Chapter 3

Determinants of the Forest-Water Relationship

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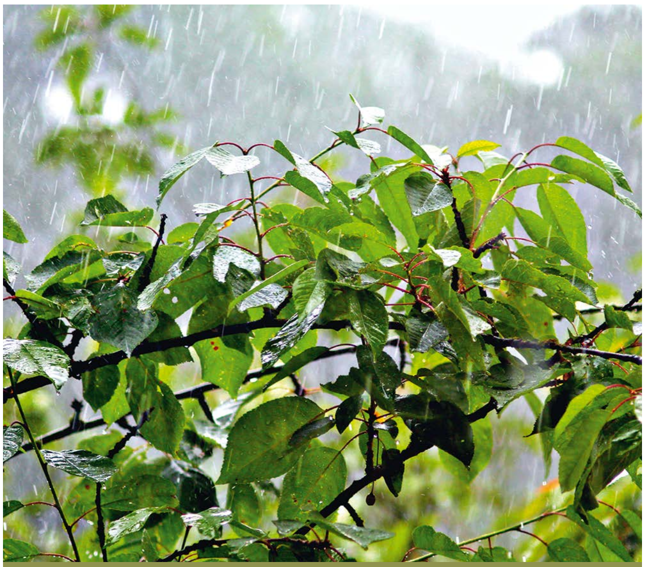
3.1 Introduction

As outlined in Chapter 2, our analysis of forest-water relations addresses four important subsystems of a linked planetary social-ecological system: climate, forests, water and people. In this chapter, we consider how each of these subsystems is changing (trend) and what is causing the change ('determinant'). We discuss the critical determinants of change in forests as they relate to water quality and quantity. Chapter 4 then presents the impacts of these changes on water quality and quality.

3.1.1 What is a Determinant of Change?

In this chapter, interactions between forests and water are examined. The biophysical factors that significantly influence those interactions are termed determinants of change. They include, for example, gravity, soil pedology or climate change. Determinants of change occur over different scales both temporal and spatial. Some essential determinants of change for forest water use and yield may rarely occur but have a substantial impact; while others have a more frequent or constant impact on forest hydrology. Certain determinants of change operate on a very small scale, while other determinants of change may impact water resources across basins, regions or even globally. Each of these temporal and spatial scale determinants of change on forest water will be discussed separately.



Leaf area is an important measure for the water use of trees
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As described in more detail in Chapter 2, for almost 30 years, global studies have shown that trees evapotranspire (i.e., use) most of the precipitation that they receive (Running et al., 1989) through evaporation from their leaves via stomata (Whitehead, 1998). Stomata are the very small openings on the leaf surface through which carbon dioxide (CO_2) diffuses into the leaf, and water and oxygen (O_2) diffuse out of the leaf. Diffused atmospheric CO_2 is converted into carbohydrates while water vapour diffuses out of the leaf resulting in increased atmospheric relative humidity and atmospheric cooling (Li et al., 2015). Any factor that increases tree leaf area and the fraction of time stomata are open will thus create more sites for water loss, cooling and carbon gain. Conversely, any factor that decreases tree leaf area or leads to stomatal closure reduces the number of sites for transpiration and also reduces carbon gain (Tyree, 2003). Changes in leaf area thus comprise a standard measure by which changes in water use by the forest (or vegetation in general) may be gauged (Sun et al., 2011). As a control of forest water use, leaf area can serve as a proxy for assessing forest water use and yield (Caldwell et al., 2015). Leaf area may also have an impact on forest water quality through changes in soil erosion and stream turbidity by buffering forest soil from the direct impact of precipitation. The canopy absorbs much of the precipitation energy during the fall of a raindrop (Kang et al., 2008). The erosive force of the raindrop is reduced after the precipitation falls from the leaf onto the forest floor and therefore so is the erosive capacity of the water (Karamage et al., 2016). Forest canopies further protect water quality by reducing stream temperature and maintain higher levels of dissolved oxygen during warmer months (Moore et al., 2005). In addition to leaf area, other factors (e.g., previous land use history, slope, soil parent material) control forest-originated stream water quality (Neal, 2002; Clinton, 2011). However, as a single determinant of change, leaf area index (LAI) will be used as a measure of forest water use and yield throughout the chapter.

Although leaf area index is a useful vegetation cover indicator, there are other vegetation cover indices, including:

- Forest cover and deforestation rate (Achard et al., 2002; Mayaux et al., 2005). Forest cover rate is simple and easy to use, but it does not include any other types of vegetation. More importantly, from the forest hydrological perspective, it does not consider hydrological recovery due to forest regeneration after disturbance, which is a significant drawback for assessing forests and hydrology, particularly in large watersheds.
- Remote sense-based NDVI (normalised difference vegetation index, Matsushita et al., 2007) and equivalent clear-cut area percentage (Lin and Wei, 2008). Like LAI, NDVI is useful for vegetation changes at a relatively coarse level in vast regions of the globe, but it also suffers from 'saturation effects' of remote sensing spectrum data (Liu et al., 2012).
- Equivalent clear-cut area (ECA) is defined as the area that has been clear-cut or naturally-disturbed, with a reduction factor (ECA coefficient) to account for the hydrological recovery due to forest regeneration. It is an integrated indicator that combines all types of forest disturbances spatially and temporally and considers the vegetation and hydrological recovery following disturbance. ECA has been successfully used in forest hydrological research in British Columbia and elsewhere (Lin and Wei, 2008; Wei and Zhang, 2010; Lewis and Huggard, 2010). However, the demand for detailed data at the plot level makes it difficult to apply at the continental or global scale.

3.1.2 Three Dimensions of Determinants of Change

All determinants of change may be defined by the three dimensions of time, space and condition state. Time impacts a determinant in two ways: length of time and frequency (or how often a determinant of change is active, also known as 'return time'). As with time, there are two components for defining the spatial dimensions of determinants of change: resolution describes the primary scale at which a determinant operates, and ranges from the microbial to global scale; extent addresses the area over which a determinant of change typically occurs. Some forest determinants of change may be very impactful within a very limited spatial area. Although resolution describes the scale at which a determinant of change impacts on forest hydrology, the extent describes how common a particular determinant is across an area. A finer spatial resolution does not necessarily equate to a significant extent. For example, the cutting of trees for wooded figurine carving may have a significant local impact on forest hydrology, but the extent of such a practice might be insignificant if considered on a regional or global scale. Conversely, increasing atmospheric CO_2 would be a determinant with a global impact on forest growth and water yield. In this example, the CO_2 determinant acts at a microscopic spatial resolution (i.e., leaf stomata), but a vast extent (i.e., global).

The 'condition state' is the final dimension required to define a determinant of change as a function of relative impact on forest hydrology. Substantial changes in specific determinants may have little impact on forest hydrology and vice versa. A change in a determinant's condition state is, therefore, an indication of a determinant's stability and sensitivity. For example, methane (CH_4) is a much more efficient absorber of solar radiation compared to CO_2 (Lashof and Ahuja, 1990). Therefore, small increases in atmospheric CH_4 may have more impact on global warming and forest water use than significant increases in atmospheric CO_2. Each of these determinants of change will be discussed in more detail below.

