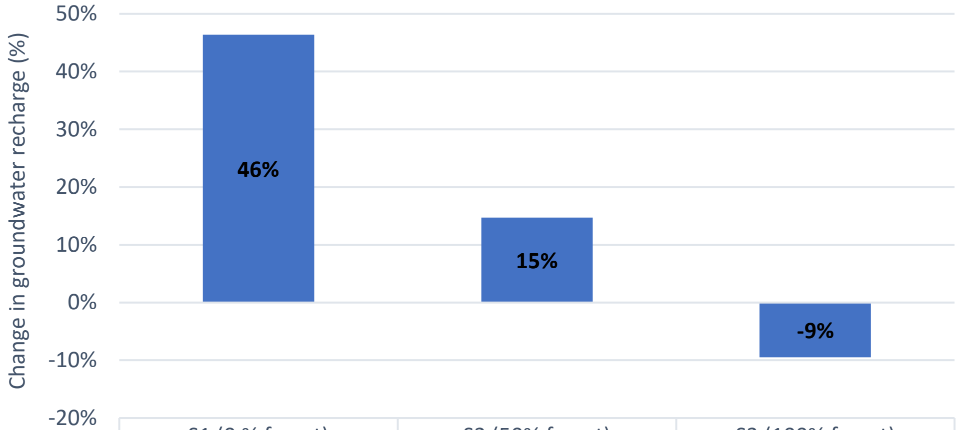


Figure 11: Groundwater recharge response



	S1 (0 % forest)	S2 (50% forest)	S3 (100% forest)
Series1	46%	15%	-9%

Figure 12: Percentage of change compared to reference scenario

The percentage of change relative to reference scenario showed that if there would be no forest (S0) groundwater recharge would have increased by 46%. Compared to S2 scenario, there is 15 % observed increase. However, fully forested area would result in 9 % decrease in groundwater recharge relative to reference scenario. Average cell response of groundwater recharge across the Atlantic Forest biome has been found to decrease as the forest cover (%) increases.

4.2.3 Soil moisture

Soil moisture is measured in saturation degrees. The soil is fully saturated with water when it reaches 1, and fully dry when 0. In the scenario with 0 % forest cover, yearly averaged soil moisture over 30 years has been found to be 0.717, Scenario S2 and S3 resulted in 0.708 and 0.703, respectively. The Reference scenario showed soil moisture value to be 0.702 which is lower compared to fully forested scenario.

In addition, a simple linear regression was calculated to assess average cell response of soil moisture based on forest cover. Standardized beta coefficient resulted in -0.70, however significant relationship was not found. For answering the research question (RQ1) this means that increase in forest cover in the Atlantic Forest biome does not have a statistically significant effect on soil moisture.

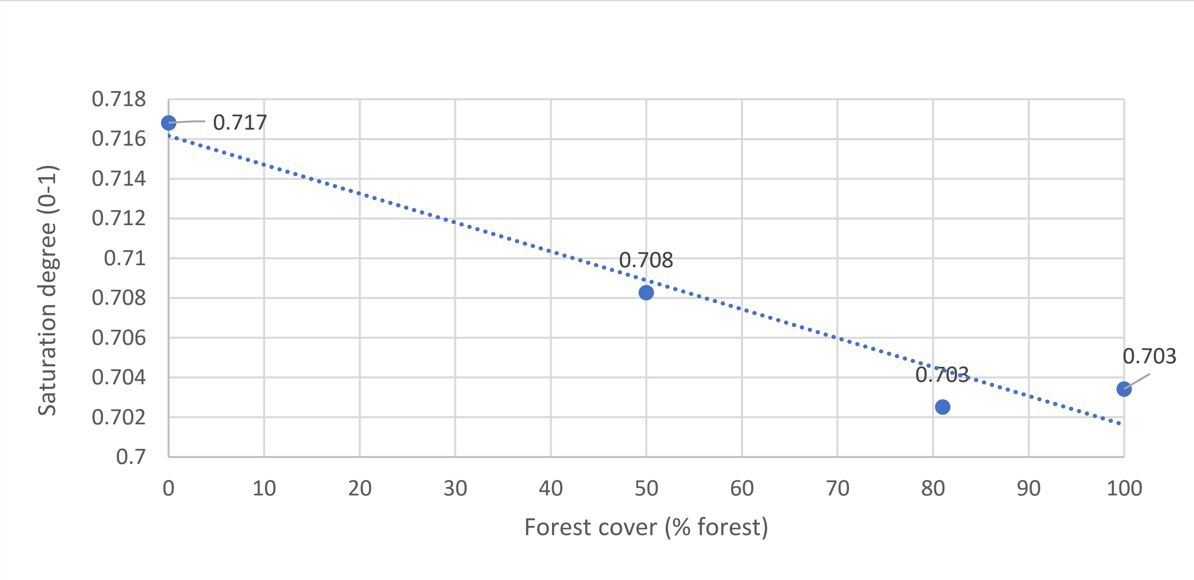


Figure 13: Soil moisture response

Despite insignificant statistical results, percentage of change compared to reference scenario was plotted. Scenario 1 showed difference of -16% in soil moisture relative to reference scenario. Scenario 2 showed -6 % of change whereas Scenario 3 resulted in positive change of 3 %. Meaning that compared to reference scenario, fully forested Atlantic Forest biome would experience a slight increase in soil moisture.

