Ecohydrology: Understanding and Maintaining Ecosystem Services for IWRM

Chapter · September 2015

DOI: 10.1007/978-3-319-12194-9_8

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Chapter 17

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DOI: 10.1007/978-3-319-12194-9_8

In book: Sustainability of Integrated Water Resources Management: Water Governance, Climate and Ecohydrology, Chapter: 8, Publisher: Springer International Publishing, Editors: Shimelis Gebriye Setegn, Maria Concepcion Donoso, pp.pp 121-145

Abstract
Since historical times, natural ecosystems such as forests and wetlands are known to regulate water flow and maintain water quality. The past half a century however has witnessed unplanned and rapid development with widespread ecosystem degradation. Meanwhile water treatment and supply happens on an ad-hoc basis that is neither sustainable nor affordable for most communities. The revival of an ecohydrological approach is called for, with increased use of ecosystem services in water resources management. The affordable and sustainable aspects of this approach make it especially pertinent for developing countries, given the increasing challenges posed by mounting population, consumption and climate change. This chapter describes the general links between different ecosystems, hydrology and water quality, and outlines the steps in developing an ecohydrological approach. The next chapter describes case studies that have successfully incorporated an ecohydrological approach in different realms of water resources management in the developing world.

17.1Ecosystem services: revival of old practices

“Water is the driving force of all nature” – Leonardo da Vinci

17.1.1 Forests, wetlands and ecosystem services

Water is life, as goes the ancient saying. At the same time, organisms and ecosystems markedly influence the quality, quantity and flux of water on the landscape. Forests regulate the water cycle by storing rainwater in the canopy and forest floor, facilitating the percolation of rainwater underground and feeding springs and streams well into the dry season. The removal of forest cover has been unequivocally linked with flash floods and soil erosion following heavy rainfall as well as springs and rivers drying up earlier than in catchments with intact forests (eg. Munishi & Shear 2005, Giambelluca & Gerold 2011). Wetlands store large amounts of water during the rainy season and recharge downstream rivers. Wetlands are also known as the kidneys of the landscape on account of their ability to trap and remove excess nutrients in runoff, that would otherwise create harmful algal blooms and other problems for aquatic ecosystems and water quality (eg Mitsch & Gosselink 1993). Aquatic organisms in streams feed upon and help decompose organic matter, thereby contributing to maintaining water quality.

Harnessing this inherent capacity of ecosystems to maintain water quality and to regulate hydrology is then the logical way to manage water resources sustainably and affordably across vast areas in developing countries. This awareness of the role of forests and wetlands in maintaining water quality and flux and preventing soil erosion goes back in time. Traditions such as sacred groves arose to protect forests from being cut down; patches of pristine old growth forest are still preserved to this day on account of their status as sacred groves, such as those present in various parts of Africa (Sheridan & Nyamweru 2007) and throughout India (Malhotra *et al.* 2001, Khan *et al.* 2008). Similarly, the traditional use of wetlands in Uganda centred upon water, grazing, hunting and fishing while in the recent past, unsustainable practices of land drainage and sand mining have happened (Iyango et al 2012).

17.1.2 Rising demands, degrading ecosystems, imperiled fresh-water

Over the past century the growing human population along with increasing levels of consumption of natural resources has led to the degradation of forests, wetlands, lakes, rivers and oceans worldwide. This degradation has caused major alterations in river flows, tremendous declines in water quality and increasing uncertainty in seasonal water availability. The loss of hydrologic regulation by ecosystems has also increased the frequency and magnitude of natural disasters: unprecedented deforestation and development practices that promote runoff are directly leading to an increase in flooding frequency. In a study over 1990-2000 with data from 56 developing countries, Bradshaw et al (2007) confirmed this relationship, with models predicting a 4-28% increase in flood frequency accompanying a 10% decrease in forest area. The same decade saw over 100,000 deaths, 320 million people displaced and a loss exceeding US$ 1151 billion resulting from floods where deforestation played a significant part.

Accompanying the diminishing ecosystem services is an accelerating thirst for water in cities, both in direct consumption as well as in water utilized in manufacture of consumer goods. At the same time, in developing countries, around 770 million people lack access to adequate clean drinking water while more than 2.5 billion people lack access to sanitation (UNICEF 2013). Providing adequate safe water to meet basic human needs is a serious and a growing problem that is all the more acute in the dry season and in years with low rainfall. The extremely limited piped water supply and inadequate wastewater treatment systems persist because of limited resources and funding, an absence of effective policies, planning, management practices, regulations and implementation. Even when funding has been available, the conventional response has been to construct large, centralized energy-intensive wastewater treatment plants (eg UNEP 2004). However, even the few cities in the developing world that have such physico-chemical treatment plants can handle but a fraction of the daily wastewater generated, much of which is discharged untreated into rivers, creeks and seas.

While technical solutions for point pollution control and flood control are necessary, and have their place in water resources management, their enormous construction and operating expenses make them impractical to be widely applied. Hence any water management plan that solely relies upon technical solutions is unsustainable. Besides, the lack of understanding and consideration of ecosystem services reflects a trial and error approach to water management rather than the implementation of a policy toward sustainable use of water resources (UNEP 2004). Attaining sustainability in freshwater resource use requires not only reducing pollution but also arresting the degradation of ecological processes in landscapes. A catchment-level planning and management strategy provides a coordinating framework for water supply protection, pollution prevention and ecosystem preservation.

17.1.3 Nature as an ally: the ecohydrological approach

Ecohydrology has been defined as the integrated study of ecosystems and hydrological characteristics and processes (Zalewski 2000). The linkages between ecosystem function and hydrological processes influence water dynamics and quality (eg Breshears 2005). In addition, ecohydrology seeks to understand anthropogenic impacts upon these linkages (Nuttle 2002). Ecohydrology is both an old and a new field (Jackson et al. 2009); old in that ecosystem services have been historically used, and new, in that the emergence of modern tools (such as laser spectrometry for stable isotope analysis, time domain resistivity for estimating soil moisture and PIT tags for tracking fish movement) and techniques (remote sensing and GIS) can aid understanding ecohydrological linkages to meet the increasingly tight challenges facing sustainable water resources management.