3.2 Determinants of Change by Temporal Scale

3.2.1 Why Does Temporal Scale Matter?

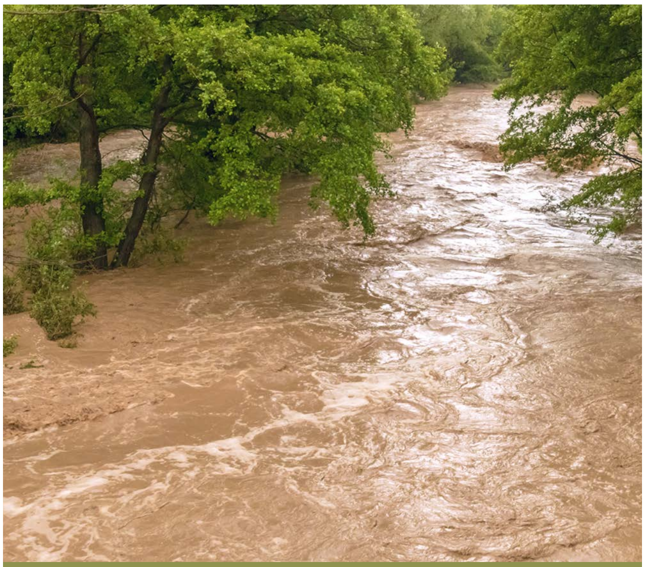
Trees have a lifespan, from germination through seedling development, into sapling stage, eventually maturing, reproducing and ultimately dying as a result of natural or anthropogenic causes. The duration of this lifespan varies considerably, ranging from short-term fast-growing tree plantations, which may be clear-felled as quickly as six years after planting (Hinchee et al., 2011), through to ancient forest trees surviving for over a thousand years (Eifert, 2000). The lifespan of an individual tree is dependent on the environmental condition of the forest in which the tree is growing. A forest may take the form of a cohort of evenly-aged trees all established at approximately the same time and developing in unison, as is the case in a tree plantation, re-forested stand, or natural forest recovering after a catastrophic disturbance (e.g., wildfire, hurricane, tornado) (Lines et al., 2010). Conversely, some ecosystems may experience very infrequent, large scale, stand killing disturbances that can lead to multiple age class forests (Dale et al., 2001). The temporal scale under which these changes occur can impact the stability of the stream water quality and quantity as occasional small gaps in the forest cover have less impact on hydrology than do large areas of tree loss (Hansen et al., 2008).

3.2.2 Temporal Duration

The temporal duration of a determinant of change can be an essential contributor to forest hydrology. Short-term disturbances can have significant, long-term impacts on water yield (e.g., wildfire, Hallema et al., 2017). There is no general rule regarding temporal disturbance duration and impact, but an understanding of how each scale can impact forest hydrology is vital to effective water management. The next sub-section examines how short, medium and long-term temporal duration determinants of change influence forest water use and yield.

3.2.2.1 Short-Term / Event-Based (e.g., days or months)

Event-based determinants of change in forest ecosystems are of short duration (days or months) and may or may not have long-term consequences for water use and water yield. For example, floods, resulting from extreme rainfall events, have short-term impacts of varying severity (Chen et al., 2015). However, if there is no substantial change in leaf area or soil condition of the affected stand, then the forest/water relationship should stabilise



Flooding in forest after a heavy storm
Photo © iStock:VioNet

and return to a steady state in a relatively short time (Chen et al., 2015). On the other hand, an event-based determinant such as a wildfire – also a short-term event – may have long-term impacts even if only a small area of the forest is impacted (Hallema et al., 2017). The resultant decrease in leaf area will have immediate consequences through reduced evapotranspiration (water use) and lead to increased streamflow from the deforested watershed (dependent on antecedent soil moisture levels, recharge within the soil water profile and soil water infiltration capacity). The hydrological response following wildfire will impact both water quantity (e.g., average daily, seasonal and annual flows) and water quality through the potential for increased stream sedimentation (Richter et al., 1982). Nitrate inputs (Riggan et al., 1994) and water temperature can increase due to a loss of forest stream shading (Hitt, 2003). Recovery from these impacts will be dependent on the reestablishment of trees and restoration of leaf area and litter cover within the stand, which may take years before a hydrological response is restored to pre-fire conditions (Brown and Smith, 2000; Cuevas-González et al., 2009). Another important short-term determinant of change having long-term impacts on forest and water relations is logging (Gilmour and Gilmour, 1971; Storck et al., 1998).

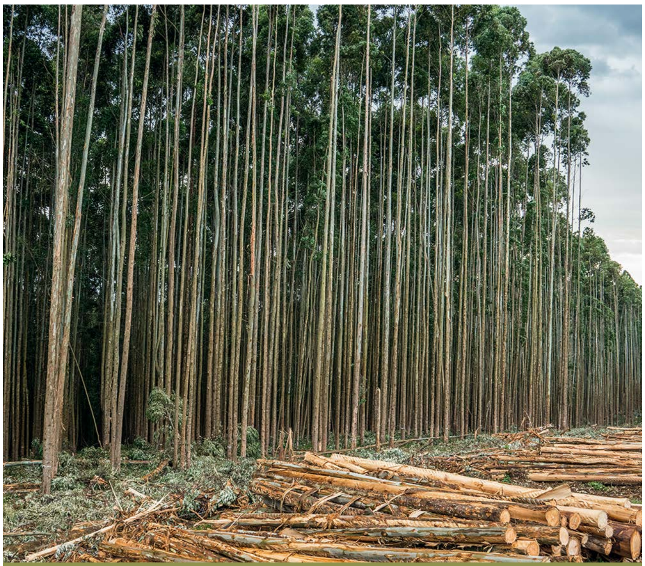
3.2.2.2 Medium-Term (e.g., years)

Medium-term determinants of change that impact forest and water relations are numerous. They include disease/pest infestations (and associated leaf area changes linked to defoliation or mortality); changes in population density/demographics (Yin et al., 2017). Urbanisation can in turn increase the need for timber and other forest products with resultant changes in road and infrastructure development (Debel, et al., 2014). All of the above, result in changes in leaf area to a greater or lesser extent, with resultant impacts on streamflow. Some determinants of change result in maintaining or even increasing forest coverage, such as conservation and afforestation (Zhang et al., 2017b) efforts or a move towards alternative energy sources (e.g., photovoltaic, wind or biogas), leading to reduced deforestation and increased leaf area (Maiwada et al., 2014). However, there are exceptions to this, such as in Brazil, where a developing bioethanol industry led to forest clearing for sugar cane, with reduced forest leaf area (Lapola et al., 2010).

