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Evaluating the Flow Regulating Functions of Natural Ecosystems in the Zambezi River Basin

Matthew McCartney, Xueliang Cai and Vladimir Smakhtin

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Front cover photograph shows Lukanga Wetland, Zambia (*photo credit:* Matthew McCartney, IWMI).

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Contents

Acronyms and Abbreviations

BFI	Baseflow Index
FDC	Flow Duration Curve
FRIEND	Flow Regimes from International Experimental and Network Data
GLWD	Global Lakes and Wetlands Database
GRDC	Global Runoff Data Centre
HGM	Hydrogeomorphic
SADC	Southern African Development Community

Summary

By affecting transpiration and evaporation and influencing how water is routed and stored in a basin, forests, wetlands and floodplains play a crucial role in the hydrological cycle. A major role widely attributed to them is regulating flows (i.e., both attenuating floods and maintaining flow during dry periods). However, these services are seldom, if ever, explicitly factored into the planning and management of water resources. One reason for the failure to include them is lack of understanding of the hydrological functions occurring, their dynamic nature, and the interaction of these functions with the catchments in which the ecosystems are located. Very often, it is unclear exactly which functions are performed and how these functions change over time (i.e., between seasons and between years). Furthermore, both the lack of quantitative information and a recognized method to incorporate them into decision-making processes, make it very difficult to integrate natural hydrological functions into the planning and management of water resources. This report summarizes the findings of a literature review conducted to find evidence of the flow regulating functions of the major ecosystems in the Zambezi River Basin. It also describes a pragmatic approach for quantifying the flow regulating functions of floodplains, headwater wetlands and miombo forests in the basin. The method utilizes observed streamflow records and flow duration curves to derive a simulated time series of flow in the absence of the ecosystem. This can then be compared with an observed time series to evaluate the impact of the ecosystem on the flow regime. The method has been applied to 14 locations in the basin. Results indicate that the different ecosystems affect flows in different ways. Broadly: i) floodplains decrease flood flows and increase low flows; ii) headwater wetlands increase flood flows and decrease low flows; iii) miombo forest, when covering more than 70% of the catchment, decreases flood flows and decreases low flows. However, in all cases there are examples which produce contrary results and simple correlations between the extent of an ecosystem type within a catchment and the impact on the flow regime were not found.

Evaluating the Flow Regulating Functions of Natural Ecosystems in the Zambezi River Basin

Matthew McCartney, Xueliang Cai and Vladimir Smakhtin

Introduction

Forests, wetlands and floodplains influence the hydrological cycle by affecting rates of evapotranspiration and by modifying how water is transmitted and stored in a basin (Bruijnzeel 1996; Bullock and Acreman 2003). Though rarely quantified, a function widely attributed to them is as natural regulators of river flow; storing water when it is wet and then releasing it slowly when it is dry (Blumenfeld et al. 2009). The natural regulation of flows is often assumed to translate into benefits for human populations living downstream. By reducing the frequency and damaging impacts of floods and simultaneously ensuring that water is available (i.e., for drinking, irrigation, industry, etc.) at times that it would not be otherwise, natural regulation is widely viewed as an "ecosystem service" (MA 2005; Blumenfeld et al. 2009).

Notwithstanding the fact that if natural ecosystems regulated flows in a way ideal for people there would be no need to build dams, natural ecosystems are increasingly perceived to play a role akin to human-made reservoirs. In recent years, this has led to the proposition that natural ecosystems should be considered as "natural infrastructure" and much more closely incorporated into decision-making processes pertaining to water resources (Emerton and Bos 2004). However, currently the hydrological functions of natural ecosystems are poorly understood and rarely explicitly factored into the management of water.

One reason for the failure to include natural ecosystems in water planning and management is lack of understanding of the complex interaction of the hydrological processes occurring within them and their dynamic nature. Very often it is unclear which ecosystems actually perform which functions, what the magnitude of any changes in flow are, and how functions change over time (i.e., between seasons and between years). The absence of both quantitative information and a recognized method to include them makes it very difficult to incorporate natural hydrological functions in decision-making processes. It would be easier to include natural ecosystems in water planning and management if the impact of natural ecosystems on flows could be quantified, in the same way that the impact of a human built dam can be calculated. If this was possible, the implications of naturally induced changes in flow regimes for communities living downstream of natural ecosystems could be properly deduced.

Against this background, this report describes research conducted with the primary aim of developing and testing a method to quantify the impact of natural ecosystems – floodplains, headwater wetlands and forests – on river flows in the Zambezi River Basin. It summarizes the results of a literature review conducted to find evidence for their role in regulating flows (i.e., both attenuating floods and maintaining dry-season flows) in the basin. It briefly describes different possible approaches for quantifying the impact of natural ecosystems on flows and explains the limitations of each. It then provides a detailed description of a simple pragmatic method developed to estimate the impact of natural ecosystems on flow and describes its application to 14 locations within the basin. Finally, the results obtained are presented, the strengths and weaknesses of the method discussed and the implications of the findings summarized.

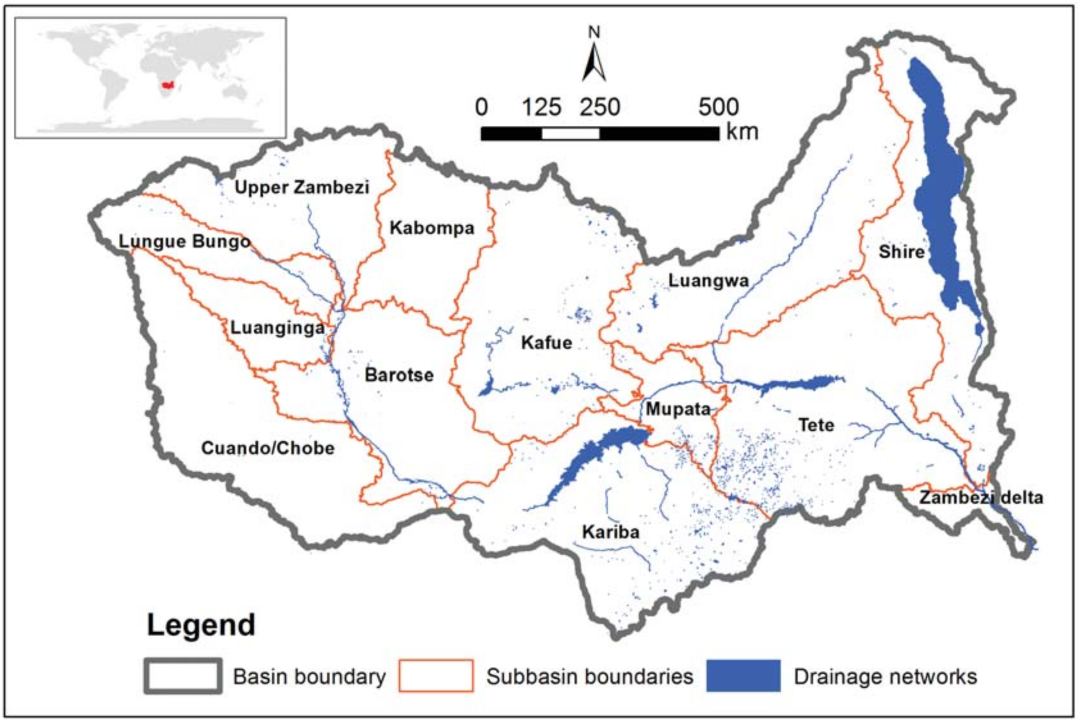
The Zambezi River Basin

The Zambezi River Basin is the largest river basin in the Southern African Development Community (SADC) region with a total drainage area of approximately 1.34 million square kilometers (km^2). The main stream, with a total length of 3,000 km, originates in the Kalene Hills in northwest Zambia at an altitude of 1,500 m and flows eastwards to the Indian Ocean. The river has three distinct stretches: the *Upper Zambezi* from its source to Victoria Falls, the *Middle Zambezi* from Victoria Falls to Cahora Bassa and the *Lower Zambezi* from Cahora Bassa to the delta. Typically, for planning purposes, the basin is divided into 13 major subbasins (Figure 1). The main tributaries are the Shire, the Luangwa, the Kafue, and the Kabompo rivers (World Bank 2010).