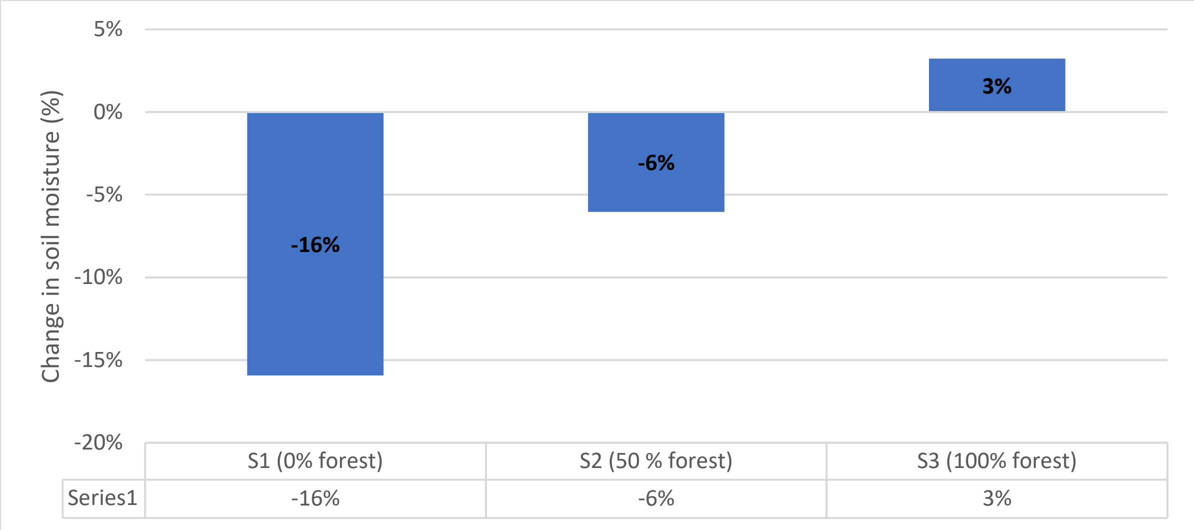


Figure 14: Percentage of change compared to reference scenario

However, PCR-GLOBWB calculates soil moisture in two layers (lower and upper soil layer). The results below show the soil moisture between the two soil layers. Water saturation in the upper soil layer is increasing as the forest cover increases. The soil moisture saturation in the upper soil layer for each scenario is indicated in shades of red and lower soil layer in the shades of blue, in Figure 15. The upper soil layer shows an increase in soil moisture saturation as the forest cover increases whereas lower soil layers demonstrate the opposite trend. S3 with 100% forest has the lowest saturation degree of the lower soil layer (0.646) and the highest saturation degree of the upper soil layer (0.766).These results have not been standardized. Moreover, upper soil moisture increase because in PCR-GLOBWB short vegetation takes up water from the upper soil layer and tall vegetation from the lower soil layer. This, as there is more forest cover (more tall vegetation), lower soil layer decreases. Forests take up water stored in the soil and transpire it, therefore with more forest's evapotranspiration increases and in turn lower soil layer decreases in moisture.