3.2.2.3 Long-Term (decades to centuries)

Long-term (i.e., decades to centuries) determinants of change having impacts on forest and water relations include elevated CO_2. While increases in tree water use efficiency due to elevated atmospheric CO_2 have been well established (Keenan et al., 2013), nutrient limitations may reduce the efficiency of tree water use (Oren et al., 2001). Additionally, increases in tree water use efficiency may not translate into increased stream flow as trees may increase leaf area and therefore total water use (and productivity) given the available water resource (Tian et al., 2010). Long-term changes in forest exposure to ground level ozone (O_3) can increase forest water use (and reduce stream flow) by causing leaf stomata to remain open and thus increase water diffusion from the leaf (Sun et al., 2012). Global climate change (i.e., long-term temperature and precipitation changes, changes in relative humidity, climate extremes) is one issue of significant concern regarding changes in forest water use and yield (WEF, 2017). Changes in precipitation and increasing air temperature will have significant impacts on global to local hydrology with or without forests being present (IPCC, 2014). The changes in the distribution, timing and amount of precipitation are still mostly unknown due to uncertainty regarding how quickly reductions in GHGs can be achieved (Kirtman et al., 2013). Globally, precipitation has increased during the 20th century as the atmosphere has warmed and the hydrologic system has accelerated (IPCC, 2014). At a smaller scale, current regional patterns of precipitation change may persist, intensify or dissipate in the years and decades to come (Kirtman et al., 2013). Likewise, global air temperature has increased by approximately 1°C since the 19th century, and all projections are for continued global warming with regional areas of minor warming (or even cooling) (IPCC, 2014). All warming will increase the forest potential evapotranspiration (PET) (Lu et al., 2005). The combination of increased precipitation and forest stream water flow, along with uncertainty regarding the frequency that the determinant of change will occur, the seasonality of change, and other factors (e.g., increased wildfire) make predictions of climate change impacts on future water yield difficult (IPCC, 2014).

Forest area increases (e.g., Indonesia, Hansen et al., 2013) could further stress areas receiving reduced precipitation as leaf area and evapotranspiration (ET) increase. Increasing water vapour associated with increasing ET could promote additional precipitation downwind,



Water towers project in Mau Forest, Kenya - Eucalyptus tree plantation
Photo © Patrick Shepherd/CIFOR

but the amount, location and timing are uncertain (Sheil, 2018). Establishment of a commercial forestry industry using introduced tree species (e.g., South Africa, Brazil), bush encroachment or infestations of invasive tree species (alien or indigenous) have all contributed to increased atmospheric water vapour (Stanturf et al., 2014). Further examples that impact forest water use and yield include changes in species composition (genetic changes/genus exchange) and associated water use/yield changes within commercial forestry or pollutant deposition (acid rain). Various governance and management measures – such as protecting water towers – all have an impact on leaf area (see Chapters 6 and 7).

3.2.3 Temporal Frequency

The temporal frequency of a determinant of change can be more impactful in altering water quantity and quality than duration. Infrequently triggered determinants of change can have significant long-term impacts on water yield. For example, major wildfires and hurricanes may only occur once every several decades in a particular forest, but a single event can result in substantial changes to forest structure. These structural changes can have significant implications for water yield and quality (Riggan et al., 1994; Brown and Smith, 2000; Cuevas-González et al., 2009; Hallema et al., 2017). Aside from the structural and functional forest changes, infrequent event-based determinants of change may alter forest management and risk perception. If an event has a small annual chance of occurrence, less preparation may be given to resistance and resilience measures before the event (Pilling, 2005). As climate variability increases, previously rare disturbances will become more common (IPCC, 2014); preparing for the extreme will become more critical moving forward.

3.3 Determinants of Change by Spatial Scale

No determinant of change will likely fit into only one spatial scale, but any given determinant will be more commonly observed at one scale over another. For example, drought can occur at either the basin or regional spatial scale, and across the short, medium and long-term temporal scales (Breshears et al., 2005; IPCC, 2014). As previously stated, tree leaf area will be the standard by which changes in forest water yield will be discussed for each determinant of change.

3.3.1 Why Does Spatial Scale Matter?

The understanding of the determinants of change of forest water quantity and quality by scale allows for the consideration of strategic and operational planning. Strategic planning provides guidelines for adapting or mitigating adverse impacts of large-scale or large spatial extent determinants of change (FAO, 2013). Once developed, these guidelines can provide extensive decision-supportive information across a range of forest conditions. Knowledge about the smaller scale or smaller spatial extent determinants of change is very useful for developing location-specific forest management practices. The details associated with operational planning are needed to put general knowledge regarding water resource management into practice (Cosgrove and Loucks, 2015). Consideration of spatial scale thus facilitates risk assessment and mitigation (primarily at a large scale) and optimisation of water production (primarily at a small scale, with potential for extrapolation).

3.3.2 Spatial Differentiation of Change

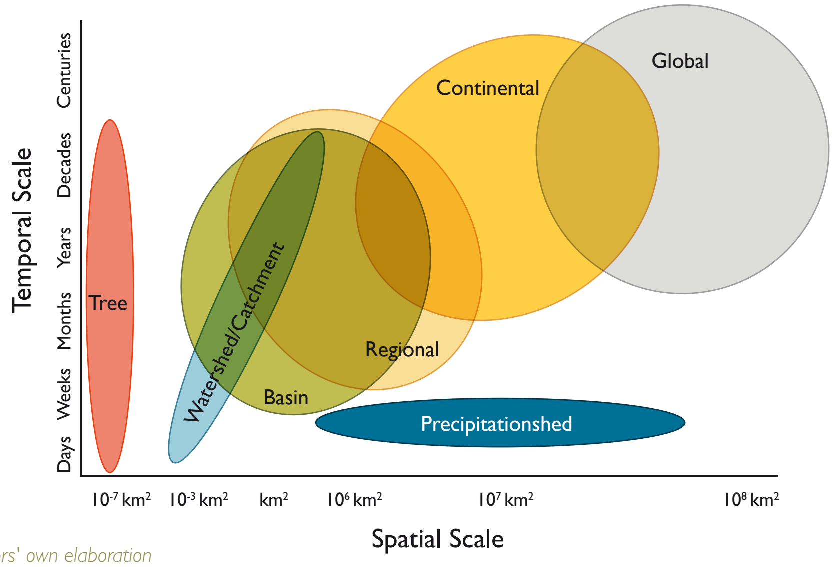
The differentiation between spatial scales can be used to examine forest hydrology (Figure 3.1). There are many temporal and spatial scales for defining and assessing forest ecosystems (Flipo et al., 2014; Figure 3.1). At its lowest common denominator, any determinant of the forest/water relationship could be considered at the level of a single tree, as every determinant fundamentally impacts one tree at a time. The tree is the scale at which individual changes and the resultant impacts on water resources can be multiplied and/or extended spatially. However, this extremely fine resolution has limited practical benefit and is too complicated to account for variations in responses across space (Lovell et al., 2002). Consequently, for strategic and operational planning purposes, risk assessments or management decision-making purposes, it is usually necessary to plan over a larger area (Schulze, 2000; Environment Agency, 2009). In hydrological terms, these might be referred to as Hydrological Response Units (HRUs). In this report, three spatial units are adopted which are common within much of the published literature, namely (in decreasing order of scale): continental scale; regional scale; and basin/watershed/catchment scale (Lovell et al., 2002). These delineations relate to ecological, geopolitical, meteorological, hydrological and operational separations that facilitate the understanding and prediction of the potential changes (impacts) on forest/water processes that may be wrought by respective determinants of change (Edwards et al., 2015).