Lying between latitudes 10° and 20° south and between longitudes 20° and 37° east, the climate of the basin is largely controlled by the movement of air-masses associated with the Inter-Tropical Convergence Zone (ITCZ). Rainfall occurs predominantly during the summer (November to March), and the winter months (April to October) are usually dry. The average annual rainfall over the basin is 990 millimeters (mm), varying from 1,200 mmy^{-1} in the northern parts to 700 mmy^{-1} in the southern and southwestern parts of the basin (World Bank 2010). However, rainfall is characterized by considerable spatial and temporal variation throughout the basin. Droughts of several years' duration have been recorded almost every decade (Tyson 1986). Floods also occur frequently. Although more pronounced in the more arid (lower) regions, unpredictability is also a feature of the wetter (higher) areas. The average annual potential evaporation is about 870 mm (Matondo and Mortensen 1998).

The basin is underlain by Precambrian crystalline and metamorphic rocks, which form part of the African and Post-African Tertiary planation surfaces (Acres et al. 1985). Basement aquifers, which develop within the weathered regolith and fractured bedrock, play an important role in the hydrology of the region (Bullock 1992b). Depressed areas are covered by sedimentary layers of varying thickness. The topsoil is generally shallow and there are serious problems of erosion by water and wind in parts of the basin.

FIGURE 1. Zambezi drainage network and the 13 major subbasins.

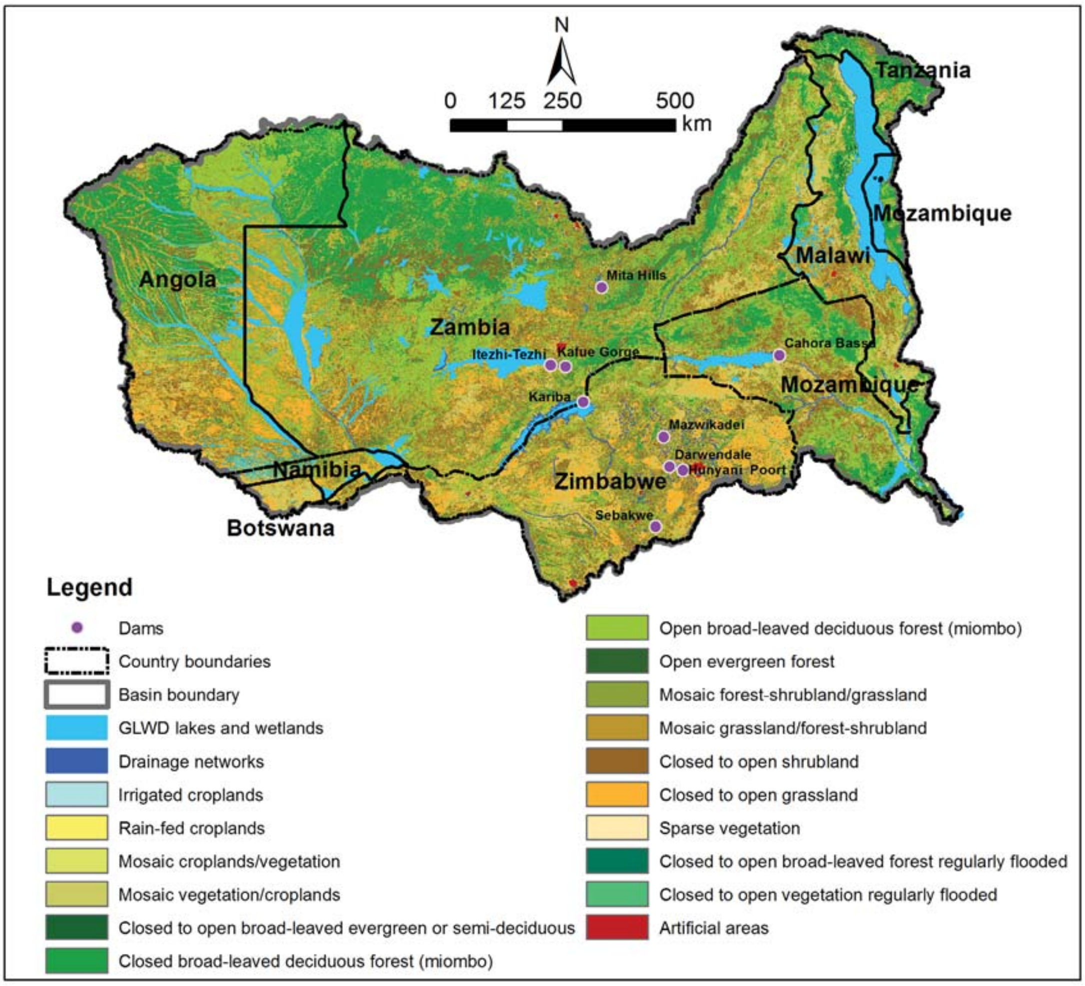


Throughout the basin runoff arises in response to complex interactions between surface flow and saturated and unsaturated subsurface flow.

The natural flow regime of the Zambezi River reflected the rainfall and was characterized by high seasonal and annual variability. The total discharge of the river is estimated to be 130,500 million cubic meters (Mm^3) (4,134 m^3s^{-1}) which equate to 95 mm over the entire basin (i.e., a runoff coefficient of 9.6%). Currently, due to the absence of large dams, the Upper Zambezi remains the most natural portion of the river. Further downstream, the flow is regulated by a number of large dams, built primarily for hydropower generation (Beilfuss and dos Santos 2001). The operation of these dams has resulted in an increase in dry-season flows and a delay and decrease in peak flows during the flood season. These changes in the flow regime have had an impact on the morphology and ecology of the river and the Zambezi Delta (Nugent 1983; Ronco et al. 2010; Beilfuss and dos Santos 2001).

The Zambezi River Basin comprises a mosaic of miombo woodland, grassland, savannah, agricultural land and wetlands (Appendix A). The evolution of the basin and its major biomes and species distribution are described in Timberlake, 2000. Figure 2 shows the wetland areas from the Global Lakes and Wetlands Database (GLWD) (Lehner and Döll 2004) together with the GlobCover land use map (Arino et al. 2007) and the major dams in the basin. Miombo woodland (i.e., closed/open deciduous woodland dominated by the genera *Brachystegia*, *Julbernadia* and/or *Isoberlinia*) is the most extensive tropical seasonal woodland and dry forest formation in Africa and covers a substantial part (607,523 km^2, 45%) of the basin (Timberlake 2000; Appendix A). The Central Zambezian Miombo woodland is one of the largest

FIGURE 2. Land cover, dams and the riparian country boundaries of the Zambezi River Basin.



ecoregions in Africa, ranging from Angola up to the shores of Lake Victoria in Tanzania.