The ecohydrological approach to water resources management utilizes the functions of various ecosystems present in a catchment to maintain natural flow patterns, year-round water availability, flood protection and water quality (Hunt and Wilcox 2003). Ecosystems confer resiliency to a watershed from extremes of high and low rainfall years, thereby buffering against uncertainty associated with climate change. Hence the understanding of the hydrology-ecosystem links in a catchment and the maintenance and utilization of ecosystem services confers sustainability to water resources management (McClain et al 2012).

Even though forests and wetlands have been utilized in the past for their ecosystem services, the challenges today of vastly increased water demand, rising costs and degrading ecosystems impose the need for a detailed understanding of the basic ecohydrological processes that affect water quality, dynamics and ecosystems. Both seasonal and inter-annual patterns in precipitation are changing and getting more uncertain as a consequence of climate change. This uncertainty in precipitation inputs is transferred into streamflow and the water balance of a catchment. For instance, Setegn *et al.* (2014) examined the impact of downscaled precipitation predictions by an ensemble of General Circulation Models for the Blue Nile river basin upon streamflow, with the finding of a high likelihood of agricultural drought on account of the water balance being very sensitive and tightly coupled to rainfall. The preservation of natural water storage on the landscape can partially buffer a catchment against the vagaries of climate change.

17.2 Ecohydrology of watershed ecosystems

The essence of the ecohydrological understanding of a catchment is knowing how much water enters and leaves the catchment, followed by how natural ecosystems influence quality, quantity and flux of water, and finally how to maintain these natural ecosystems, so as to avail ecosystem services for water management. Developing this understanding typically involves the following steps:

1. Characterizing the water cycle in a catchment by monitoring water inputs and outputs, by analyzing long term meteorological and hydrological data (if that exists) and by calculating a water budget for the catchment.
2. Noting the climatic, edaphic, biotic and anthropogenic factors that affect water availability and quality.
3. Investigating the links between hydrology/quality and aquatic and terrestrial plant and animal communities present in the region.

Ecohydrology thus not only seeks to use ecosystem services to ensure the availability and quality of water in a practical and economical manner, it also aims to understand how to preserve ecosystem structure and function, so as to maintain ecosystem services. For instance, Saha et al (2009) used stable isotope analysis to detect the specific water and nutrient sources of different plant communities in the Everglades; maintenance of community diversity requires maintaining seasonal water levels to avoid undue flood/ drought stress to the communities. While animal communities do influence water quality, most ecohydrological investigations concern plant communties; plants are not only the primary producers, they also exert important feedbacks on the hydrological cycle, such as soil water uptake/transpiration (eg Eamus *et al.* 2006), creating microclimates that affect local precipitation and evaporation, and in wetlands, plant communities influence water flow and biogeochemical cycles (Rodriguez-Iturbe 2000, Rodriguez-Iturbe *et al.* 2001, 2005). It is this interlinked set of communities, ecosystem and hydrological processes that provide ecosystem services, the most crucial of which is year-round water availability and quality.

To briefly illustrate the range of topics that come under the umbrella of ecohydrology, some examples of specific ecohydrological questions pertinent for water resources management are (i) How does the flow, depth and seasonal availability of water in wetlands/savannas determine nutrient cycling and vegetation zonation? (ii) What are minimum environmental flows required in rivers to maintain aquatic ecosystems and fish populations and thereby self-purification processes? (iii) How does land cover change in watersheds alter the rainfall-runoff-infiltration relationship and thereby affect the flow regime in streams? (iv) How can one accurately estimate evapotranspiration of different plant communities, such as evergreen forests and monoculture plantations? This section lays out some of the fundamental areas of ecohydrological understanding that govern the quality, quantity and flux of water in watersheds.

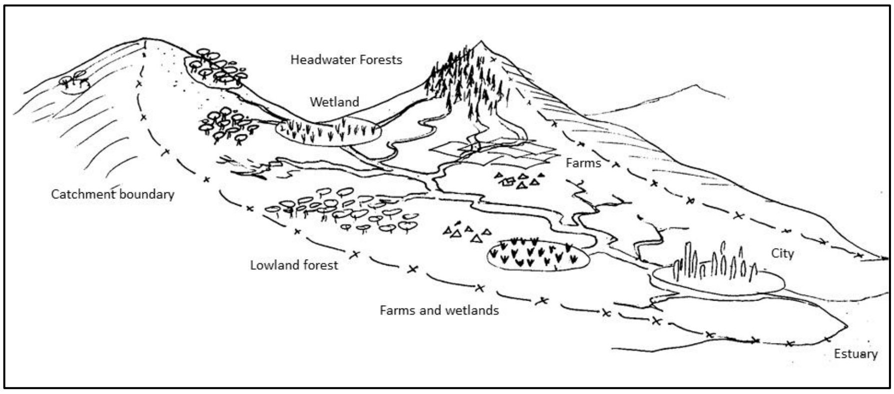

Figure 1: Ecosystems within a typical river catchment

A river basin or catchment typically includes different ecosystem types that each have their individual sets of hydrological processes and behavior affecting water availability and quality in the catchment. Figure 1 illustrates some typical ecosystem types present in a catchment such as headwater forests, wetlands, lowland forests, farmland and urban areas. It is helpful to visualize the ecosystems that lie along the hydrological path of water overland in the catchment, i.e from the headwaters to the outputs, keeping in mind that a large fraction of total water in a catchment short-circuits this overland path by entering the atmosphere via evapotranspiration. Some of the water infiltrates underground in parts of the catchment to re-emerge above the surface as springs, inputs into streams, rivers and wetlands as well as submarine groundwater discharge. Widely occurring ecosystem types are categorized at the broadest level into forest, grassland/cropland and wetlands. Each of these broad categories are further classified; for instance, the hydrological processes in an old growth primary forest differ considerably from a single-species plantation forest, or a regenerating secondary forest. Sections 17.3 – 17.5 examine some of the widely-occurring ecosystem types from a hydrological perspective.