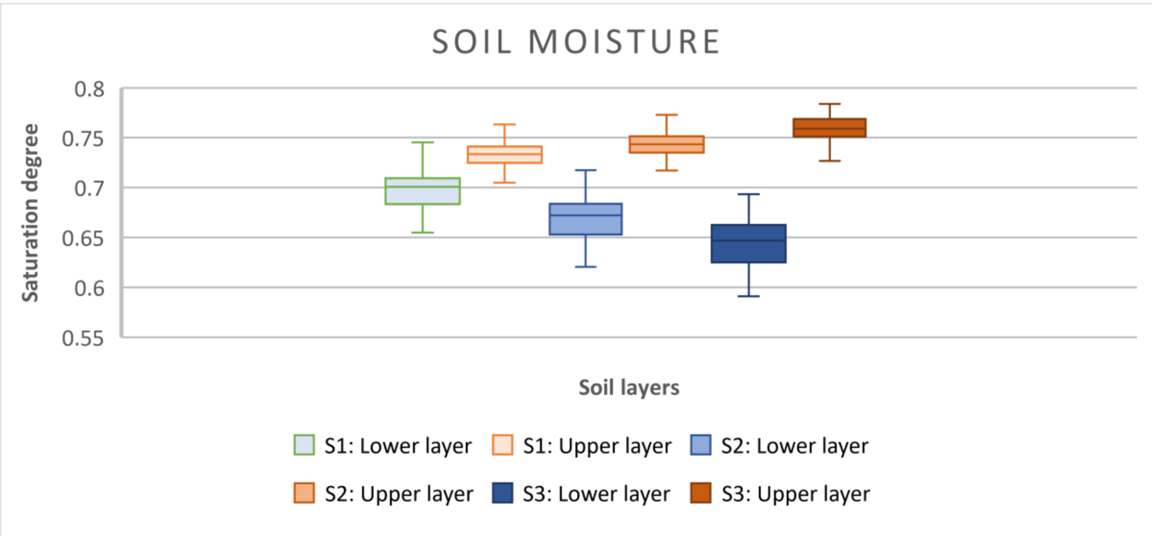


Figure 15: Soil moisture in upper and lower soil layer

4.3 Discharge

In order to answer research question 2; in what way does reforestation influence discharge at the outlet of the surrounding watersheds (see method 3.3.2) flow duration curve was plotted and marginal change of discharge analysed. By creating a flow duration curve, it was possible to calculate the percentage of time that a particular discharge exceeds during given period. The percentage of highest flow moments are represented on the graph between 0-10% and lowest flow moments between 90-100% on the x-axis. Flow duration curve combines the flow characteristics over the whole range of discharge without regard to the order of occurrence and it combines it into a single curve. This way it is clear to compare and identify where the greatest difference of low and high flows occurs instead of chronologically comparing discharge for each scenario. Discharge was analysed per watershed and detailed description is given in the appendix. Here flow duration curve for the entire (total) area is shown. Total flow duration curve shows the discharge of all watersheds per scenario, and it was used for simplifying analysis of results.

4.3.2. Total flow duration curve

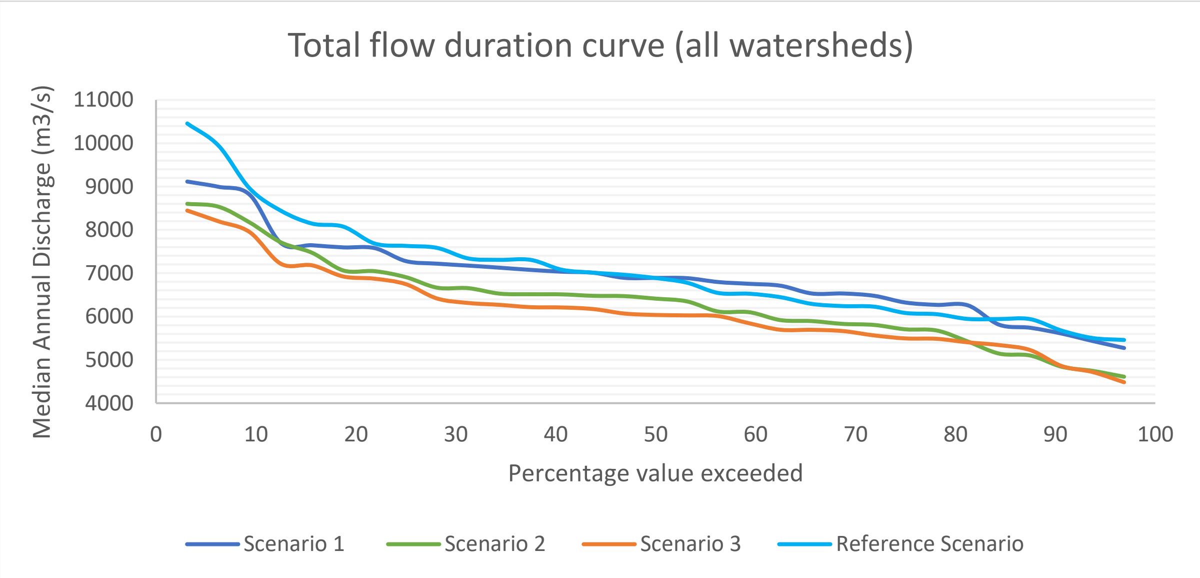


Figure 16: Total flow duration curve

Total flow duration curve shows median discharge of all watersheds per scenario. Reference scenario shows high discharge value that is exceeded 10 % of the time which is higher than for scenario 1 that does not have any forest. Steep slope and exceedance of high flows could be explained by high run-off due to intense rainfall. Since the data is taken from yearly average value this could mean that during several years there was more precipitation than usual. However, the curve for reference scenario shows higher discharge than S1 with no forest. This was unexpected and the reason could be that the groundwater recharge is high due to additional incoming water and if soil is already saturated with water this could result in high discharge. Scenario 2 neatly shows mitigation of impact due to moderate forest cover as there in no excess high or low flows. Scenario 3 has lowest flow composition which shows that high forest cover decrease discharge. Overall, observing all scenarios a decrease in discharge is seen.

4.3.3 Marginal change

Only 3 out of 6 watersheds are shown because these watersheds had sufficient amount of outlet points identified unlike others that had only one or two which was not representative. The results were not standardized. The median of 30-years discharge was plotted against scenarios as a function of forest cover. The regression displays a positive trend meaning that the discharge increases with more forest cover. For this watershed, each additional % of forest will result in an increase of 0.84 m^3/s in discharge. This was unexpected, however the reason for that was possibly due to forest expanding over the areas that previously did not have vegetation. It can also depend on the type of soil that the reforestation takes place on. Possibly there was a forest on clay soils and a formerly agricultural area with sandy soils. When trees are planted on sandy soils, infiltration can rise, and water can then seep into the groundwater. Groundwater may have had a high rate of recharge and additional source of incoming water, thus generating more discharge.