3.3.2.1 Continental Scales and Global Scales

Our understanding of land use practices, land-atmosphere interactions (and the role of trees and forests, in particular), in the hydrologic cycle across land surfaces has increased over the past 80 years (Dooge, 2004; Suni et al., 2015). We expect larger scale change in land use practices to have an impact on the total amounts of atmospheric moisture that are circulated across terrestrial and continental surfaces. Sheil and Murdiyarso (2009), suggested that continuity of forest cover from upwind coasts helps to sustain transport of atmospheric moisture deep into continental interiors (e.g., the Amazon basin). However, it is challenging to estimate the amount of continuous forest cover necessary from upwind coasts to supplement atmospheric moisture in continental interiors. The continuous and ongoing anthropogenic transformation of the ecosystem, in particular, increasing leaf area, presumably contributes to significant changes in land-atmosphere

Figure 3.1

Primary temporal and spatial resolutions of ecosystem hydrologic scales as defined in this document. The relative differences are more important than the absolute range values



Source: Authors' own elaboration

interactions and thus to the cross-continental hydrologic cycle (Ellison et al., 2012).

Long-term and large-scale increases in forest evapotranspiration may increase precipitation and cross-continental transport of atmospheric moisture. The notion that forests produce massive amounts of atmospheric moisture, and more than most other land cover types, is not controversial. Decades of paired-catchment basin studies have focused on the role of forests in allocating precipitation over evapotranspiration and streamflow. Many studies have concluded that evapotranspiration in forests is close to the energy-determined potential rate with the remainder exported as streamflow (Bosch and Hewlett, 1982; Lu et al., 2003; Brown et al., 2005; Farley et al., 2005; Filoso et al., 2017). Most literature labels forest and cropland evapotranspiration as 'consumption' (Hoekstra and Mekonnen, 2012; Schyns et al., 2017), but from the atmospheric moisture perspective, trees, forests and other forms of vegetation are producers (Ellison et al., 2012).

Several researchers (Nobre et al., 2014; Keys et al., 2016; Keys et al., 2017; Wang-Erlandsson et al., 2017; Ellison et al., 2017) are exploring whether reductions in forest cover reduce continental scale precipitation. The concept assumes that terrestrial interiors are heavily dependent upon upwind land-atmosphere interactions and the production of atmospheric moisture through precipitation recycling (Bosilovich, 2002; van der Ent et al., 2010). If correct, the spatial organisation of a land use practice may have significant implications for downwind water availability (Ellison et al., 2017), and suggests that their impact increases as one moves further away from upwind coastal frontiers. The further from upwind coasts an individual catchment basin is located, the more it will depend on upwind terrestrial evapotranspiration and the smaller the impact of oceanic evaporation. Likewise, the more conversion from forest to urban settlement and other land uses occurs in upwind locations; the more downwind basins are likely affected by the change in land use practices. However, specifics of location relative to global circulation matters (van der Ent et al., 2010). Ecosystems outside of strong prevailing, moisture-laden, winds will have less precipitation compared to other areas where the influx of additional atmospheric moisture is more common (Figure 3.2).

3.3.2.2 Regional Scale

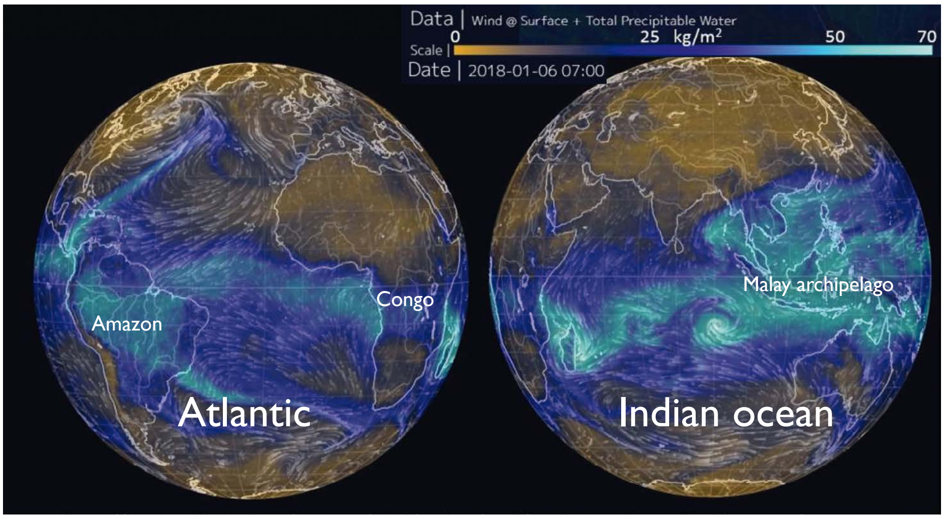
While determinants of change at continental and global scales are essential for understanding whole Earth processes, their role at a scale appropriate to forest management has not yet been adequately studied and quantified (Ellison et al., 2012; Sheil, 2018). For example, forest carbon sequestration slows global warming but competes with other forest environmental services such as efforts to increase forest water yield (Sun et al., 2011). Consequently, the regional resolution is considered the most extensive scale at which determinants of change of forest/water relationship can realistically still be managed. Some determinants of change that could be considered principally regional in scale include large-scale deforestation, afforestation or reforestation with resultant changes in forest/water interactions (Burt and Swank, 1992; Caldwell et al., 2012).

3.3.2.3 Basin and Watershed/Catchment Scale

Basins are smaller than regions, so there is a higher likelihood that an individual determinant of change could impact the entire spatial domain of a forested basin compared to one that is regional (Caldwell et al., 2012).

Figure 3.2

Wind speeds and total precipitable water is reduced over most forested land areas compared to oceans



Source: https://earth.nullschool.net/#2018/01/06/0000Z/wind/surface/level/overlay=total_precipitable_water/orthographic

However, similar to regions, there is a higher likelihood that a determinant of change will impact individual forests within a basin rather than the entire area. As the spatial area of a determinant of change decreases, so does the frequency and severity of impact on forest water yield and quality. For example, the probability of a cyclone occurring within a specific basin is less than the probability of a cyclone occurring within a region in which there are many basins. Likewise, the probability of a severe cyclone within a specific basin is less than the probability across all basins. Individual forest basin disturbance risk to water resources thus decreases from the region to the basin scale.

The watershed is the finest delineation of forest area that will be discussed as a determinant of forest water and represents the finest scale by which forest changes in water resources can be observed. Stands are the geographic scale below watersheds, but stands are often not delineated by water flow (Edwards et al., 2015). Instead, stands may present a particular forest or species type. A watershed may have one or many stands. The size of a watershed varies: as topography increases, the size of the watershed becomes smaller. Therefore, flat areas such as a coastal plain would likely have a more extensive watershed delineation than a mountainous forest. Management practices focus on either the watershed or stand scale, and determinants of change can be watershed specific. If water resources are managed at a watershed scale, then understanding evapotranspiration processes associated with the watershed is very important. For example, watershed management is essential in South Africa, where streamflow reductions (from high evapotranspiration rates) resulting from commercial tree plantations have been quantified per watershed (Gush et al., 2002), and commercial plantations are regulated/restricted according to their watershed-scale water resource impacts.