17.2.1 Catchment level water balance

Determining water availability for various human uses and ecosystem needs requires the computation of a water balance for the catchment. Computing a water balance or water budget involves quantifying how much water enters and leaves the catchment over a period of time, and what is the change of the water stored in the catchment. The primary input into most catchments is precipitation in the form of rain and/or snow, although a few catchments like the Okavango delta in Botswana have river inflow as the main input. A major output or flux of water out of a catchment is evapotranspiration (ET) that is often 50-100% of incoming precipitation in the tropics and subtropics. River discharge can be another important output. In some parts of a catchment, surface water percolates down to recharge groundwater, while in the dry season, groundwater discharges to the surface as springs and seeps. While rain and river discharge can be measured, and ET estimated, it is far more difficult to estimate net groundwater recharge accurately, which is often obtained from the residual term of a water balance. There are several methods and modeling tools to estimate the water balance of a watershed system.

Many of the water balance equations defined based on the Law of Conservation of Mass and is expressed in a form as given below:

P - ET - Q ± ΔS ± Residual = 0

where: **P** = precipitation, **ET** = evapotranspiration, **Q** = water yield (streamflow), **S** = storage (**Δ** signifies "change") and **Residual** = error in all terms plus seepage or leakage in or out of the watershed.

If there is significant human activity in the catchment, water abstractions and return flows are included in the term Q. A water balance can be calculated at daily, monthly and annual time scales, depending on the frequency of data availability.

The hydrological model SWAT - Soil and Water Assessment tool simulates the hydrological cycle based on the water balance equation.

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw} \right)_i$$

Where SW_t is the final soil water content (mm), SW_o is the initial soil water content on day i (mm), t is the time (days), R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), W_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm), and Q_{gw} is the amount of return flow on day i (mm).

The water balance is deceptively simple and is also remarkably powerful as a conceptual model and analytical tool. It serves as a constant reminder of the compensatory changes in water movement and storage that are continually occurring in forest ecosystems. Natural or anthropogenic disturbance alters the water balance and initiates compensatory changes. Apart from determining the water available in a catchment (or at any scale over which a water balance is computed), this exercise can also yield quantitative estimates of water inputs and outputs that are difficult to measure directly. For instance, Saha *et al.* (2012) performed a water balance for the Everglades National Park with daily data over 2002-2008 that indicated net groundwater discharge in the summer months and groundwater recharge during the rainy season along with quantitative estimates.

Evapotranspiration is a very large component in the water cycle of almost all regions on our planet. But there is no single method to measure ET due to a wide variety of vegetation all over the world. In particular, the estimation of ET in woody vegetation is very difficult. Plant species and communities vary widely in their water uptake and transpiration (Douglass 1966), that also changes seasonally. Hence evapotranspiration over woody vegetation is an active area of research. It is necessary to be aware that there is considerable uncertainty in ET estimates obtained in commonly-used hydrological models as well as in global datasets. For better accuracy, it is advisable to compare ET estimates from various approaches such as vapor transport models (Saha et al 2012), eddy flux (Schedlbauer et al 2011), diurnal water table levels and stand-level sapflow (Villalobos 2010) and remote sensing (Nouri et al 2013). However, all these methods require location-specific studies. In the absence of such studies and/or detailed meteorological data, global ET datasets can be used to get an idea, as discussed below.

17.2.2 Data needs and limitations

The availability of data is vital for performing water balances, for monitoring water availability and as inputs into ecohydrological research. Unlike the Everglades which has the benefit of having very spatiotemporally detailed meteorological and hydrological data, much of the world has very sparse or no data available. In such data limited areas, the use of global and remote sensing data provides a first approach. Precipitation estimates for tropical regions are available in TRMM datasets (NASA) while evapotranspiration datasets (MODIS) are available for most of the global terrestrial surface at a 1 km resolution. While there is active research on estimating river level/discharge as well as soil moisture from remote sensing measurements (Brocca et al 2013), there still is the need for establishing monitoring stations and networks on the ground, for calibration/validation of these products. The cost of installing, operating and maintaining such monitoring programs is worthwhile given that reliable data enables better assessment of water dynamics and availability in regions subject to increasing human demands as well as uncertainties under climate change conditions.

17.3 Forest ecosystems and hydrology

17.3.1 Headwater catchment forests

Rivers typically originate as streams in elevated parts of a catchment. These hilly or mountainous regions have high-altitude grasslands and/or forests and occasional wetlands as natural ecosystems; forests exist today either from protection on account of their water-harvesting functions or because they occur in the steepest areas unsuitable for agriculture or large-scale human settlement. In the subtropics and tropics, depending upon the location (latitude/longitude) and altitude, such forests can be broadly classified as deciduous forests (typically lowland to 1500 m), tropical montane evergreen cloud forests occurring at altitudes between 1000 and 2000 m, and evergreen coniferous forests (2000 – 3500 m). In addition, there are single and mixed species plantations, often with fast-growing exotic species such as Eucalyptus in Asia, Africa and Latin America. The differences in canopy structure, plant species water uptake and soil type in these different forests lead to differences in the partitioning of precipitation into canopy interception, throughflow and stemflow, percolation and infiltration, evaporation, water uptake and transpiration and surface runoff. Figure 2 illustrates the typical hydrological processes in the forest canopy and stand.