Wetlands, comprising swamps, marshes, and seasonally inundated floodplains, are also a major feature of the basin covering a total area of at least 63,266 km^2 (4.7%) according to Lehner and Döll (2004). However, this is certainly an underestimate since in addition to the major wetlands (Table 1) smaller wetlands (e.g., *dambos*/*vleis*) are widespread in the headwaters of many

TABLE 1. Major wetlands in the basin.

Name	Location (latitude and longitude) and subbasin	Area (km^2)	Description (e.g., wetland type)
Zambia			
Swamps of the Kabompo River	Kabompo	180	Small riparian swamps, extending in narrow strips.
Swamps of the Lungue-Bungo River	The Lungue-Bungo River and two tributaries (Litapi and Lutembwe)	1,000	Large permanent swamp in the triangle of land between the two tributaries (papyrus, phragmites and floodplain grasslands).
Luena Flats	Luena River	897	Papyrus and phragmites swamps with grass floodplains fed by several small streams (i.e., Nkala, Luambua, Lukuti and Ndanda).
Nyengo Swamps	Luanginga River	700	Seasonal flood waters spread between the Luanginga, Ninda and another tributary.
Lueti and Lui Swamps	Lueti and Lui rivers	375	Floodplain wetlands + patches of permanent swamp that merge with Barotse floodplain.
Barotse Floodplain	Upper course of the Zambezi River 14°19’-16°32’S/23°15’-23°33’E	7,700	Floodplain wetland located on Kalahari Sand.
Sesheke Maramba Floodplain	Zambezi along the northern border of the Caprivi Strip	1,500	Floodplain.
Busanga Swamp	Kafue 14°05’-14°21’S/25°46’-25°57’E	600	Permanent shallow swamp.
Lukanga Swamp	Lukanga but with spill from Kafue 14°00’-14°40’S/27°19’-28°00’E	2,100	Reed/papyrus swamp.
Kafue Flats	Kafue River 15°11’-16°11’S/26°00’-28°16’E	7,000	Floodplain swamps and marshes located between Itezhitezhi and Kafue Gorge dams.
Zimbabwe			
Mid-Zambezi Valley and Mana pools	Zambezi 15°36’-16°24’S/29°08’-30°20’E	360	Floodplain – pans and pools.
Malawi			
The Shire Marshes	Shire River draining Lake Malawi 16°11’-17°05’S/34°59’-35°19’E	740	Two tracts of permanent swamp and lagoons in the Chikwawa and Bangula areas plus floodplain.
Namibia			
Cuando-Linyanti-Chobe-Zambezi (including Linyanti Swamp, Eastern Caprivi wetland, Chobe swamps)	Cuando, Linyanti (Chobe) 17°39’-18°40’S/23°18’-25°10’E	Total 3,930 900 (Linyanti Swamp)	Floodplain, swamps and shallow lakes through the Caprivi Strip. Near the Chobe-Zambezi confluence in phase flooding of both rivers may inundate 1,700 km^2 of floodplain.
Mozambique			
Lower Zambezi	Downstream of Tete, particularly in the vicinity of the Shire River	>325	Floodplain, swamps and shallow lakes (e.g., Lake Mimbingue and Lake Tanie).
Zambezi Delta	Zambezi downstream of Caia	1,300	Zambezi discharges via distributaries through a wide delta. Swampy floodplain and areas of mangrove forest extending up to 15 km inland along the main channels.

Source: Hughes and Hughes, 1992.

tributaries in the basin. Although the impact of individual small wetlands on flow may be negligible, because there are so many of them, their cumulative impact may be significant. In the remainder of this report a distinction is made between floodplains and headwater wetlands because, as described in more detail below, their hydrological functions are widely believed to be different.

Review of the Regulating Functions of the Major Ecosystems

The way ecosystems interact with the hydrological cycle is very complex. The overall impact of any system, at any time, "emerges" as the result of a myriad of dynamic, complex and interlinked processes. Consequently, the hydrological functions of different ecosystems (i.e., the response of different types of forests and wetlands) vary both in time and space and are currently not well understood. The three major aspects of the hydrological cycle in which the influence of different ecosystems remain unclear are:

- Total annual discharge (through impacts on evaporation and hydrological flow paths).
- Dry-season river flows (through storage of water retained during the wet season).
- Flood flows (through retention of floodwater and/or impact on runoff-generating mechanisms).

Headwater Wetlands

Wetlands can be considered as sinks into which surface water or groundwater flows from a surrounding catchment. Within landscapes they are "natural harvesters" of rainwater and are, by definition, sites where water occurs at, or close to, the ground surface. A common perception is that all wetlands regulate flows. However, the functions of any particular wetland will depend both on its biophysiographic characteristics and its location in a catchment. As a result, although most scientific research supports the notion that wetlands play a significant role in the hydrological cycle it is "difficult to make definitive statements regarding the role of various types of wetland in runoff production or water detention" (Carter 1986).

A comprehensive global review of the role of wetlands in the hydrological cycle was based on 169 quantitative studies mostly from Europe and America, but also from Africa and Asia (Bullock and Acreman 2003). These studies used a variety of approaches to infer the hydrological functions of wetlands, all of which have limitations (Table 2). The review found that:

- Some studies (30 out of 66) concluded that wetlands located in the headwaters of river systems (e.g., fens, bogs and *dambos*) reduce flood peaks, but a substantial number (27 out of 66) concluded that they increased flood peaks.
- Approximately half the studies (11 out of 20) concluded that headwater wetlands increased flood event volumes even if the flood peak itself did not increase.
- Most studies (48 out of 77) concluded that wetlands increase average annual evaporation or reduce annual volumes of river flow but about 10% of studies (7) found the opposite and the remaining 25% were neutral.
- Most studies (47 out of 71) found that wetlands reduce the flow of water in downstream rivers during dry periods but in 20% of the cases wetlands were found to increase dry-season river flows.

The results of studies specifically of *dambos* and other headwater wetlands in sub-Saharan

TABLE 2. Basis for inferring wetland hydrological functions.