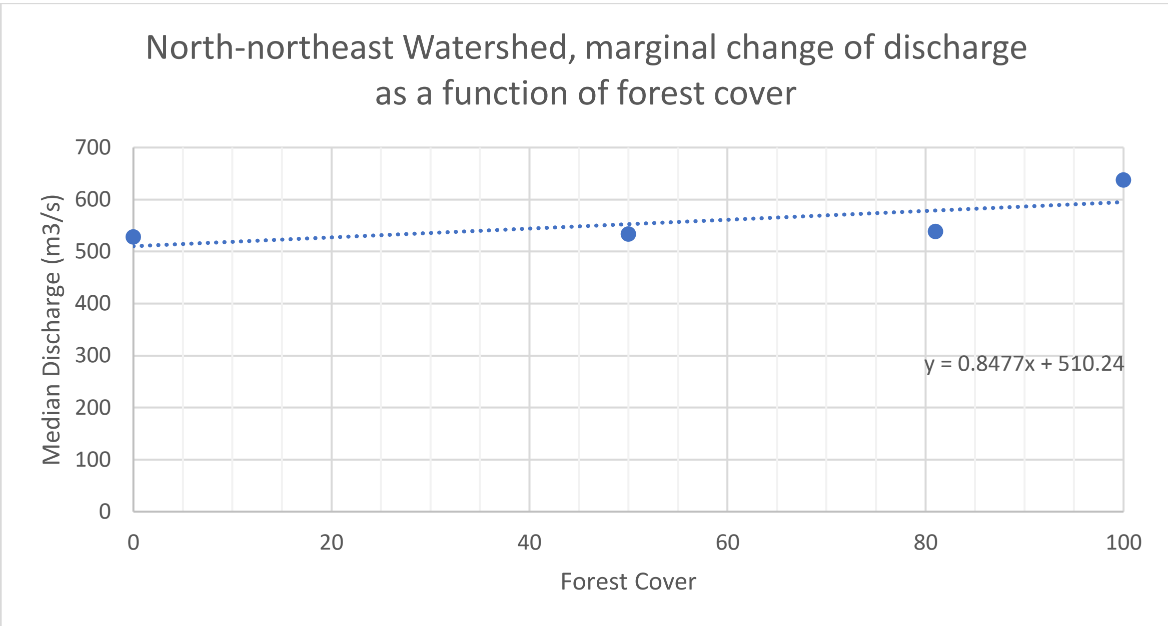


Figure 17:Percentage of change compared to reference scenario

In the South-Southeast Watershed, marginal change of discharge as a function of forest cover has been found decreasing by value of 5.863 m^3/s as the percentage of forest increases. Median discharge over the whole area for 30 years has been plotted against scenarios and can be seen in figure below. Reason for decrease can be explained by the increase in evapotranspiration which is seen to increase for scenarios with more forest cover.

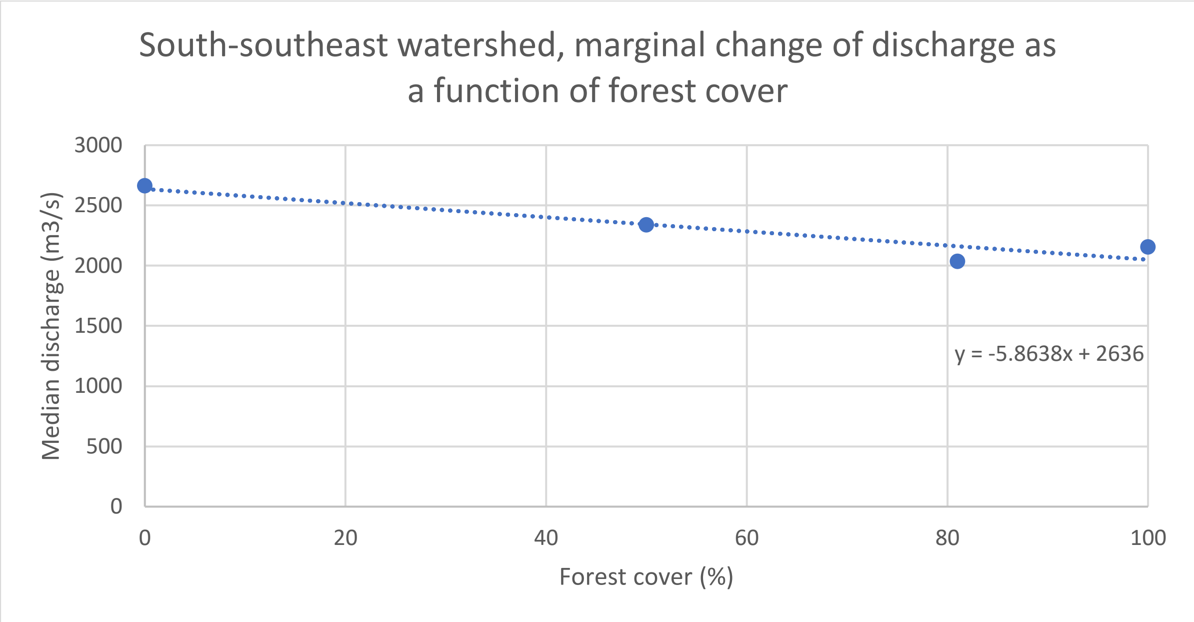


Figure 18:South-southeast watershed, marginal change of discharge as a function of forest cover

For the East Atlantic watershed looking only at the S1, S2 and S3 the yearly averaged discharge rate is mostly constant. However, regression shows decrease of 11.27 m3/s for percentage of forest cover increase. For the reference scenario discharge rate increased. Looking at the forest fractions for this watershed there is 0.89 forest cover for the reference scenario. Increasing forest cover in this watershed decrease discharge because the forest would transpire more and would increase infiltration due to roots and contribution of organic matter formation. Thus, improving the soil water holding capacity and enabling for better infiltration.