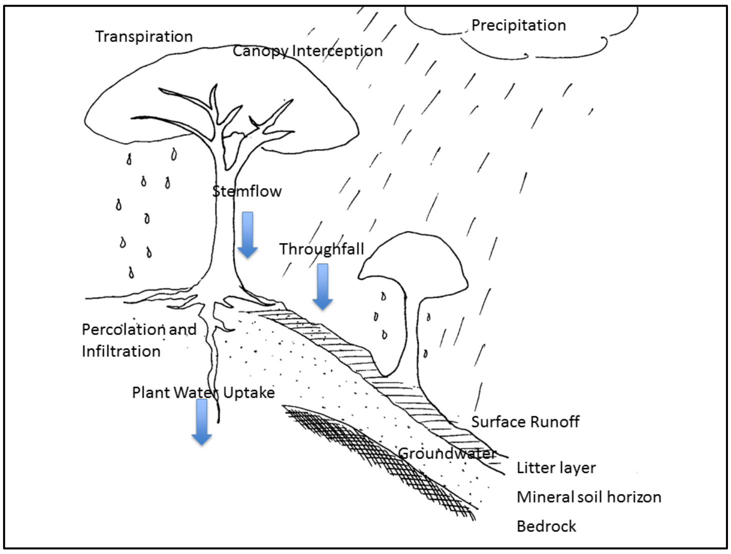

Figure 2: Hydrological processes in a forest canopy

Hydrological processes:

Forests essentially function as sponges on the landscape, by intercepting rainfall and allowing time for rain to percolate into underground and recharge groundwater (Fig 2). In the absence of forest cover, rainwater immediately flows off overland as surface runoff. This is why streams in forested catchments flow longer in the dry season than streams in deforested watersheds. For instance, the removal of Shola evergreen tropical montane cloud forests in the Western Ghats ranges in India has resulted in the inability of the land to retain water, thus resulting in a destructive cycle of monsoon flooding and subsequent drought (Kadur & Bawa, 2005). The author has also noticed this in streams of thickly forested Bori National Park in central India that has streams flowing all through the dry summer, while streams outside the National Park in catchments converted completely to agriculture run dry months earlier.

Interception of rain and snow by forest vegetation is an important hydrologic process. It may account for a substantial proportion (as much as 20 to 30%) of annual precipitation, even though many factors are involved in accurately measuring the fraction of precipitation that is intercepted, making it difficult to characterize interception by forest type (Crockford and Richardson 2000). Some of the intercepted precipitation evaporates back into the atmosphere, while another fraction percolates down leaves, stems, branches and trunk into the soil, and is termed stemflow.

Forest soil and litter layer

While the canopy forms part of the sponge, the other part is the forest floor. Forest vegetation and forest soils develop together, one influencing the other, over the course of centuries; once washed away upon deforestation, forest soil can take centuries to form again. The combination of (a) annual additions of leaf litter and woody debris, (b) root growth, (c) the actions of microbes, insects and other invertebrates, and small mammals, and (d) biogeochemical cycling lead to the development of unique soil properties in forests relative to most other land covers and land uses. Forest soils typically have high organic matter with water holding capacity and permeability. As a result, incident rainfall or snowmelt rarely exceeds the infiltration capacity of forest soils and overland flow alongwith surface erosion is rare, except under very high rainfall events that saturate the soil. The soil is the nexus for many ecological processes (energy exchange, water storage and movement, nutrient cycling, plant growth and carbon cycling at the base of the food web).

The forest canopy intercepts the kinetic energy of rain and along with the protective influence of the litter layer ensures that the porosity and permeability of forest soils remains intact — and that soil particles are not detached and converted to sediment. One centimeter of rain on 1 hectare has a total mass of 100,000 kg (110 tons), which exerts a considerable erosive force on soil that is stripped of its protective canopy and litter layers.

Forest-climate linkages

Forest vegetation has an obvious influence on microclimate (air temperature, humidity, and wind speed) under the canopy; for instance, the average nighttime temperature inside a Shola cloud forest in the Western Ghats is around 10 degrees higher than the exposed grassland (Meher-Homji 1991), with forest edge effects of lower humidity penetrating about 15-20 meters inside the forest studied (Jose et al 1996). Primary forests thus shield the soil from high evaporative demand.

Given the complexity of wind circulation patterns and other factors that define climate, the influence of forests on regional, continental, and global climate is not as straightforward. Despite the complexity, there is a large body of experimental and modeling work investigating the role of forests in influencing rainfall that has found evidence of considerable effects that forests have on local precipitation. For instance, Moreira et al (1997) used stable isotopes of oxygen and hydrogen to find that almost half the rainfall in the eastern Amazon resulted from transpiration from local forests. Shukla et al (2001) used numerical models to arrive at a similar conclusion, that deforestation would lead to changes in rainfall patterns, with negative implications for regeneration of many Amazonian forest tree species. Similarly, forests along the fog-enshrined Pacific coastline of the Americas intercept moisture on their leaves (Cavalier & Goldstein 1989).Dawson 1998, estimated that 34% of the ecosystem water input in a California redwood forest resulted from fog dripping from trees, and only 17% in a deforested catchment bereft of tree condensation. Tropical cloud forests have a similar interception of moisture from clouds that enshroud these forests much of the year, thus constituting an important moisture source even in the absence of direct rainfall (Bruijnzeel 2001).

17.3.2 Single or mixed-species plantations

Plantation forestry is common and widespread and is managed for timber and pulp. Being much younger than old growth forest, and having typically uniform stands of even-aged trees with similar architecture, their canopy is more open as compared to native forests that have an interwoven closed canopy. It follows that hydrological partitioning in such forests are more skewed towards runoff with lesser infiltration than native primary forests. Krishnaswamy et al (2012) report that exotic *Acacia* plantations in the Western Ghats had higher fraction of rainfall leave as runoff as compared to primary evergreen forest in the same region, while degraded heavily-used forest had the highest runoff fraction. Furthermore, many exotic fast-growing species have water uptake rates higher than native vegetation which results in higher evapotranspiration and consequently, lower streamflow (Putuhena & Cordery 2000).

17.3.3 Lowland forests

Lowland forests span a range of types associated with rainfall, from evergreen forests in high rainfall areas to increasing deciduousness and finally scrub forests at the arid end of the rainfall gradient. The processes of moisture interception, percolation and transpiration occurring in headwater catchment forests also occur in lowland forests. Streams passing through lowland forests flow for longer durations than streams in adjacent watersheds; in addition, streams running through forests are clear and cool. Deforestation in lowland forests thus affects water quality (soil erosion) as well as reduced infiltration and baseflow.

17.3.4 Savannas – grassland and woodland matrix

Savannas occur in areas where potential evapotranspiration exceeds rainfall and occupy large areas throughout the tropics and subtropics. Fires, both natural and anthropogenic occur frequently, almost on an annual basis. There is usually considerable heterogeneity in topography and moisture, which results in a mosaic of vegetation (D'Odorico & Porporato 2006). Gallery forests occur alongside river courses in savannas, on account of the availability of year-round moisture and usually have very different plant species from the surrounding savanna.