Basis for inferences	Methodology	Limitations
Comparison of the same basin with or without a wetland.	This method is restricted to computer model simulations in which the model is calibrated "with" or "without" a wetland. Model runs with the wetland case reversed generating simulated hydrological outputs. Differences between simulated "with" and "without" wetland scenarios are attributed to the presence of the wetland.	To a large extent based on perceived understanding of how the wetland functions.
Comparison of the same basin before and after draining a wetland or neighboring drained and undrained wetlands.	Hydrological variables (e.g., flow) are observed prior to draining a wetland. The wetland is drained and the same variables are observed after drainage. Differences in the pre- and post-drainage variables are attributed to the wetland. Alternatively, outputs from two adjacent catchments, each with wetlands, are observed. Wetlands in one of the catchments are drained, and changes in the differences between the outputs of the two catchments are attributed to the presence of the wetlands.	Responses of the drained wetland may differ to a large extent depending on the land use which replaces the wetland. The immediate impact of drainage may differ considerably from the long-term impact.
Comparison of paired catchments, one with a wetland and one without.	Hydrological variables are observed for two catchments, similar in all respects except that one contains one or more wetlands, whilst the other does not. Differences in the outputs are attributed to the wetland(s).	If the two catchments are identical it is not clear why one contains wetland(s) whilst the other does not.
Comparison of several catchments with varying proportions of wetlands.	Hydrological variables are observed for several catchments, each containing different proportions of wetland. Differences in outputs are attributed to the different proportions of wetland.	Differences in the non-wetland characteristics between catchments are ignored.
Comparisons of inflows and outflows from a wetland system.	Hydrological inputs and outputs from a single wetland are measured. Differences between inputs and outputs are attributed to the wetland.	Ignores the effect of the additional catchment between the upstream and downstream limits of the wetland.
Comparison of a wetland hydrological response with the response elsewhere in the catchment.	Hydrological outputs from a wetland are compared with those from other non-wetland portions of the same catchment. Differences between the responses are attributed to the wetland.	Ignores the differences in catchment characteristics between the different portions of the catchment. Why is the wetland situated in one portion and not in the other?
Conclusions derived from a detailed understanding of wetland processes.	Individual component processes are observed in detail and understood within a single wetland. The understanding of the processes is the basis for inferring the influence of those processes on hydrological variables.	Extrapolation of a single process in isolation. Processes may not be homogeneous across the entire wetland.

Source: Modified from Bullock and Acreman, 2003.

Africa are also variable (Table 3). These seemingly contradictory results of the role of headwater wetlands in regulating flows reflect differences in climate and underlying geology as well as differences between vegetation in the wetland and the surrounding catchment (i.e., the interfluve). Evidence that headwater wetlands promote evaporation comes primarily from research conducted on catchments where the interfluves have been deforested (e.g., Stewart 1989; Faulkner and Lambert 1991; Lupankwa 1997). Deforestation of the interfluves may have a dual effect on evaporation by decreasing it on the interfluve and increasing it from the wetland through promotion of dry-season water transfer from the interfluve to the wetland (McFarlane and Whitlow 1990).

A study conducted on four small research catchments (each approximately 1 km^2) in the Kafue Basin in Zambia found that evaporation from the surrounding miombo woodland exceeded that from the headwater wetlands (Balek and Perry 1973). This has been confirmed by a more recent study conducted in a different but nearby catchment (von der Heyden and New 2003). A modelling study of a small wetland (1.21 km^2) in the Zambezi River Basin in Zimbabwe confirmed that

TABLE 3. Generalized summary of conclusions on the influence of *dambos* and other seasonal African wetlands upon streamflow response.

Reference	Effect of dambo presence upon				
	Catchment yield	baseflow		Stormflow	
		Volume	Duration	Volume	Timing
Malawi					
Drayton et al. 1980			No effect		
Hill and Kidd 1980	Decrease				
Smith-Carrington 1983	Increase	Decrease	Decrease	Increase	Attenuate
Noor 1996		Decrease	Decrease		
South Africa					
Schulze 1979			Increase	Decrease	Attenuate
Zambia					
Kanthack 1945		Increase	Increase	Decrease	Attenuate
Balek and Perry 1973	No effect		Increase	Increase	Attenuate
Mumeka and Mwasile 1986				Increase	Attenuate
von der Heyden and New 2003	No effect	Minor increase	No effect		
Zimbabwe					
Bell et al. 1987		Decrease	Decrease		
Bullock 1992b	No effect or decrease	No effect or decrease	No effect or decrease		
McCartney 2000		No effect	No effect		
McCartney et al. 1998				Increase	

Source: Modified from Bullock, 1992a.

the significance of a headwater wetland (a *dambo*) in the evaporation budget of a catchment depends to a large extent on the status of the vegetation in the surrounding catchment (Bullock and McCartney 1996). This study found that evaporation from the wetland contributed 70% of the total from the catchment if the interfluve was fully deforested but only 25% of the total if the interfluve was completely covered with miombo vegetation.

The role of headwater wetlands in the maintenance of dry-season baseflows has been questioned in recent years. Many studies conducted in southern Africa, some in the Zambezi River Basin, have indicated that augmentation of dry-season flows is primarily a function of groundwater discharge rather than a consequence of water stored directly within the wetland (Bullock 1992b; McCartney and Neal 1999; von der Heyden and New 2003). In many instances the wetland acts as a conduit for discharging groundwater originating on the interfluves, or perhaps even further away if it represents the discharge of deep regional groundwater, rather than the source of water per se.

Studies have also provided evidence that contradicts the widely accepted role of wetlands in flood attenuation. For example, the hydrological studies of Hewlett and Hibbert (1967) identified headwater wetlands close to river margins as flood generating areas. In a study of headwater wetlands in the UK, Burt (1995) concluded that "...most wetlands make very poor aquifers .... accordingly, they yield little baseflow, but in contrast, generate large quantities of flood runoff. Far from regulating river flow wetlands usually provide a very flashy runoff regime." Similarly, in the Kafue Basin in Zambia, *dambos* were found to be the main source of runoff not because of insufficient potential interception but because the shallow aquifer was found to effectively fill and then generate saturated overland flow which was rapidly conveyed to streams (Balek and Perry 1973). A detailed study conducted in Zimbabwe found that the role of a *dambo* in flow generation was dynamic; the organically rich soils attenuated floods at the start of the wet season when the wetland was reasonably dry, but added considerably to both flow volumes and peak flows later in the season once the soils were saturated. In some storm events, up to 70% of flow was rainfall that fell during the event and was transferred rapidly to the stream as saturation overland flow (McCartney et al. 1998).

Floodplains

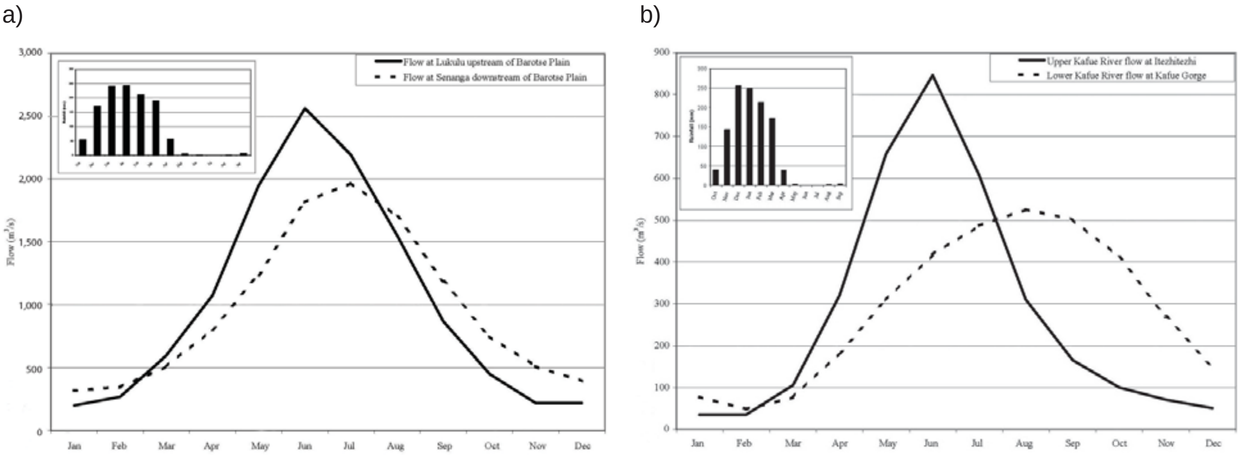
In contrast to the contradictory findings from studies of other wetland types, hydrological studies are reasonably consistent in their findings for floodplains. The global review of Bullock and Acreman (2003) found that most studies (23 out of 28) concluded that floodplains reduce or delay downstream floods. This function arises in part because floodplains provide space for water to spread and in part because the higher hydraulic roughness of floodplains (cf., river channels) reduces the velocity of flow. Evapotranspiration from floodplains may be significant so that total downstream flows may be less than those upstream. For example, the estimated average annual evaporation from the Kafue Flats (947 mm) equates to a total loss of approximately 6,600 Mm^3y^{-1} (Mumeka 1992).