3.4 Determinants of Change by Condition State

Determinants that experience a large change in their condition state can often be very disruptive of water resources and are often the focus of forest management and restoration. For example, a trend toward more frequent and severe droughts can reduce forest water yield. Initial measures to eliminate water scarcity may include forest thinning (Douglass, 1983), while longer-term solutions may include tree species replacement (Burt and Swank, 1992). In total, there are three types of condition state: static, variable and trending. A fourth condition state termed 'new normal' (see Chapter 1) combines aspects of the previous three states. Each condition state will be defined separately.

3.4.1 Static Condition State

Static condition state determinants of change are essential for forest structure and function, but often (with notable exceptions) receive little attention. Such determinants of change may be considered permanently fixed (e.g., gravity), or, if they do experience change, such change will occur over very long timeframes, such as thousands of years (e.g., soil pedology). Changes in static condition state would likely have enormous implications for forest hydrology but the forces needed to change these determinants of change would also cause other significant changes (probably cataclysmic concerns).

3.4.2 Variable Condition State

The condition state of most determinants of change is variable. Historically, variable condition determinants of change of forest hydrology are centred on a mean value.

Moist forested landscape in Morne Trois Pitons National Park in Dominica
Photo © Andre Purret

However, the average is seldom observed. Instead, variability either increases or decreases the value centred on the mean. One of the primary concerns related to anthropogenic climate change is that variability is increasing, even if (for some parameters) the mean remains the same or similar. For example, annual precipitation may have remained constant over the past century in some regions, or without significant trend over the full measurement period, but seasonality or precipitation intensity has changed (or fluctuated between 'episodes'). More intense rain events followed by more prolonged periods of drought could produce the same amount of annual precipitation as more evenly distributed and less intense rains, but the impact on forest hydrology would be very different. For this reason, variability of determinants of change serves as a growing area of concern among forest managers.

3.4.3 Trending Condition State

A trending condition state is difficult to determine, as identification requires years of careful measurement and observation. Unlike a variable condition state, the mean of the trending condition state changes over time. If the factors impacting the determinant of change are well known and predictable, then changes in the trending condition state can also be predicted. However, if factors are not well known, then the rate of change, magnitude and even direction of the trending condition state cannot be anticipated. The changing condition state represents a fundamental shift in forest function. Forest managers and water users must, thus, also change their practices if forest water resources are to be sustainably managed under such changing conditions.

3.5 Atmospheric Determinants

Atmospheric determinants of change are the most important with regards to the extent, frequency and severity of forest water resources. In Chapters 2 and 5, climate appears as one of our mega determinants of change; clustered under 'global environmental change', which comprises one of the axes for the scenario analysis undertaken in Chapter 5 and referred to in Chapter 2. The interaction of precipitation and air temperature are the two most significant determinants of forest type and distribution. For these reasons, changes in atmospheric determinants of change have large impacts on forest hydrology (Novick et al., 2016). Figure 3.3 shows which forests globally are experiencing the highest rates of climate change. The spatial scale of atmospheric determinants of change range from global (e.g., carbon dioxide) to stand level (e.g., tornado and hail). Predominant airflow patterns in combination with topography determine climate (IPCC, 2014).

3.5.1 Climate

Some components of climate, including air temperature, precipitation, relative humidity, and wind speed, are determinants of change of forest water quantity and quality (Aber et al., 1995; Furniss et al., 2010). Also, there are many ways to examine temporal climatic change determinants of forest water including daily, monthly, annual, seasonal and event-based. Finally, there are different attributes of each component including, minimum, maximum, average and extreme. Even this non-exhaustive list would produce 80 (4 components x 5 temporal scales x 4 attributes) possible combinations, and there would be thousands of combinations of climate determinants if all were considered. That level of analysis is beyond the scope of this report. However, a few of the most frequently cited climate determinants are discussed.

3.5.1.1 Precipitation

Precipitation is the most robust single determinant of stream flow (Sun et al., 2011). Regardless of the change in other factors, reductions in precipitation will result in reduced streamflow. Dry forest types require a minimum of 300-400 mm of annual precipitation for full canopy cover (Ricklefs and Relyea, 2014); at this level, there will be no streamflow (Caldwell et al., 2012). The intensity and duration of precipitation also determine the timing of streamflow. Intensive or long duration rains can cause soil saturation and a significant proportion of fast flow (i.e., the percentage of rain that drains from the forest within 48 hours of a storm event). Conversely, frequent, gentle rains can allow most of the precipitation to be absorbed by the forest soil and slowly released over many months.

3.5.1.2 Air Temperature

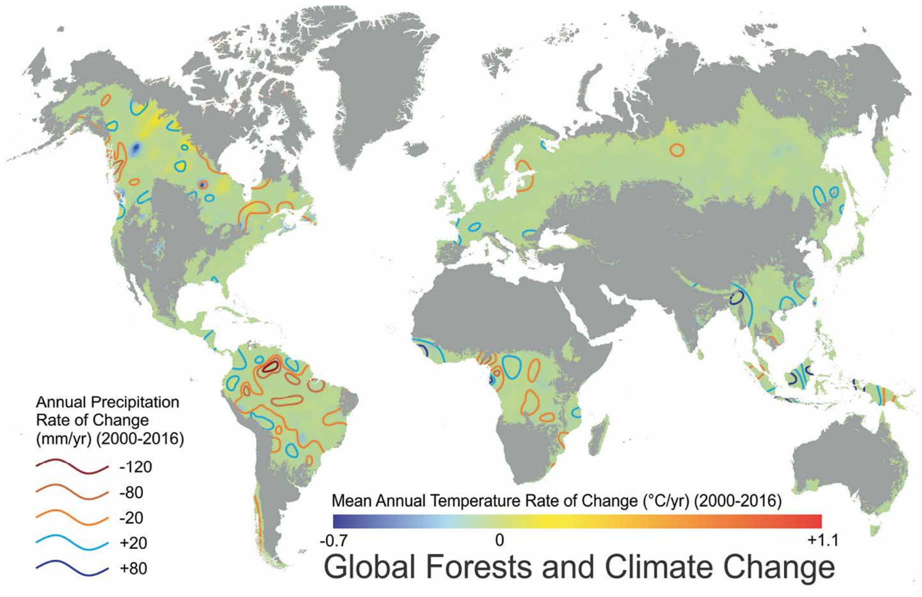
Air temperature also serves as a significant determinant of forest water quality and quantity (Sun et al., 2011). Foliar cover provided by forest prevents direct solar radiation on streams (Dugdale et al., 2018) However, a lack of forest cover can significantly increase water temperature, leading to reduced water oxygen concentrations and water quality, especially under climate warming (Matthews, 2016). Additionally, as air temperature increases so does the vapour pressure gradient and tree demand for water (Zhang et al., 2015). Therefore, all other determinants of change being constant, increased air temperature reduces forest streamflow through increased tree evapotranspiration and stream water evaporation (Sun et al., 2011).