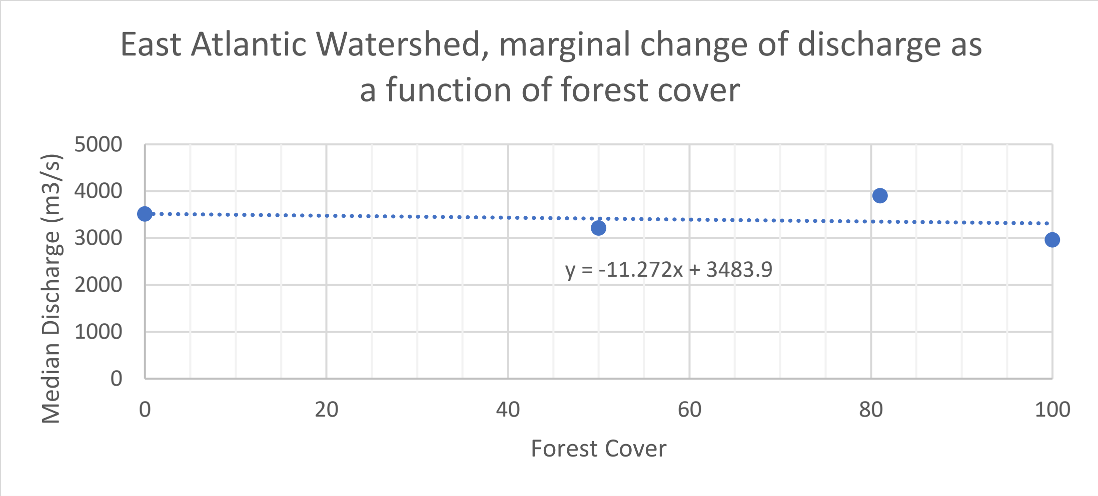


Figure 19:East Atlantic Watershed, marginal change of discharge as a function of forest cover

5. Discussion and conclusion

The objective of this thesis was to quantify the hydrological changes of increasing levels of reforestation and assess the overall impact on the hydrology of Atlantic Forest under feasible scenarios for the expansion of the Atlantic Forest.
Averaged yearly evapotranspiration over the whole area for the period 1980-2010 resulted in linear increase with forest cover. Evapotranspiration has been found to increase as the forest increases. In particular, evapotranspiration increased for 0.965 standard deviation for each standard deviation increase in forest cover. The relationship is linear and statistically significant. These results have been found in similar studies. Pereira et al., (2014) has reported increase in evapotranspiration in the scenario with the highest percentage of forest cover. However, their study area was confined to East Coast of the Atlantic Forest and SWAT model was used. Another study which looked into land use changes in the Sao Francisco basin has also found that forests have increased evapotranspiration values of the area. The results found in this thesis research confirm earlier findings that forests increase evapotranspiration. For overall balance of the region that could result in decreased soil moisture, balanced discharge and possibly more precipitation elsewhere. Despite decrease in soil moisture as the forest cover increases, higher rates of evapotranspiration and photosynthesis were found to increase periodicity of precipitation (Cristiano et al., 2015; Ellison et al., 2012). This is however highly dependent of the process of moisture cycling and climatic conditions which were not analysed in this thesis.

Ground water recharge decreased for 0.862 standard deviation for each standard deviation increase in forest cover. A linear decreasing relationship has been found between groundwater recharge and forest cover. The results were statistically significant. This means that with increase in forest cover, groundwater recharge decreases as the forest by roots uptake soil water. Oliveira et al., (2017) have reported decrease in groundwater recharge as the density in vegetation (shrub and woodland) in Brazilian Cerrado increases. Soil moisture has also been found to decrease with increase in forest cover. However, when forest cover is increased to 100 % areas behave differently since they had different land use before which can result in unexpected changes such as the one observed for S3 when soil moisture increased compared to the reference scenario. This observation was supported with linear regression that showed statistical insignificance and no relationship between increase in forest and soil moisture. While unstandardized results in lower soil layers shows decrease in soil moisture, the upper soil layer exhibits an increase as the forest cover increases. Short vegetation in PCR-GLOBWB absorbs water from the upper soil layer and tall vegetation from the lower soil layer, thus more moisture in the upper soil layer. As forest cover increases, evapotranspiration increases as well, thus decreasing the soil moisture in lower soil layer. Due to forests absorbing soil moisture and release it through transpiration.

However, the percentage of change relative to the reference scenario showed that if there would be 100 % forest, soil moisture would increase by 3 %. This means that compared to reference scenario, a fully forested Atlantic Forest biome would experience a slight increase in soil moisture. On the other hand, groundwater recharge would decrease by 9 %. When comparing reference scenario to a 100 % evapotranspiration would increase by 3 %. A possible explanation for increase in groundwater recharge is that forests increase infiltration, however soil moisture would decrease which could be explained by increase in evapotranspiration. For answering the research questions this means that increase in forest cover in the Atlantic Forest biome does not have a statistically significant effect on soil moisture but has on the evapotranspiration and groundwater recharge.