Gosselink et al. (1981) determined that under natural conditions the forested riparian wetlands adjacent to the Mississippi in the United States had the capacity to store about 60 days of river discharge. However, human interventions in particular canalization, leveeing, and drainage on the floodplain had reduced the storage capacity to less than 12 days' discharge (i.e., an 80% reduction of flood storage capacity). This loss of floodplain capacity was an important factor contributing to the severity and damage of the 1993 flood in the Mississippi Basin (Daily et al. 1997). Similarly, the floodplain of the Bassee River in France provides an overflow area when the Seine River floods upstream of Paris (Laurans 2001). In the UK, removing floodplain storage on the River Cherwell by the construction of embankments was found to increase flood peaks downstream by up to 50% (Acreman et al. 2003).

The magnitude of the flood reduction function of floodplains depends on the topography, vegetative cover, soil and geology of the floodplain as well as on other biophysical factors including whether or not tributaries flowing across the floodplain contribute substantial volumes of water.

In contrast to Europe where 90% of floodplains are intensively cultivated and heavily modified (Tockner and Stanford 2002) most African floodplains, including those of the Zambezi River Basin, remain largely intact. It is therefore to be anticipated that the floodplains of the Zambezi will regulate flows. Indeed mean monthly flow data presented in Beilfuss and dos Santos (2001) indicate that both the Barotse Plain and the Kafue Flats (i.e., prior to construction of the Itezhi-tezhi Dam) floodplains, decrease flood peaks, delay the time to peak and increase dry-season flows (Figure 3).

FIGURE 3. a) Mean monthly rainfall in the Zambezi headwaters region (inset), and hydrographs of mean monthly flow upstream and downstream of the Baratose Plain (1950 - 1999); and b) Mean monthly rainfall in the Upper and Middle Kafue catchment (inset), and hydrographs of mean monthly flow upstream and downstream of the Kafue Flats before construction of the Itezhi-tezhi Dam (1907 - 1969).



Source: Beilfuss and dos Santos, 2001.

A study of the impact of the Eastern Caprivi wetlands on flood flows in 2004, based on analysis of water level measurements and satellite images, concluded that the wetlands significantly attenuated the flow – reducing both the rate of rise and the rate of decline of water levels by storing large volumes of water during the flood (Murwira et al. n.d.). However, more recent studies of the Barotse floodplain, the Kafue Flats and the Chobe Swamps concluded that only the Kafue Flats provides “a considerable reduction in peak flows” and in all cases “the retained volume of water is only a very small percentage of the total volume of floods” (SADC 2010). However, no data were provided to support the statement.

Forest with Particular Reference to Miombo

Globally, there is considerable controversy about the hydrological impacts of forests with respect to floods, low flows and even annual runoff (Hewlett and Helvey 1970; Taylor and Pearce 1982; Hewlett and Bosch 1984; Bruijnzeel and Bremmer 1989; Ives and Messerli 1989; Kirby et al. 1991; Johnson 1995; Hofer 1998a, 1998b; Ives 2004; Calder 2006). As with wetlands, the influence of forest on flows depends on a large number of complex biophysical factors and their interactions and it is differences in these factors that cause many of the differences in research findings (Cosandey et al. 2005).

Though it is recognized that much of the functioning of miombo woodland is linked to rainfall, the detailed role of miombo woodland in hydrological functioning has not been studied extensively. Nevertheless, almost all past research in the tropics has indicated a consistent picture of increase in total flow yield, arising as a consequence of decreased evaporation, when tall (deep-rooted) vegetation (i.e., forest) is replaced with shorter vegetation (i.e., grass) (e.g., Sharma 1984; Dubreuil 1986; Bruijnzeel 1996). In addition, research in South Africa has indicated that commercial timber plantations, comprising exotic species (i.e., pine, eucalyptus and wattle), reduce both the total annual runoff and low flows from catchments, in proportion to the area planted and depending on the type of tree (Scott et al. 1998; Dye and Versfeld 2007). Although miombo woodlands comprise natural indigenous trees, evidence indicates that evapotranspiration rates are indeed higher beneath miombo vegetation than other land covers (Balek and Perry 1973; Bullock and McCartney 1996; von der Heyden and New 2003). For this reason the clearing of the miombo woodland as an approach for increasing water resources in southern Africa has been proposed by Hough (1986).

A common and popular view is that forests reduce flood flows and that deforestation in many parts of the world has resulted in increased flooding (Myers 1986). From theoretical considerations it seems logical that the amount of rainfall entering the soil depends on how much is intercepted by the vegetation and the infiltration characteristics of the soil surface. Consequently, forests are expected to reduce floods by removing a proportion of the storm rainfall (i.e., through interception) and by enhancing infiltration.

Soils under most miombo woodland exhibit generally high infiltration and percolation rates, with exact values depending on soil texture and organic-matter content, soil-surface structure and the extent of plant and litter cover. Although many miombo woodland soils are clayey, microaggregation of the clay particles imparts to them the infiltration and permeability characteristics of more sandy profiles (Frost 1996). The size of these water-stable microaggregates is positively correlated with the amount of organic carbon in the soil, reaching an asymptote at 2% organic carbon (Elwell 1988; King and Campbell 1994). Because most miombo woodland soils have less carbon than this, small declines in organic matter content can greatly reduce stability, particularly if the aggregates are exposed to raindrop impact, mechanical deformation or animal hoof pressure (Frost 1996). Hence, it is to be anticipated that removal of miombo woodland would result in an increase in flood flows. This predicted increase is confirmed by experimental research on small catchments. The removal of 95% of the miombo woodland and its replacement with subsistence agriculture in catchments (ca. 1 and 1.5 km^2) in the Kafue Basin in Zambia resulted in a significant decrease in the time to peak and approximately a 100% increase in the height of the peaks of flood hydrographs in these catchments (Mumeka 1986).