3.5.1.3 Wind Speed

Standard meteorological stations measure wind speed at ground level, with results relevant for evapotranspiration of short vegetation, but not for taller tree canopies. Wind speed depends on the height in the atmosphere and the surface roughness of the vegetation (Irwin, 1979), as well as season and location on the globe (van der Ent et al., 2010). A recent 'stilling' or reduction of measured wind speed data over the northern hemisphere could be

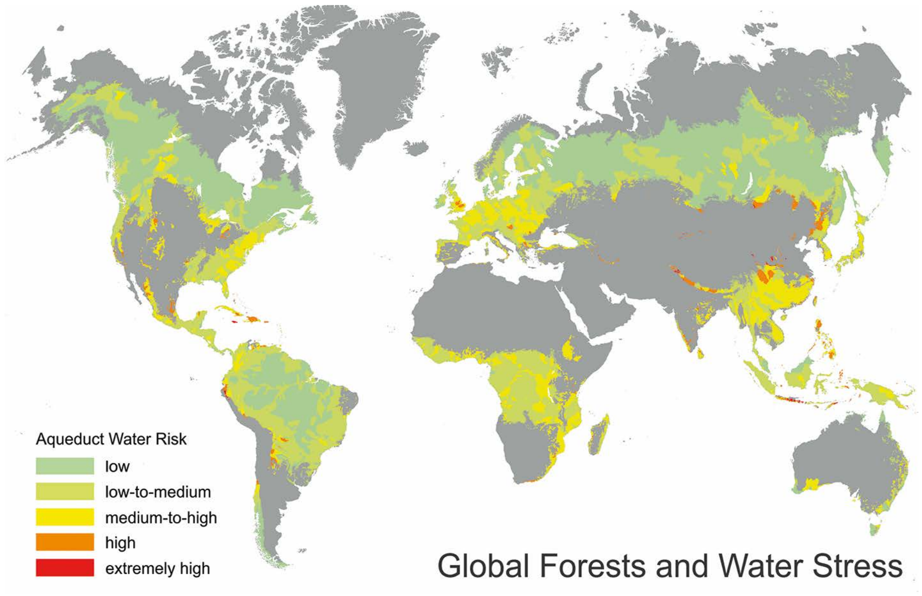
Figure 3.3

Changes in precipitation (Figure 3.3 (a)), do not necessarily correlate with water shortages (Figure 3.3 (b)) due to water demand and absolute differences in precipitation and forest water use



a)

Sources: Hansen/UMD/Google/USGS/NASA; CPC Global Daily Temperature; CPC Global Unified Gauge-Based Analysis of Daily Precipitation



b)

Sources: Hansen/UMD/Google/USGS/NASA; WRI Aqueduct Global Maps 2.1 Data

Box 3.1

Which forests are experiencing the most substantial rates of climate change over time?

Forests provide ecosystem services by protecting water supplies. Over 80% of global forest cover is in areas of low or low-to-medium water security risk mapped by the World Resources Institute (Gassert et al., 2014); less than 4% of global forest cover is in areas of high or extremely high water risk primarily because forests tend to occur in areas of low human population density.

Also, forests provide climate services by removing carbon from the atmosphere and, in tropical regions, mitigating warming through evaporative cooling (Bonan, 2008). At the same time, carbon removal through forest growth requires water, affecting the partitioning of water supplies and altering hydrologic cycles and atmospheric water exchanges at regional and continental scales (Ceci, 2013).

The complex forest-water-climate interactions occur in the contexts of both deforestation and climate change; alterations in forest cover or climate can lead to deviations from, or intensification of, the feedbacks between forest, climate and water. Changes in temperature and precipitation can directly alter the long-term composition of forests (Rustad et al., 2012). Changes in forest composition can lead to increases in the frequency, duration and intensity of natural disturbances – such as drought, fire and pest outbreaks – that can increase tree mortality and alter the structure of forests (Dale et al., 2001; Allen et al., 2010). Boreal forests in Canada and Russia have faced the most significant stress of increased temperature since 2000, while tropical forests in the Amazon basin have faced the most significant stress of decreased precipitation since 2000 (Boisvenue and Running, 2006).

partly attributed to an increase of vegetation roughness (Vautard et al., 2010), with trees outside forest increasing roughness more than closed forest stands. Increasing tree roughness and decreasing windspeed would reduce forest transpiration (Fisher et al., 2005) and therefore increase forest stream flow.

3.5.2 Atmospheric Chemistry

3.5.2.1 Air Pollution

Air pollution can increase or decrease forest water yield. Nitrogen deposition from the burning of fossil fuels can fertilise forest and increase leaf area (Pregitzer et al., 2008; Quinn et al., 2010), leading to reduced water yield. However, too much nitrogen can lead to a condition of nitrogen saturation (as observed in the north-eastern US and parts of Europe) (Aber et al., 1989). The progression of nitrogen saturation leads to forest mortality, reduced leaf area and increased streamflow (Lovett and Goodale, 2011; McNulty et al., 2014). Nitrogen deposition can also be converted into highly leachable nitrate through soil nitrification, and negatively impact water quality (Aber et al., 1989). Additionally, ozone formation in the troposphere occurs when nitrogen oxides (NO_x), carbon monoxide (CO) and volatile organic compounds (VOCs) react in the presence of sunlight (Krupa and Manning, 1988). Ozone can damage forest leaf stomata that regulate carbon dioxide intake and water loss, making trees less water use efficient (McLaughlin et al., 2007). Reduction in forest water efficiency translates into increased forest water use and decreased streamflow. Black carbon (i.e., soot), can also impact hydrology by changing the albedo and therefore melting of glacial water (Box 3.3).

Box 3.3

Forest fires and their impacts on glaciers, snow cover and hydrology

Forest fires, both natural and human-induced, are frequent globally and their incidence and spread are increasingly affected by climate extremes (Kale et al., 2017). Studies from the Tibetan Plateau and the Indian Himalayas suggest that up to 40% of all black carbon emissions come from biomass burning, including forest fires (Zhi et al., 2011). When light absorbing impurities like black carbon settle on white snow or glacier surface, they reduce snow albedo and enhance glacier and snowmelt, and thus affect the overall hydrological regime. A study in the Indian Himalayas found that black carbon aerosols could potentially heat up the Himalayan atmosphere by 0.04-0.06 K/day and that could result in a 5-20% reduction in snow cover over a decade (Bali et al., 2016). The deposition of black carbon on snow increases surface temperature by approximately 1°C, which has a more significant impact on snow melt than CO_2-induced atmospheric temperature rise (Qian et al., 2015), reducing snow and ice cover in the region (Barnett et al., 2005)

3.6 Anthropogenic Drivers of Forest Change

Temporal and spatial drivers of change of forest water can each be further divided into 'direct' (or 'proximate') and 'indirect' (or 'ultimate', 'root' or 'underlying' causes) drivers (Lambin et al., 2003). Proximate causes of land-use change constitute human activities or immediate actions that originate from intended land use and directly affect land cover (Ojima et al., 1994) and typically involve a physical action on land cover. Indirect causes are fundamental forces that underpin the more proximate causes of land-cover change and operate more diffusely or at a different scale (e.g., national or global economy), often by altering one or more proximate causes (Lambin et al., 2003).