There is considerable pressure on savannas; for instance, deforestation in Tanzania has been the highest in the savanna woodlands (2000-2012) on account of ease of access, felling of woodland trees for charcoal and agricultural expansion following increases in irrigation. Similarly, efforts to control Amazon deforestation have increased the pressure on the Cerrado savanna ecosystem in central Brazil for conversion to agriculture for soyabean and biofuel demands. The effects of deforestation in savanna woodlands are similar to those in lowland forests.

17.3.5 *Forests and Water Management*

Paired-watershed studies, that are comparative studies in adjacent forested and deforested catchments (eg Brown et al 2005) support traditional evidence that watersheds with forest cover have a more regulated river flow than watersheds within the same climatic zone that are deforested. Forests dampen high flows immediately following heavy rainfall events, while prolonging baseflow in streams in the dry season (eg Bruijnzeel 2002, Krishnaswamy et al 2013). Deforested watersheds exhibit high runoff following heavy rainfall events that lead to soil erosion, landslides and floods.

Now there is considerable confusion over the role of forests in catchments when the goal of water management is to maximize water yield from a catchment.It is important not to confuse annual water yield with the duration of flow. A deforested watershed typically sees a higher water yield as a result of much lower evapotranspirative losses, which also varies by forest type (Brown et al 2005). It is important to note that while the annual water yield can increase following deforestation and decrease following reforestation, looking at the flow duration curves gives an idea of how long the rivers flow in the dry season. For instance, Lele et al (2008) report on a case of paddy farming in South India that was irrigated from a reservoir, which in turn was filled by a river arising in the Western Ghats hills. There were concerns that reforestation in the hills would lower streamflow in the wet season months thereby decreasing water stored in the reservoir during the paddy season, which in turn would reduce the irrigated area under paddy cultivation. This is an example of contrasting watershed uses, of paddy farmers not favoring reforestation to ensure high water yields, even though reforestation would lead to longer baseflows in the river (Krishnaswamy et al 2013) and other watershed benefits such as water quality and reduced soil erosion.

17.3.6 Riparian/gallery forests – the last defense against non-point pollution

Riparian areas or riverbanks include the transition or ecotone between terrestrial and aquatic ecosystems that has special implications for biogeochemical reactions (McClain et al 2003). Forests growing along these riverbanks are called riparian or gallery forests (Fig 3) and provide a host of essential functions, including: (a) shade that cools water temperature and thereby increases dissolved oxygen concentration, (b) leaf litter inputs to microbes and invertebrates at the base of the food web, (c) structural support of stream banks, (d) large woody debris that stabilizes channels, diversifies stream habitat, and provides essential cover, and (e) hydraulic resistance to flood flows and sediment transport. Riparian buffers also intercept sediment in runoff arriving from adjoining slopes, especially if these slopes contain farmland and roads. Riparian forests, often being the last patches of forest left on the landscape, provide the last remaining hábitat for regional biodiversity (Naiman et al 1993).

The importance of riparian trees in maintaining water quality and the aquatic ecosystem has been known for a long time. *Terminalia arjuna* trees that grow along stream courses in peninsular India have been protected as sacred trees since many centuries. Many countries have riparian buffer guidelines under best management practices for watersheds, whereby no cultivation or settlement is allowed within 30-50 m on either side of a stream bank. In essence, riparian buffers provide the last defense in multiple use watersheds with large tracts of farmland, pastureland and settlements, hence need to be critically enforced. Most watersheds in the world today do not have the benefit of large tracts of pristine old growth forests to stabilize the soil.

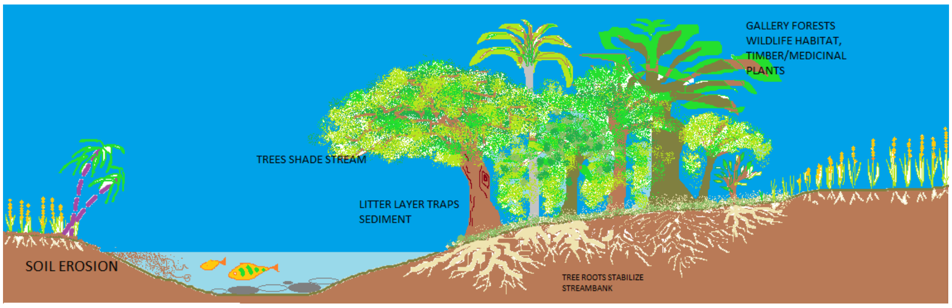

Figure 3: Natural vegetation on the right bank of the stream (riparian buffer) protects stream ecosystems and water quality, while the left bank has agriculture on the bank, which results in soil eroding into the stream.

Investigations over the past couple of decades has focused on biogeochemical cycling in riparian zones where periodic inundation creates a fluctuating aerobic/anerobic environment in the soil, that in turn accelerates the processes of nitrification and denitrification (Pinay et al 1993, Orr et al 2007). Results indicate that the soil and leaf litter in riparian zones are able to entrap chemical fertilizers present in various forms of nitrogen and phosphorus; nitrogen forms then undergo various biogeochemical transformations depending upon the residence time of the groundwater in the soil and the degree of anoxia (Hill 1996, Ross & Carpenter 2002). Phosphorus, which is the limiting nutrient in many aquatic ecosystems (Schindler 1977, Elser et al 2007)

The width of a riparian buffer necessary for a certain desired level of sediment entrapment and possibly nutrient retention depends upon many factors: rainfall, the slope of the watershed, the soil type, presence of floodplains and watershed land use. GIS models using the Universal Soil Loss Equation predict a required width that can be compared against the recommended uniform regulation to examine whether the recommended width is adequate (Xiang 1993, Baker et al 2001). Steep channels can also short-circuit a riparian buffer adjoining a stream; for instance Wenger (1999) suggests three approaches to determine buffer widths, and a slope greater than 25% calls for a wider buffer. However, the use of models requires trained personnel and data such as land cover, topographic and meteorological data and resources that are unavailable for much of the developing world. Hence fixed width buffers (Fig 4), such as the recommended 30 m buffer width in the flat agricultural plans of Ohio, USA or the 50 m buffer law in Tanzania is a first step towards protection of stream banks that achieve a level of sediment entrapment that is vastly preferable to no protection at all. Location-specific studies are necessary to analyze the sources of sediment and the efficiency of varying buffer widths. For instance, Isabirye *et al.* (2014) indicated that sediment trapping efficiencies of upto 80% were obtained from just 10 meter buffer widths, and that the current 100-200 m buffer width may need to be rethought. However, as a cautionary note, buffer efficiencies depends not only upon the particular watershed topographic, soil, climate and land use it also depends upon the vegetation stage and type in the buffer that can change from area to area. Hence, it is better to recommend a buffer width as wide as is feasible in a given area.