The flow duration curve has shown overall decrease in discharge. However, fully forested area could result in more low-flows and possible draughts. Scenario with 50 % forest cover showed that forests are able to buffer effects of intense rainfall and provide steady discharge flows. Marginal change analysis per watershed resulted in unexpectedly high discharge value for S3. Areas that previously didn't have forest, in this scenario become fully forested. The soil composition was not looked into, however a possible explanation for this increase could be that there could have been an agricultural area with sandy soils and forest on clay soils. When forest was put on sandy soils it can increase infiltration and then water can percolate into the groundwater, which possibly could have had high recharge rate. Comparing to the other watersheds where is seen that with increase in forest there is decrease in discharge possibly due to increase in evaporation.

One limitation of the thesis is due to the parametrization of the model, different vegetation types such as savannas, fields and woody savanna are considered as forest which has an influence on the resulting values for hydrological indicators. In nature they have different evapotranspiration rates and might transpire less or more than native remain of Atlantic forest. Thus, the results do not completely realistic representation of forest and forested areas. Moreover, forest fractions differ per cell which had influence on the watersheds results. Overall, forest fraction did increase for a targeted fraction, but watersheds had different values of forest fractions. Also, number of outlet points was not the same for all watersheds which made them incomparable for precise hydrologic response assessment. In addition, changes in the watershed area such as construction of reservoirs or recent land use changes and irrigation practices were not looked into but might have significant impact on the results.

The results were averaged over the whole area for the period of 30 years for the cell response and thus do not show exact value of the chosen parameters. Moreover, statistical analysis was done with averaged values for only 4 data points. Having a small number of samples does not provide representative regression curve. Errors in manual extraction of output data in QGIS for each hydrological parameter over the 30 years explain odd behaviour of reference scenario in the analysis. Validity of results could improve by increasing forest cover by equal fraction in all the model cells. This would reduce difference in land cover fractions for watershed. Parametrization could improve by adding appropriate parameters to account for other land cover types and to distinguish them from forest (tall vegetation). Also, statistical analysis could be done on monthly data instead of yearly average across 30 years. Nevertheless, results of this study support existing findings and shed a light on the importance of further research into reforestation effects on hydrology. Considering the fact that there is increasing amount of reforestation initiatives within the Atlantic Forest, it is therefore recommended for policy makers and non-governmental organisations to further research possible impacts of reforestation on the hydrological response. Forests provide beneficial ecosystem services, but soil and climate conditions have to be taken into consideration prior reforestation. As results have shown soil moisture has decreased due to increase in forest cover. If area is already prone to drought, forest could further exhibit drought effects. For the Atlantic Forest biome, a moderate increase in forest cover could provide positive effects such as decrease in discharge and increase in evapotranspiration and groundwater recharge.

To conclude, increase in forest cover showed marginal changes as increase in evapotranspiration, ground water recharge and a decrease in soil moisture. However, the relationship between soil moisture and forest cover has not been statistically significant. Whereas the hydrological response of reforestation on evapotranspiration and groundwater recharge has been found statistically significant. Overall, discharge has been found to decrease with increase in forest cover.

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Appendix I: Forest fractions per watershed

Table 6: Reference scenario- forest fraction per watershed

Reference scenario

nr	Watershed	Mean forest fraction	Mean short vegetation fraction	Mean Paddy fraction	Mean Non-Paddy fraction
1	North-Northeast	0.35627	0.64373	0.000330564	0.039792582
2	Sao Francisco	0.602584	0.107629	0.000185595	0.006450798
3	East Atlantic	0.892371	0.113797	0.009643919	0.003695298
4	Parana	0.776582	0.397416	0.001463954	0.006755239
5	South-Southeast	0.886203	0.223418	0.000219134	0.006307916
6	Uruguay	0.780487	0.219513	0.000323258	0.001547959
Total		0.814219	0.185781	0.001366597	0.006556884

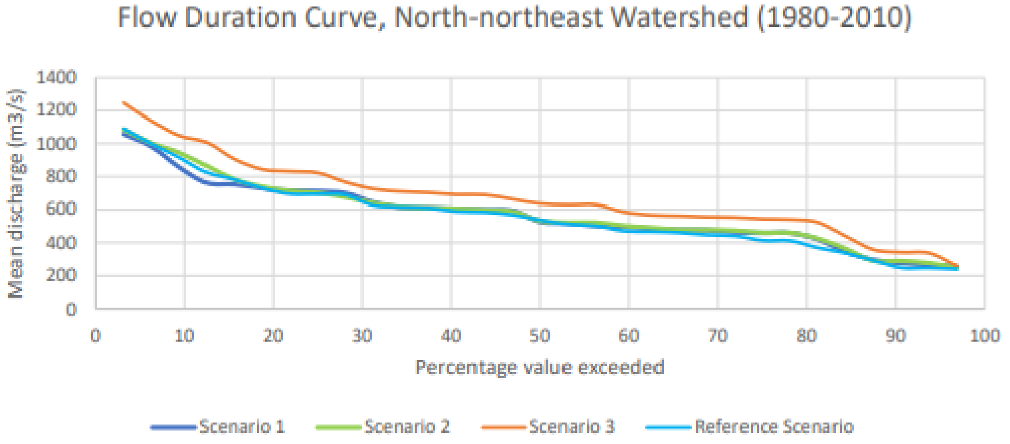
Table 7: Scenario 1- forest fraction per watershed