Research in recent years has greatly increased the understanding of biophysical processes by which forested areas affect floods. This knowledge, gained from studies in many parts of the world, including South Africa (Hewlett and Bosch 1984), and involving many disciplines including hydrology, soil science, and climatology, demonstrates a great complexity in how the biophysical processes affecting flood response interact (Calder 2006). In broad terms, this research indicates that the effects of forests on flood flows are most significant for small storms, early in the rainy season when the soil moisture and interception "deficit" constitute a significant proportion of the storm rainfall. However, the impact of forests decreases for larger storms and later in the season when the soil moisture deficit is less (Calder 2006). Furthermore, scientific evidence also suggests that although the effects of forests on floods may be detectable on small catchments the "signal" is likely to be weaker on large catchments. Three reasons have been suggested for the weaker response on large catchments:

- Processes which alter the magnitude of the peak of a flood in small catchments may have less effect, proportionately, in large basins because the flood peaks arriving from a number of small catchments are not likely to arrive simultaneously (i.e., they will not be synchronized).
- The proportionate change in land use is likely to be higher on small catchments.
- Storms of sufficient spatial scale to saturate large basins are likely to be of the largest magnitude and for these extreme storm events the effects of forest on flood response are expected to be least pronounced.

Most miombo woodland soil-moisture levels are rapidly recharged at the start of the rains (Frost 1996). Hence, though there is currently little evidence to support the hypothesis, current science perception would suggest that the role of miombo woodland in flood mitigation is likely to: i) decrease as the severity of the flood increases; ii) decrease as the wet season progresses; and iii) be marginal, on the scale of the major subbasins or indeed of the whole Zambezi River Basin.

Overview of Possible Methods for Evaluating Natural Flow Regulation

In order to properly incorporate natural regulating functions into decision-making processes a method is required that quantifies, within the biophysical context of any catchment, differences in flow regime in the presence or absence of an individual ecosystem. Since, as explained previously, natural regulating functions are dynamic it is essential that the full range of flow variability is examined and not just individual high- and low-flow events. Furthermore, to be widely applicable (e.g., in the Zambezi River Basin), such a method must also be relatively simple and able to work with readily available data. Consequently, it should not involve the application of complex data-intensive hydrological models. To date, greater effort has been put into developing methods for evaluating the functions of wetlands (including floodplains) than has been put into other ecosystems. For wetlands, approaches can be divided into two broad types: i) functional assessment, and ii) hydrological analyses of flow regimes.

Functional Assessment

Functional assessment involves the identification of key characteristics or predictors, which can be related to functions without the need for detailed studies. Within the context of wetland hydrological functions the most widely used predictors are hydrogeomorphic (HGM) units (Brinson 1993). The primary purpose of HGM classification is to group together wetlands that perform similar functions. Landscape setting, water source and hydrodynamics provide the basis for the classification. Studies in the USA support the use of HGM classification as a surrogate for more quantitative descriptions of wetland hydrology (Cole et al. 1997; Shaffer et al. 1999). However, although the approach has been used to identify certain hydrological characteristics of wetlands (e.g., hydroperiod/depth to water table) it has not been used for detailed evaluation of regulating functions.

Perhaps the most rigorous application of the functional assessment approach is that presented by Maltby (2009). Based on studies conducted in Europe (primarily in the UK) it provides a detailed process for identifying, mapping and characterizing HGM units in the field, based on checklists of observations related to geomorphological, hydrological and ecological indicators as well as vegetation. Based on information obtained, all HGM units are assigned a hydrological code which indicates the likelihood of one or more selected processes occurring to varying degrees. This is followed by a functional assessment (based on a process of scoring using look-up tables) which determines whether, and to what degree or likelihood, the hydrological functions are actually being performed. The outcome of the assessment is a statement on the likelihood of occurrence of specific functions (e.g., “floodwater detention”) and to some extent their significance. By completing the assessment for each HGM unit it is possible to identify a general pattern of the function of interest across a whole wetland.

In southern Africa, a similar approach, based on the HGM units, has been developed. The WET-EcoServices approach can be used to assess inland wetland ecosystem services including flood attenuation and the maintenance of dry-season flows (Kotze et al. 2009). Wetlands are divided into discrete HGM units and ecosystem services are assessed for each HGM unit. Although the choice of characteristics is based on a rational process (again using look-up tables), that is derived from the services that different HGMs typically provide, there is little quantification. The method does enable a score of the “likely extent” to which a service is delivered to be determined but does not enable the magnitude of impacts to be quantified. The approach is perceived primarily as a method for highlighting important ecosystem services that should be considered in more detail in evaluating and planning development options or managing an individual wetland (Kotze et al. 2009).

Although, in theory, the HGM units approach requires fewer data than flow analyses it nevertheless requires detailed understanding of landscape setting, water source and hydrodynamics in order to predict hydrological functions. For many of the wetlands in the Zambezi River Basin these data are simply not available. Furthermore, the method is currently not well enough advanced to provide quantitative estimates of impacts on specific floods and low flow events.

Hydrological Analyses of Flow Regimes

Analyses of river flows provide an alternative to functional assessment and are more appropriate when a detailed understanding of HGMs is lacking, as is the case in the Zambezi. Direct comparison of flows upstream and downstream was the approach most commonly used in past studies of the hydrological function of floodplains in the Zambezi (Mumeka 1992; Beilfuss and dos Santos 2001; Murwira et al. n.d.). However, since the assumption is made (though rarely explicitly stated) that any differences in flow are a consequence solely of the floodplain, this method is only strictly applicable if the floodplain is small compared to the gauged catchment. This assumption is not valid if the flow is altered (i.e., either attenuated or increased) by the intervening catchment, even in the absence of the ecosystem. Flows are likely to be altered regardless of the presence or absence of a local anomaly (i.e., forest, floodplain or wetland) as a consequence of a combination of factors including: i) resistance to flow in the reach of interest, which results in flow attenuation, and ii) additional inflow, which results in an overall increase in flow. For most of the large floodplains in the Zambezi the intervening catchment is a significant proportion of the total catchment area to the downstream gauge and consequently the assumption is not strictly valid.

To avoid this problem, the method of Smakhtin and Batchelor (2004) derives a reference condition which is effectively the time series of mean daily flows downstream of the ecosystem of interest, which would have been recorded if the ecosystem was not present. Generating this time series requires some form of simulation (i.e., a method of creating the flow series in the hypothetical situation that the ecosystem was not present). Options include both rainfall-runoff modeling and flood routing techniques. However, both of these approaches are data-hungry and have other limitations (Smakhtin and Batchelor 2004). An alternative to these techniques combines elements of hydrological regionalization with spatial interpolation of streamflow records (Hughes and Smakhtin 1996).

Method

In this study, a slightly modified form of the approach recommended by Smakhtin and Batchelor (2004) was developed. The approach, which, for a given location, simulates the time series of flow that would have occurred if a specific upstream ecosystem was not present, is dependent on the analyses of time series of flow from various locations within a catchment.

Data

The method requires long (ideally 25 years or more) time series of flow data at a daily time step. Flow data for the Zambezi were obtained from two sources: i) the Global Runoff Data Centre (GRDC), and ii) the Flow Regimes from International Experimental and Network Data (FRIEND). The FRIEND database is limited to data up to 1994, but does contain stations with more than 25 years of data. From the two databases 102 gauging stations were identified with more than 25 years of daily flow data. The locations of the stations were mapped in relation to the major wetlands and forests in the basin. The SRTM (ca. 90 m) spatial resolution “hole-filled” digital elevation data (available at http://srtm.csi.cgiar.org/) were used to determine the catchment area to each station.