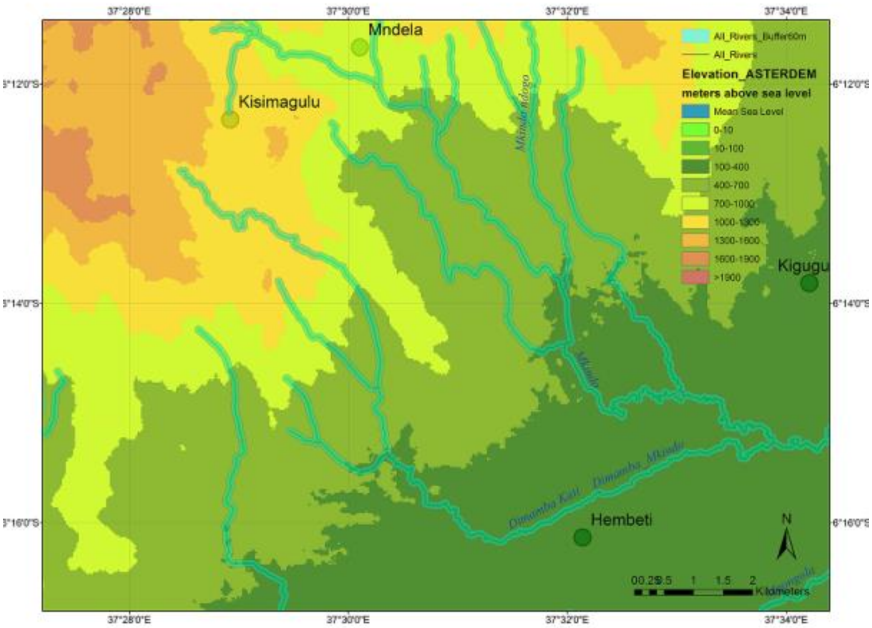

Figure 4: Illustration of a 50 m riparian buffer on either side of rivers; map shown for the Mkindo catchment, Wami river basin, Tanzania.

17.4 Wetlands: kidneys of the landscape

17.4.1 Freshwater wetlands

Wetlands occupy the land-water interface and are some of the most biologically productive environments on earth. Wetlands occur in depressions in every river basin throughout the world, and can be as small as an acre. Even though wetlands occupy less than 9% of the planet's area, they contribute greatly to biodiversity support, water quality improvement, flood abatement, and carbon sequestration (Mitsch & Gosselink 1993, Zedler & Kircher 2005). A large section of the world's population depends upon wetlands for growing rice, palm, sago and fisheries. Wetland drainage and loss has been significant worldwide, and hence 144 countries signed the Ramsar Convention in 1971 to identify and promote the protection of major wetlands which are deemed as Ramsar sites. While large freshwater wetlands such as the Pantanal, the Everglades, the Okavango Delta and the Tonle Sap in the Mekong basin are well known.

The U.S. Fish and Wildlife Service developed a non-regulatory, technical definition of wetlands that emphasize these concepts via the following three points: (1) hydrology--the degree of flooding or soil saturation is such that at some time during the growing season, the substrate is saturated or covered by shallow water; (2) vegetation--plants adapted to grow in water or in a soil or substrate that is occasionally oxygen deficient due to water saturation (hydrophytes) are found; and (3) soils--those saturated long enough during the growing season to produce oxygen-deficient conditions in the upper part of the soil, which commonly includes the majority of the root zone of plants, predominate (i.e., hydric soils).

17.4.2 Benefits of wetlands

Flood control, Water storage and groundwater recharge:

The most significant social and economic benefit that wetlands provide is flood control. Wet grasslands alongside river basins and marshes with centuries of peat buildup in the soil act like sponges, absorbing rainfall, controlling its flow into streams and rivers and at the same time, recharging groundwater in the dry season when the water table falls. When peat becomes completely saturated and unable to absorb any more water, surface pools and peatland vegetation – including sedge meadows and some types of forest – help to slow and reduce runoff. Similarly, floodplains alongside the lower reaches of major rivers, such as the Nile, Parana, Yangtse, Ganges-Brahmaputra and Danube allow heavy rainfall or spring snowmelt to spread out slowly. When the peat bogs are drained or the floodplains reduced, the risk of flash floods is increased.

Water quality:

Wetlands act as filters on the landscape, cleaning up water in a number of ways. Excess nutrients (chemical fertilizers in runoff) are entrapped in the soil, transformed by microbial processes to less ecologically harmful forms or taken up by wetland plants. Similarly, heavy metals and toxins in runoff are trapped in wetland sediments.

Perhaps the most important water quality ameliorative function of wetlands is denitrification, or the transformation of nitrate to nitrogen gas by soil microbes (Forshay and Stanley 2005, Craig et al. 2008). Because of extensive wetland and riparian forest loss, nitrification of waterways increased drastically during the 20th century (Malakoff 1998, Walter and Merritts 2008). Excessive nitrate in the water can contribute to eutrophication. Eutrophication creates extensive algal blooms; upon death the algal mats are decomposed by microbial activity that lowers dissolved oxygen in bottom waters. This leads to dead zones / hypoxia with attendant extermination of marine and estuarine life and an abrupt change in ecosystem structure. Dead zones have spread exponentially in coastal oceans since the 1960s and have have now been reported from more than 400 systems worldwide, affecting a total area of more than 245,000 square kilometers (Diaz & Rosenberg 2008). To avoid collapse of marine ecosystems along with their fisheries, it is imperative to reduce nutrient loading into rivers, for which the only feasible solution from a water management perspective involves the use of natural wetlands and riparian buffers to entrap and prevent some fraction of nutrients from reaching rivers.