3.6.1 Forest Transitions and Land Use Change

Deforestation, forest degradation, plantation development and increases of trees outside forest have altered the distribution of trees and mixture of forests (Ordonez et al., 2014). Such trends have been linked to anthropogenic factors in various parts of the world (Lambin et al., 2001; Turner et al., 2007; Haberl et al., 2007; Zomer et al.

2016), with strong time dependence of patterns in many instances. Forest-transition theory describes and explains non-linear changes in tree cover (i.e., the loss of natural forests followed at some point by an increase in planted and managed trees) as a country develops (Mather and Needle, 1998; Dewi et al., 2017). Forest transitions to other cover classes occur at continental scale, but also at a finer-grained basin scale (Dewi et al., 2017). Rather than a one-way human land cover change relationship, humans and natural systems interact to create changes in forest cover (Liu et al., 2007). For example, Meyfroidt et al. (2014) and Robbins et al., (2015) linked tropical tree crop expansion and commodity agroforests.

Determinants of change of land use (and land cover) change have increasingly become global (Lambin and Meyfroidt, 2011), with commodity markets connecting patterns of change across many locations. Protecting forests in one location without changing demand for products that caused the forest change is likely to deflect rather than reduce forest conversion (Meyfroidt et al., 2013; Dewi et al., 2013; Minang and van Noordwijk, 2013). Intensive debate on the scale at which agricultural intensification slows down or speeds up deforestation has focussed on the drivers that can be used for leverage in the coupled and globally connected social-ecological systems (Byerlee et al., 2014; Carrasco et al., 2017; Law et al., 2017).

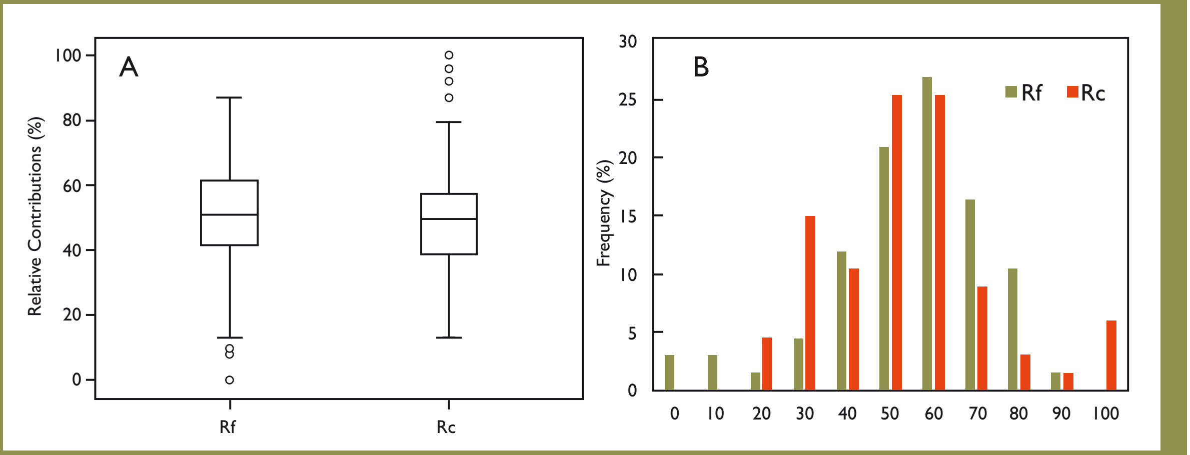
Box **3.2**

Figure **3.4**

Interactions of climate and land cover changes as determinants of hydrological change

Forest cover change and climate variability are commonly viewed as two significant determinants of change for hydrological variations in forest-dominant watersheds. The influences from climate must be either removed by possible methods such as paired watershed experimental studies (PWE) or explicitly accounted for to assess the effects of forest cover change on hydrology, (Wei and Zhang, 2010; Zhang and Wei, 2012; Liu et al., 2014). Any research in large watersheds (>1000 km^2) has to explicitly include climate into the analysis so that the relative effects of forest cover change on hydrology can be quantified because the PWE approach is not suitable for large watersheds. Thus, the relative contributions of forest cover and climate variability to hydrology are often assessed in large watershed studies, while these are not ordinarily available in PWE studies. Also, there are essential feedbacks between those two determinants of change. For example, forest changes can also affect hydrology through their impacts on climate alteration due to their cooling effects and atmospheric recycling (Ellison et al., 2012). These feedbacks may not affect the assessment of the above-mentioned relative contributions as they are already reflected in climate data collected.

Numerous studies on separating the relative contributions of forest cover change and climatic variability to annual water yields have been conducted in the past few decades (Zhang et al., 2017a). A recent review based on 168 studies from large watersheds (i.e., > 1,000 km^2) around the globe shows that forest cover and climate variability play a co-equal role in annual water yield variations (Figure 3.4, Li et al., 2017). Also, the effects of forest cover change and climate variability on annual water yield variations can be additive or offsetting due to their directional influences. The effects of deforestation (more) or reforestation (less) annual water yield (AWY) variations are mono-directional, and their effects are cumulative over a specific period. In contrast, the effects of climate variability on AWY variations tend to fluctuate or be multi-directional and consequently may lead to possible cancellations or additions over the deforestation or reforestation period (Aber et al., 1995). Thus, the difference in the impact directions may make the hydrological effects of forest cover change more pronounced. Both the magnitude and direction of two determinants of change must be considered for assessing and managing hydrological changes.



Source: Cited from Li et al., 2017

(A) Boxplot of the relative contributions of forest cover change (Rf) and climate variability (Rc) to large scale (i.e., > 1,000 km^2) annual watershed water yield variations; and

(B) Histogram of relative contributions of forest cover and climate variability to annual water yield variations. The averaged Rf and Rc are 50.1 ± 18.9% and 49.1 ± 19.5% respectively

Changes in forest cover, especially conversion to agriculture, can have significant impacts on water quality (Scanlon et al., 2007).

3.6.2 Demographic Change and Urbanisation

Two processes of demographic change can drive tree cover (or forest) transitions (see previous section) in opposite directions, with hydrological consequences as discussed in the next chapter: increasing human population and urbanisation. An increase in human population density has historically always been associated with a reduction of forest cover (Köthke et al., 2013). A decrease in rural population, started primarily since the industrial revolution in the 19th century, may present an opportunity for forest regeneration in some areas (e.g., Agnoletti. 2014; Box 3.4). At the same time, urbanisation is associated with a change in lifestyles which can exert more pressure on the forest for production (DeFries et al., 2010). In a pantropical data set, Dewi et al. (2017) found the two patterns combined, with a tree cover of 20-30% for the highest population densities in (peri)urban sub-watersheds, a 'more people, less forest' part of the curve and a 'more people, more trees' phase. The nuance depends on the operational forest definitions used (van Noordwijk and Minang, 2009; Chazdon et al., 2016). A recent change in the eastern states of the US suggests a new period of forest cover loss, after earlier re-expansion (Drummond and Loveland, 2010), linked to shifting lifestyles.