In addition to the land cover map (Figure 2), high resolution Google Earth images were used to assist with the identification of sites for analyses. Gauging station locations were imported into Google Earth. By zooming-in around the gauging stations it was possible to identify land cover in the catchments upstream of them and map small (particularly headwater) wetlands and forest patches. Altogether 18 sites, each representative of one particular ecosystem type, were selected for analyses. However, because of anomalies in the data that became apparent during analyses, four sites (10, 15, 16 and 18) were dropped and complete analyses were conducted for 14 (Table 4 and Appendix B).

TABLE 4. Characteristics of the catchments used in the analyses.

Site	Ecosystem	Country	River	Type station	Station ID	Catchment				
						Total area (km^2)	Wetland area (km^2)	Wetland (%)	Forest area (km^2)	Forest (%)
1	Floodplain	Zambia	Luswishi	Upstream*	1591441	2,073.7	237.7	11.5	1,729.7	83.4
				Downstream	1591440	3,575.6	448.6	12.5	2,891.0	80.9
				Reference	60334250	3,768.2	171.3	4.5	2,071.3	55.0
				Reference	1591500	222.5	3.9	1.8	72.0	32.4
2	Floodplain	Zambia	Kafue	Upstream	1591406	20,468.0	1,780.8	8.7	12,957.7	63.3
				Upstream	1591440	3,575.6	448.6	12.5	2,891.0	80.9
				Downstream	1591405	45,939.3	5,265.4	11.5	28,350.6	61.7
				Reference	1591406	23,065.0				
				Reference	1591441	2,073.7	237.7	11.5	1,729.7	83.4
				Reference	1591471	10,238.5	944.3	9.2	6,458.9	63.1
3	Floodplain (Barotse)	Zambia	Zambezi	Upstream*	60370030	146,425.5	18,403.2	12.6	106,228.9	72.5
				Upstream	1591820	29,908.3	4,722.4	15.8	15,495.7	51.8
				Downstream	1591001	299,492.4	50,410.1	16.8	182,376.7	60.9
				Reference	1591100	3,699.1	366.4	9.9	3,167.6	85.6
4	Headwater	Malawi	Bua	Downstream	65312602	4,777.4	822.9	17.2	565.4	11.8
				Reference	65312901	18.9	0.0	0.0	0.0	0.0
				Reference	65312903	431.0	0.0	0.0	41.3	9.6
				Reference	65312102	1,427.0	0.0	0.0	219.7	15.4
5	Headwater	Zababwe	Sebakwe	Downstream	63341047	1,532.6	17.2	1.1	370.5	24.2
				Reference	63341018	1,632.2	0.0	0.0	156.2	9.6
6	Headwater	Malawi	Thuchila	Downstream	60334015	197.8	20.2	10.2	138.3	69.9
				Reference	1591500	222.5	3.9	1.8	72.0	32.4
				Reference	65312109	287.1	0.0	0.0	27.5	9.6
				Reference	65312108	385.0	0.0	0.0	0.0	0.0
7	Headwater	Malawi	Lilongwe	Downstream	65312805	2,284.5	239.1	10.5	482.4	21.1
				Reference	65312901	18.9	0.0	0.0	0.0	0.0
				Reference	65312102	1,427.0	0.0	0.0	219.7	15.4
				Reference	65312903	431.0	0.0	0.0	41.3	9.6
8	Floodplain	Zambia	Kafue	Upstream*	60334005	366.9	38.9	10.6	237.5	64.7
				Upstream*	60334015	197.8	20.2	10.2	138.3	69.9
				Downstream	60334050	4,320.6	730.1	16.9	2,918.8	67.6
				Reference	1591500	222.5	3.9	1.8	72.0	32.4
				Reference	1591441	2,073.7	237.7	11.5	1,729.7	83.4

(Continued)

TABLE 4. Characteristics of the catchments used in the analyses. (Continued).

Site	Ecosystem	Country	River	Type station	Station ID	Catchment				
						Total area (km^2)	Wetland area (km^2)	Wetland (%)	Forest area (km^2)	Forest (%)
9	Floodplain	Zambia	Kafue	Upstream*	1591471	10,238.5	944.3	9.2	6,458.9	63.1
				Upstream	60334250	3,768.2	171.3	4.5	2,071.3	55.0
				Downstream	1591470	16,637.6	1,337.9	8.0	10,204.3	61.3
				Reference	60334550	17,741.7	2,270.5	12.8	13,651.0	76.9
				Reference	1591500	222.5	3.9	1.8	72.0	32.4
10†	Floodplain (Kafue Flats)	Zambia	Kafue	Upstream*	1591403	96,009.3	13,503.2	14.1	60,953.6	63.5
				Downstream	1591401	137,969.8	17,882.8	13.0	76,205.2	55.2
				Reference	60334550	17,741.7	2,270.5	12.8	13,651.0	76.9
				Reference	60332040	139,048.0	721.7	0.5	74,365.7	53.5
11	Headwater	Malawi	South Rukuru	Downstream	65312414	10,386.0	131.6	1.3	3,853.4	37.1
				Reference	55312232	877.0	0.0	0.0	0.0	0.0
12	Forest	Malawi	Rivi rivi	Downstream	65312103	534.0	12.5	2.3	53.8	10.1
				Reference	65312108	385.0	0.0	0.0	0.0	0.0
				Reference	55312232	877.0	0.0	0.0	0.0	0.0
13	Forest and headwater	Zambia	Lunga	Downstream	60334550	17,741.7	2,270.5	12.8	13,651.0	76.9
				Reference	65312108	385.0	0.0	0.0	0.0	0.0
				Reference	55312232	877.0	0.0	0.0	0.0	0.0
				Reference	60334620	1,116.3	180.2	16.1	106.9	9.6
14	Forest and headwater	Zambia	Makondu	Downstream	1591100	3,699.1	366.4	9.9	3,167.6	85.6
				Reference	63512108	385.0	0.0	0.0	0.0	0.0
				Reference	55312232	877.0	0.0	0.0	0.0	0.0
				Reference	1591460	1,521.0	212.7	14.0	145.7	9.6
15†	Forest and headwater	Zambia	Luakela	Downstream	1591237	649.4	101.3	15.6	51.3	7.9
				Reference	1591110	155.9	0.5	0.3	14.9	9.6
				Reference	1591003	353.8	12.6	3.6	33.8	9.6
16†	Forest and floodplain	Zimbabwe	Gwayi	Upstream	63351139	2,905.73	0.0	0.0	1,040.5	35.8
				Downstream	63351138	19,796.7	343.5	1.7	7,248.5	36.6
				Reference	63351137	2,398.3	0.0	0.0	229.6	9.6
				Reference	63351141	128.6	0.0	0.0	12.3	9.6
17	Forest	Malawi	Luchelemu	Downstream	65312505	260.8	0.0	0.0	243.8	93.5
				Reference	63512108	385.0	0.0	0.0	0.0	0.0
				Reference	55312232	877.0	0.0	0.0	0.0	0.0
18†	Forest	Zimbabwe	Bubi	Downstream	63351139	2,905.7	0.0	0.0	1,040.5	35.8
				Reference	55312232	877.0	0.0	0.0	0.0	0.0
				Reference	63351113	1,126.9	0.0	0.0	107.9	9.6

Notes: * Also used to develop the reference FDC; † Not used in the final analyses.

7 digit IDs are from the GRDC database and 8 digit IDs are from the FRIEND database.