A growing area of ecohydrological application is the design and use of artificial or constructed wetlands for the treatment of municipal wastewater as well as certain types of industrial effluents. The next chapter gets into that in bit more detail.

17.4.2 Estuarine wetlands: freshwater is the lifeline

Ecosystem services:

Coastal wetlands such as mangroves and saltmarshes act as frontline defenses against devastation from periodic storms and wave surges. The roots of wetland plants bind the shoreline together, resisting erosion by wind and waves and providing a physical barrier that slows down storm surges and tidal waves, thereby reducing their height and destructive power. In the Caribbean, the shoreline protection services provided by coral reefs are valued at up to US$2.2 billion annually. Worldwide, an estimated 200 million people who live in low-lying coastal regions are at potential risk from catastrophic flooding.

Mangroves and seagrass beds also constitute nurseries for marine fish, and are the basis of coastal fisheries. The ever-changing environment of fresh and saline water along with the nutrients brought by both water pools provides one of the world's most productive ecosystems - the estuarine and coastal ecosystems. In the tropics, seagrass beds cover the estuary and coastal offshore muddy/sandy bottom, where marine fish come to breed, the seagrass providing both shelter for juvenile fish from larger marine predators of the open sea, as well as food in the form of submerged aquatic vegetation and marine invertebrates.

Estuaries and freshwater management: an optimal range of freshwater inflows

From a water management standpoint, the challenge in maintaining estuarine forests and wetlands is to ensure adequate freshwater inflow via rivers that follows the natural seasonal cycle of wet and dry season flows. The inflow of freshwater has been long recognized as a crucial factor affecting the biological productivity of estuarine areas worldwide (Powell *et al.*2002), since freshwater affects bays at physical, biochemical and ecological levels. Estuaries have a unique environment with a constantly varying mix of freshwater and seawater. This mix varies seasonally from a pulse of freshwater flowing far out to sea during the rainy season, to very saline conditions in the estuary during the dry season when the freshwater flow in the river has decreased. The mix of freshwater and saline seawater also varies diurnally with tides; at high tide, the seawater opposes the freshwater and moves into the river as a wedge of denser water flowing in underneath the freshwater that is flowing seaward in the opposite direction.

Estuarine communities are adapted to this natural seasonal fluctuation in freshwater inflows. A decrease in freshwater inflow to levels lower than the natural seasonal flow regime results in increased seawater intrusion into the estuary (Nguyen & Savenije 2006). Prolonged exposure to high salinity reduces water uptake in mangroves by stressing the salt-exclusion mechanisms in roots and leaves (Parida & Das 2000). Even though mangrove species differ in their tolerances to salinity, high levels of flooding with saline water can stress even the most salinity-resistant species, resulting in eventual mangrove dieback. Coastal forests typically have a range of tree species that vary in their salinity tolerance, including very-intolerant species existing on slightly higher elevations that depend upon a rain-derived freshwater lens that floats above groundwater and occupies the vadose zone. Higher salinity in groundwater arising from decreased freshwater inflows decreases the freshwater lens (eg. Saha et al 2011).

Similarly, hyper-saline conditions in bays stress seagrasses, as well as the various organisms that reside in these habitats. Decreased river inflows into estuaries also lead to decreased nutrient inputs. At the same time, very high freshwater flows can also disrupt lifecycle process of estuarine ecosystems (Powell *et al.*2002, Tolley *et al.*2012). Keeping all this in mind, there is an optimal range of freshwater inflows into estuaries necessary to maintain estuarine ecosystems.

Freshwater flows to the estuary thus balance seawater coming in with the tide. Hence, any large decrease in freshwater inflows leads to seawater intrusion into the estuary, and possibly into coastal aquifers near the estuary in areas where the estuary and underlying aquifers are hydrologically connected, or in low elevation flat areas along the riverbanks where seawater floods in overland during low tide. Once shallow well water gets saline, wells often have to be abandoned. Sotthewes (2008) notes increasing saltwater intrusion occurring in the Pangani estuary over the past several decades and attributes it to two major factors: decreasing freshwater discharge on account of irrigation and hydropower reservoir abstractions and increasing erosion at the marine end on the account of less deposition of river sediment. Similarly, the drainage of the Everglades in the early 20^{th} century has led to decreases in freshwater discharges along the east coast of South Florida, that has progressively brought the freshwater-seawater interface inland into the Biscayne Aquifer (USGS 2013), leading to the salinization and the eventual abandonment of 6 out of 8 water supply wells in the City of Hallandale in 2011 (Reid 2011).

Policymakers thus are faced with the difficult task of developing water resource management programs that allocate freshwater between changing human and ecosystem needs in a sustainable manner. In their review of the prevailing understanding and experiences of the restoration and recovery of estuarine, coastal and marine ecosystems, Elliott et al (2007) caution that even though restoration is worthwhile, rarely can it replace lost habitat or ecosystem diversity. Theoretical ecological concepts related to restoration are well understood, such as ecosystem structure and function; however other factors such as assimilative capacity, resilience and ecosystem services are specific to the particular region or ecosystem, and typically are poorly quantified in much of the world. The linking between these ecological concepts and the management framework is required to impart a holistic approach to understanding and managing these ecosystems and the services they provide mankind.

17.5 Aquatic ecosystems and water quality

17.5.1 Assimilative capacity and self-purification

Aquatic ecosystems have an inherent capacity to maintain water quality (eg McClain et al 2008) that is referred to as the overall assimilative capacity of the particular stream, river or wetland. Ostroumov (2005, 2006) has reviewed the array of physical, chemical and biological processes that contribute to maintaining water quality; physical processes include filtering, deposition and dilution, chemical processes include sorption/release of substance from sediments and organic matter and transformation via biogeochemical reactions, while biological processes include sequestration, microbial transformation, uptake by plants and animals and nutrient spiraling. These processes are interconnected and depend upon the existence of different habitat types and zones such as stream, floodplain and riparian vegetated zone.