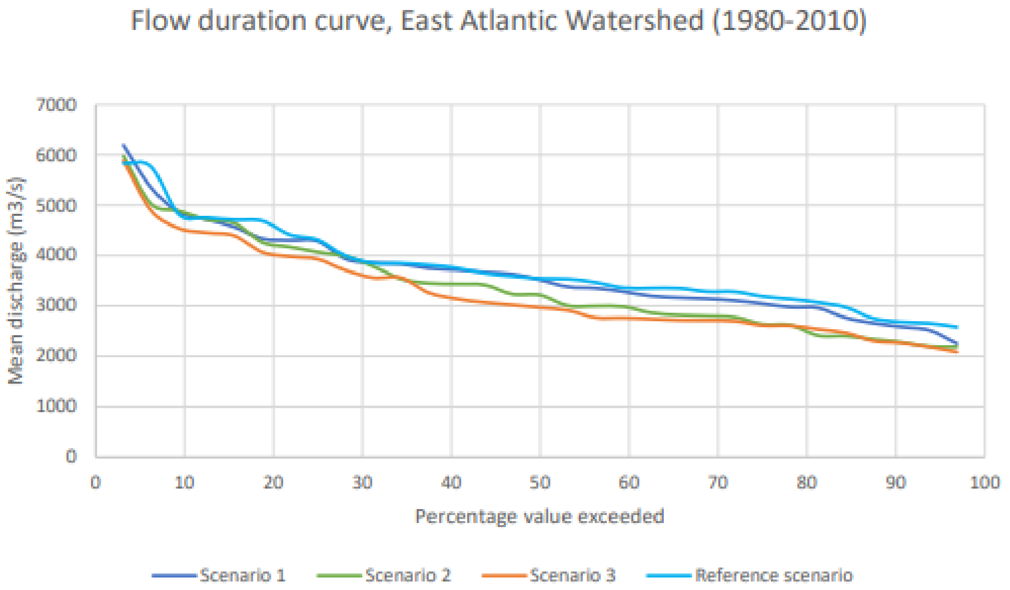
nr	Watershed	Mean forest fraction	Mean short vegetation fraction	Mean paddy fraction	Mean fraction non-paddy
1	North-Northeast	0	0.912951	0.000483	0.084098025
2	Sao Francisco	0	0.590078	0.004059415	0.403497083
3	East Atlantic	0	0.45208	0.152173	0.391039211
4	Parana	0	0.954392	0.003431	0.038821695
5	South-Southeast	0	0.768619	0.02444	0.204012431
6	Uruguay	0	0.622883	0.093763	0.28003769
	Total	0	0.664164	0.0383	0.294553998

Table 8: Scenario 1- forest fraction per watershed

nr	Watershed	Mean forest fraction	Mean short vegetation fraction	Mean paddy fraction	Mean fraction non-paddy
1	North-Northeast	0.221646	0.725690096	0.000349	0.05231443
2	Sao Francisco	0.374957	0.28908509	0.001607	0.155573669
3	East Atlantic	0.553729	0.238848461	0.060473	0.149772455
4	Parana	0.482202	0.605379595	0.001906	0.018336352
5	South-Southeast	0.550825	0.427921315	0.009391	0.08048576
6	Uruguay	0.484769	0.372256505	0.035759	0.107215326
	Total	0.505552	0.364745739	0.014961	0.11474

Appendix II: Flow duration curve





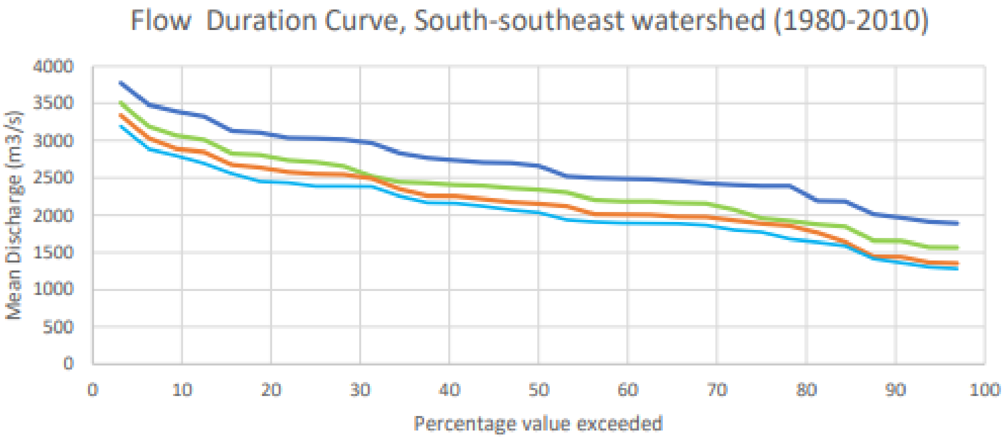


Figure 20: Flow duration curves per watersheds

North-Northeast Watershed

Figure X shows the average annual mean discharge of the North-Northeast Watershed from 1980 until 2010. Scenario 1 and Scenario 2 have similar flows whereas Scenario 3 has overall slightly higher discharge. The flow differences between scenarios can be seen at the high flow moments when compared to the low flow moments which unite at the same point. Scenario 3, at the high flow reaches value of 1247 m^3/s whereas Scenario 1 and 2 intersect at the point of 1085 m^3/s. It is unexpected that Scenario 3 (100% forest cover) has the highest discharge value.