While drivers of land abandonment are more or less well understood, impacts on forest regeneration and biodiversity are only partially understood and are very context specific – in some places, farmland abandonment leads to regrowth of natural forests and subsequent increases in biodiversity, in other instances, invasive species take over. Given this dearth of literature, more studies are needed that directly link land abandonment and regrowth of natural vegetation with local water resources.

3.6.3 Conflicts

In addition to the drivers of change associated with demographic variability, as discussed above, wars both displace populations and physically disturb forest ecosystems (Orians and Pfeiffer, 1970; Nackoney et al., 2014; Daskin and Pringle, 2018). Historically, war and conflict often place considerable pressure on the need for natural resources, including water and wood products (Homer-Dixon, 1994; McNeely, 2003). Displaced populations may seek forests for shelter, refuge and fuel (Daskin and Pringle, 2018). When such actions increase the need for fuelwood and timber, this causes a reduction in tree leaf area, which in turn may increase river flows and water yield. However, under conditions of conflict, forest use is generally (although not always) sporadic and uncontrolled, and proper forest practices that protect water quality are unlikely to be followed (DeWeerdt, 2008). Poor forest management is likely to bring about increased sedimentation and a reduction in water quality, regardless of timber loss (Fergusson et al., 2014).

The widespread use of defoliants in forested areas during war significantly reduces forest cover (Westing, 1971;

Box
3.4

Land Abandonment

Abandonment of agricultural land and subsequent natural re-growth of vegetation is a common phenomenon across all mountain regions of the world. Most of these documented cases are from the Alps (Gellrich and Zimmermann, 2007) and other mountain ranges in Europe (MacDonald et al., 2000; Sitzia et al., 2010; Tarolli et al., 2014; Regos et al., 2015; Latocha et al., 2016) where the process of land abandonment started at least a century ago in some places. In Europe, primary drivers of land abandonment were rural to urban migration and related de-population in mountain areas; lack of profitability of mountain agriculture; forest fires and in some cases, unsustainable land management practices that led to soil erosion and associated hazards. In recent years, several provisions of the Common Agricultural Policy have also led to the abandonment of farmland, especially in the mountains and such marginal areas (Regos et al., 2015; Latocha et al., 2016). In Japan, land abandonment in mountain areas started in the 1950s and was driven by macroeconomic shifts and demographic transition (Palmer, 1988) with a positive impact on biodiversity and forest regeneration (Osawa et al., 2016; Katayama et al., 2015). In the Hindu Kush Himalayas, abandonment of agricultural land through outmigration is a relatively recent phenomenon, starting in the 1990s driven by macroeconomic factors, including opening up of earlier insular economies. In Nepal and China, outmigration and labour shortages in mountain villages are the main cause of land abandonment (Jaquet et al., 2015; Zhang et al., 2016). In the Indian Himalayas, new ecosystems preservation plans that ban traditional animal husbandry practices are known to have led to the abandonment of pastures (Nautiyal and Kaechele, 2007).

Abandoned land in previously terraced landscapes was found to be particularly prone to gully erosion and landslides (Tarolli et al., 2014), while in other instances, land abandonment and increase in the area of forests and grasslands led to a decrease in soil erosion (Latocha et al., 2016). Sitzia et al. (2010) looked at 53 case studies of land abandonment and subsequent natural forest recovery and found that the results were mixed. Overall, there was a decrease "in semi-natural habitats such as meadows or pastures due to natural reforestation" and therefore, an overall loss of landscape-level diversity (Sitzia et al., 2010). None of the studies looked at the relationship between secondary forest regeneration and local level water resources.

Meyfroidt and Lambin, 2008). While this may lead to an increase in stream flow and water yield, long-term legacy on land and water pollutants may remain for some years or decades. However, there have also been instances where situations of conflict and social unrest have brought about a reduction in the use and overuse of forest areas, thus allowing forests to regenerate (Davalos, 2001; Alvarez, 2003).

3.7 Outstanding Gaps and Research Priorities

Forests are complex ecosystems even when forest structure and function are relatively stable (i.e. in steady state). Understanding the interaction of determinants of forest water quality and quantity is therefore challenging. Assessment of current and prediction of future forest water resources becomes even more challenging under the ever-changing conditions of the ’new normal’. Climate serves as the most critical determinant of forest water availability. Improved models and support for the use of short, medium and long-term weather and climate forecasting would provide the single most significant benefit for improved forest water forecasting. Beyond climate, improvement in demographic, economic and technology forecasts would also help support improved forest water management. Management options are further expanded in Chapters 6 and 7 to follow.

3.8 Conclusions

Determinants of change in the climate-forest-water-people system vary over space and time. Additionally, the relative interaction between determinants is also changing making it difficult to predict forest water flows. Under a changing climate, these factors are changing more than ever, sometimes in unanticipated ways.

The magnitude of each determinant of change influences the degree of hydrologic impact on an ecosystem. Not all determinants of change have similar impacts on forest water use and flow regime. By better understanding which determinants of change have the most significant impact on forest function, estimates of water supply can be improved while minimising assessment costs.

No single factor determines forest resources, but changes in climate are the most important determinant of hydrology, regardless of the ecosystem. In addition to differences in precipitation and other factors such as forest leaf area, air temperature and management practices can also, secondarily, impact forest water use and yield. Under a changing climate, the variability of precipitation is increasing, so more extreme ranges in water flow in all terrestrial systems should be expected.

The appropriate temporal and spatial scale for assessing and managing forest water use and yield depend on the question being asked. Questions related to regional water availability across average or extreme environmental conditions require long-term predictions of climate variability and understanding of inter-basin atmospheric and terrestrial water flow (Ellison et al., 2017). Our ability to understand the complexities and interactions of large-scale forest hydrology is not complete due to limitations in large-scale measurement, monitoring and prediction (Sun et al., 2011). Conversely, the determinants of change of local water availability have been studied for over 80 years and are well understood (Douglass, 1983).

Historical paradigms regarding seasonal weather patterns, rainfall amounts and intensity are becoming outdated, as new patterns, limited patterns or no pattern emerge under the ‘new normal’ (Thornton et al., 2014). This continually evolving context makes it very difficult to establish a baseline by which determinants of change of forest water quantity can be evaluated (Carpenter and Brock, 2006); and yet, the establishment of such a baseline is critical.

The ability to forecast how adaptive management can contribute to the stabilisation of forest water quality and quantity has never been more important, nor more challenging. Fortunately, while non-antecedent conditions are contributing to this notion of a ’new normal’, the principles of ecosystem science still apply.

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