The inherent capacity of a particular water body is assessed by ecohydrologists which then along with a factor of safety, is used by water managers to determine the total daily maximum loads (TMDLs) of pollutants in discharges by different point sources along with prevailing non-point sources. Seasonal variation in hydrology and ecology influences the TMDLs to a water body. By recognizing and supplying the self-purifying functions that a natural stream or river provides, water quality can be maintained at source which vastly decreases the expense of treatment at the user's end. In most developing countries, maintaining good water quality in streams, rivers and wetlands is the only way to ensure water quality, given the infeasibility and unsustainability of large treatment plants.

17.5.2 Maintaining aquatic ecosystems: threats and opportunities

Water flow and quality in streams and rivers are influenced by the landscapes they drain (Hynes 1975, Allan 2004). A major threat to stream ecosystems worldwide is sedimentation (Malmvquist 2002) arising from soil erosion due to deforestation and/or inadequate soil conservation measures in hillslope farms and road-building. Siltation of stream bottoms covers up the spaces underneath and in between streambed stones, thereby removing habitat for the aquatic larvae of many insects. These aquatic macroinvertebrates form a preybase for fish, and in addition, many of them facilitate the breaking down and subsequent decomposition of leaf litter and organic matter in streams. Adequate soil conservation methods such as terracing, strip mulching, dykes and bunds are necessary through the cooperation of farmers, agriculture extension and NGOs along with riparian buffers as a last defense against nonpoint pollution.

Another threat to aquatic ecosystems arises from flow alterations resulting from straightening stream courses or channelization. Straightening removes heterogeneity of in-stream habitats such as depositional gravel bars, riffle zones and deep pools that arise from the effect of meandering channels upon water flow and deposition. The past decade has seen an increase in river channel restoration activities across North America and Europe, with manuals available (such as Soar and Thorne 2001) that detail the hydraulic engineering and ecohydrological inputs necessary for restoring channel meander and stabilized streambanks.

A third threat to ecosystems arises from the introduction of exotic fish, mollusc and plant species, which alter the relationships between different species and communities, and thereby affect ecosystem function as well as ecosystem services. A global example is water hyacinth, *Eichhornia crassipes*, of South American origin that has been spreading over inland waterbodies in all other continents and if not controlled, covers lakes and wetlands completely, cutting off sunlight for native plants and lowering oxygen that results in large fish and turtle kills. Exotic species can also affect infrastructure, such as the small mollusk *Corbicula fluminea* of Asian origin that has been seen to clog up water intake pipes in cooling systems in the US. However, on the other hand, the European zebra mussel that was accidentally introduced to the Great Lakes in the US and Canada have been found to improve water quality by filtration. The control of exotic species is especially difficult and labour-intensive. Biological control solutions abound, usually based on introducing species that prey upon the target exotic species from its native area, however need to be studied very carefully as this intentional introduction can in turn cause other problems.

17.5.3 Minimum seasonal environmental freshwater flows

Tropical rivers exhibit enormous seasonal variations in flow and depth; for instance, the tributaries of the Wami and Ruvu rivers in Tanzania vary from 4-5 m depth in the wet season to less than a meter in the dry season. Over time, riverine species and communities have evolved to adapt to a natural seasonal flow cycle. Changing that cycle by changing flow magnitude, removing seasonal flow variation or sudden releases of water, typically from dam and reservoir operations or large water abstractions can completely change the aquatic environment with changes in community structure. Migratory fish in particular are seriously affected. For example, McClain et al (2014) describe flow-ecology relationships in the Mara river of Kenya/Tanzania by comparing the seasonal flow regime, channel hydraulics and biological communities; such relationships constitute valuable inputs to river management.

An Environmental Flow Assessment (EFA) in a river aims to determine the quality, quantity, and timing of freshwater flow required to maintain the aquatic ecosystem (Poff et al. 1997). Having determined the minimum flow requirements for a river, and incorporated them into policies, the far bigger challenge involves actual implementation. Part of the challenge is technical in that monitoring river flows is often absent or patchy. But the greater challenge rests in allocating a limited quantity of water amongst multiple stakeholders. To accept this, the stakeholders need to be aware of the importance of maintaining aquatic ecosystems. Dickens (2011) reviews EFAs recently carried out in 4 major rivers in Tanzania, looking at both the methodologies as well as direct relevance for water management with the heartening conclusión that the initiative, progress and implementation of EFAs in Tanzania has been exemplary for any nation. The group International Rivers has developed guidelines based upon the experience in implementing programs to restore natural flow regimes in rivers in many countries (Kendy & LeQuesne 2014). Foremost is the suggestion to take deliberate, incremental steps in a multi-stakeholder process that do not exceed the technical, financial and logistical capacity in place. It is a hopeful sign that projects in many countries have succeeded in restoring some degree of natural channel geomorphology and flow, as described in case studies by International Rivers (Kendy & LeQuesne 2014),. This agrees with the assessment by McClain et al (2008) that large river basins in the humid tropics still retain a high degree of ecosystem function.

17.6 Conclusion

This chapter has described the general hydrological behavior of various forest and wetland types commonly encountered in watersheds. Forests and wetlands act as water storage units on the landscape, thereby both regulating high flows and extending the period of low flows in the dry season. They also ensure good water quality. It has always been known that forests are beneficial for regulating water and natural resources. However, in the present era, only a fraction of watershed area is covered with natural forests, while most wetlands have been drained. Hence, the ecohydrological features of the forests and wetlands present in a catchment have to be studied and understood in order to maintain these remaining ecosystems as well as employ their beneficial hydrological services to mankind. An understanding of the ecosystem-hydrology linkages is also necessary for the restoration of ecosystems thereby increase ecosystem services and enabling sustainability in water availability, quality and management. Watershed ecosystems also buffer hydrological processes and water availability from the adverse effects of climate change; namely uncertainty associated with precipitation and increasing evaporative demand.

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