East Atlantic Watershed

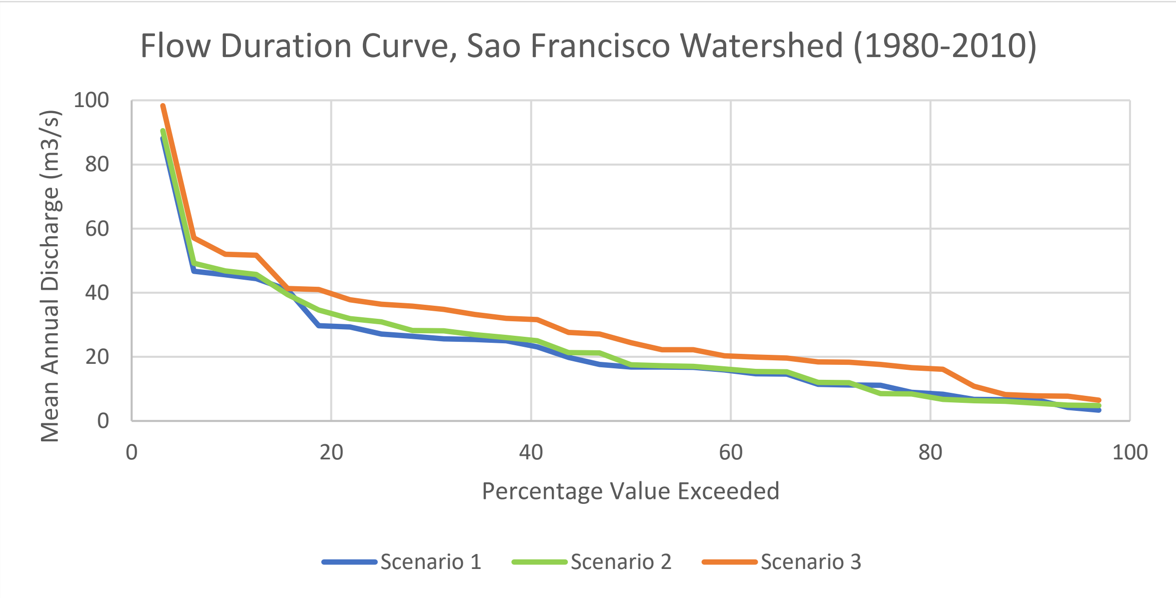
Flow duration curve for East Atlantic Watersheds displays that less than 10 % of the time, high flow moments are observed, and mid- flow is similarly distributed across scenarios. Low flow for all scenarios touch at the same point having annual mean discharge of 2081 m^3/s. Scenario 1 has the highest with annual mean discharge of 5350 m^3/s. Scenario 2 and 3 have peak flows reaching the same value.

South-Southeast Watershed

Discharge for Scenario 1 in the South-Southeast Watershed has the highest flow, and Scenario 3 with 100% forest cover has the lowest flow. Low flows for all scenarios are exceeded 80 % of the time, with slightly different values (S1: 1888 m^3/s, S2: 1566 m^3/s, S3: 1354 m^3/s). On the other hand, high flow moments are exceeded 10 % of the time reaching high values (S1: 3773 m^3/s, S2: 3506 m^3/s, S3: 3033 m^3/s).

Sao Francisco Watershed

Flow duration curve for Sao Francisco Watershed resulted in overall lower discharge values across the curve. Despite being a large watershed, results of discharge were taken from only one outlet point as that was the only point reaching the Atlantic Ocean drain. Thus, the graph below shows in very high flow moment exceeded 10 % of the time and highly contrasted low lows of around 6.5 m^3/s per outlet point for all the scenarios. Scenario 3 has the highest range of flows which is contrary to Scenario 1 and 2 that both have similar and overall lower range.



Median discharge for Scenario 3 (100%) resulted in a value of 24.4 m^3/s which is higher than the value of 16.8 m^3/s from Scenario 1 (0%). This means that the discharge is increasing as the forest cover increases as can be seen from figure below. Thus, marginal change of discharge is 0.0757 m^3/s per 1 % of more forest cover.

Parana Watershed

Similarly, to Sao Francisco watershed, Parana Watershed results were also extracted from only one outlet point. Scenarios overlap for the mid-flow values not showing a lot of difference. Mid-flow is exceeded more than 25 %. of time The absolute flow differences between scenarios can be seen at the high flow moments and a bit less at low flow moments. Scenario 1 (0% forest cover) has the highest high flow and the lowest low flow. Whereas Scenario 3 (100% forest cover) resulted in the lowest high flow and the same low flow as the Scenario 2. Overall, range of discharge for the outlet point of Parana Watershed is rather small, from lowest value of 6.2 m^3/s up to 23.36 m^3/s.