Synopsis

The approach is based on analyses of flow duration curves. A flow duration curve (FDC) shows the relationship between any given discharge and the percentage of time that flow is equaled or exceeded (Shaw 1984). The most common FDCs are those constructed using mean daily flows (Vogel and Fennessey 1995; Smakhtin 2001). A standardized (i.e., nondimensional) FDC can be constructed by dividing all flows by the long-term mean annual discharge (i.e., all flows are expressed as the ratio of the long-term mean). These standardized FDCs enable direct comparison between locations with different mean annual discharges.

To derive the time series of flow in the absence of the ecosystem, the so-called "reference" flow series, three steps are performed in sequence:

i) Estimation of a reference nondimensional FDC derived from flow gauges on unregulated rivers close to the site of interest and standardized by the long-term mean discharge estimate from observed records. This is effectively the regional FDC in the absence of the specific ecosystem of interest.

ii) Conversion of the reference nondimensional FDC to an actual FDC at the location immediately downstream of the ecosystem by multiplying the standardized curve (derived in i) by the long-term mean discharge at that specific site. This is effectively the FDC at the location downstream of the ecosystem that would have occurred in the absence of the ecosystem.

iii) Conversion of the actual FDC at the downstream location (derived in ii) into a continuous streamflow hydrograph using a spatial interpolation technique (Hughes and Smakhtin 1996). This produces a time series of flows that would have occurred in the absence of the ecosystem.

Each of these three steps is described below in detail using the floodplain on the Luwishi River in Zambia (site 1 in Table 4) as an example. For this site flow data were available from both upstream and downstream of the floodplain (i.e., GRDC gauges 1591441 and 1591440, respectively) and data were also available to compute the reference FDC (i.e., FRIEND gauge 60334250 and GRDC gauge 1591500). The area of the catchment to the upstream gauge is 2,073 km^2 and to the downstream gauge is 3,576 km^2. Thus the intervening catchment is 1,502 km^2 (i.e., 42% of the total catchment area downstream of the floodplain). Clearly, it is not appropriate to assume that in the absence of the floodplain the downstream flow would have been the same as that at the upstream gauge.

Deriving a Reference (No Ecosystem) Flow Duration Curve

Regional analysis involves pooling flow data from a number of gauging stations in order to derive a nondimensional FDC that is "typical" for a specific region. It requires the region to be homogenous with respect to flow-generating characteristics (Mkhandi et al. 2000). Delineating homogenous regions is a complex process because of the large number of factors (i.e., topography, climate, vegetation, soils, geology and others) that affect flows and currently there is no standard procedure. However, once regions have been identified, to establish regional FDCs, all gauged unregulated similar-sized river catchments in a specified region, with reliable and unmodified flow records, are identified. Each curve is then standardized by the long-term mean discharge, estimated from the observed record, and the average of all curves is calculated (Smakhtin 2000).

In this study the objective of developing a regional FDC was to be able to remove the influence of local anomalies (i.e., identified ecosystems) on streamflow. However, to the authors' knowledge, no previous studies have conducted regional analyses specifically for the Zambezi River Basin, and with the limited time and resources available for the current study it was not possible to conduct a full regional analysis for the basin. Consequently, a slightly modified approach was adopted. Rather than developing regional FDCs for different parts of the basin, "reference" FDCs were developed on a case-by-case basis. Thus for each site of interest, gauges located as close as possible to the catchment under investigation and which were deemed to be representative of the flow pattern in the "region" in the absence of the specific ecosystem under investigation, were identified. In each case the reference FDC was then developed, as described above, by combining the data from all the stations. In those instances where there was a gauge located upstream of the ecosystem of interest this gauge was used as it indicates flow in a significant portion of the catchment in the absence of the specific ecosystem.

In the case of the Luwishi floodplain, data from three gauges (i.e., GRDC gauges 1591441 and 1591500 and FRIEND gauge 60334250) were used to develop the reference FDC. The standardized FDCs for these catchments are shown in Figure 4. A regional FDC was calculated by simply averaging the nondimensional ordinates of the three curves. For the purpose of this calculation and for further application of the spatial interpolation algorithm, an FDC was represented by a table of 119 fixed percentage points (ranging from 0.1 to 0.9 (interval 0.10), from 1 to 99 (interval 1) and from 99 to 99.9 (interval 0.1)) with corresponding flows or nondimensional ordinates.

Calculating the Reference Flow Duration Curve at the Site of Interest

The next step was to calculate the actual reference FDC at the site, located downstream of the ecosystem of interest. This was accomplished by simple multiplication of the nondimensional FDC ordinates (standardized flows) by the long-term mean discharge at the site. In the case of the Liwushi floodplain, this long-term mean discharge was calculated directly from the observed flow records at the downstream site (i.e., GRDC gauge 1591440). Each standardized flow value from the FDC was multiplied by the estimate of the long-term mean discharge at the site and a table of actual flow values for the 119 fixed percentage points was produced (Figure 5). This assumes that the mean annual flow is not

FIGURE 4. Standardized FDCs derived from mean daily flow measured at gauges located in the vicinity of the Luwishi floodplain.

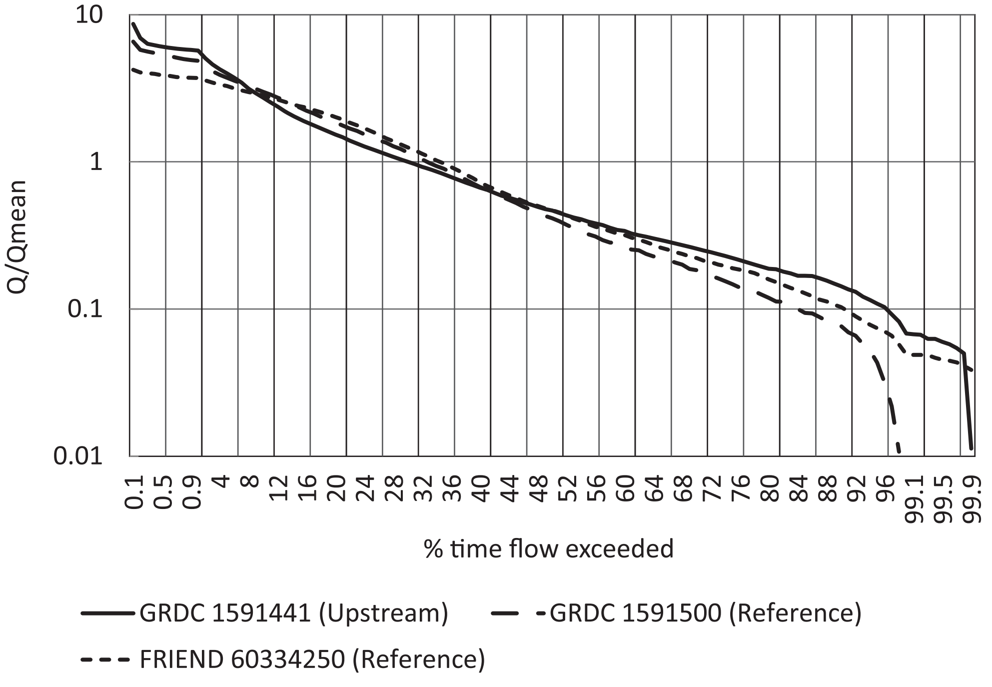
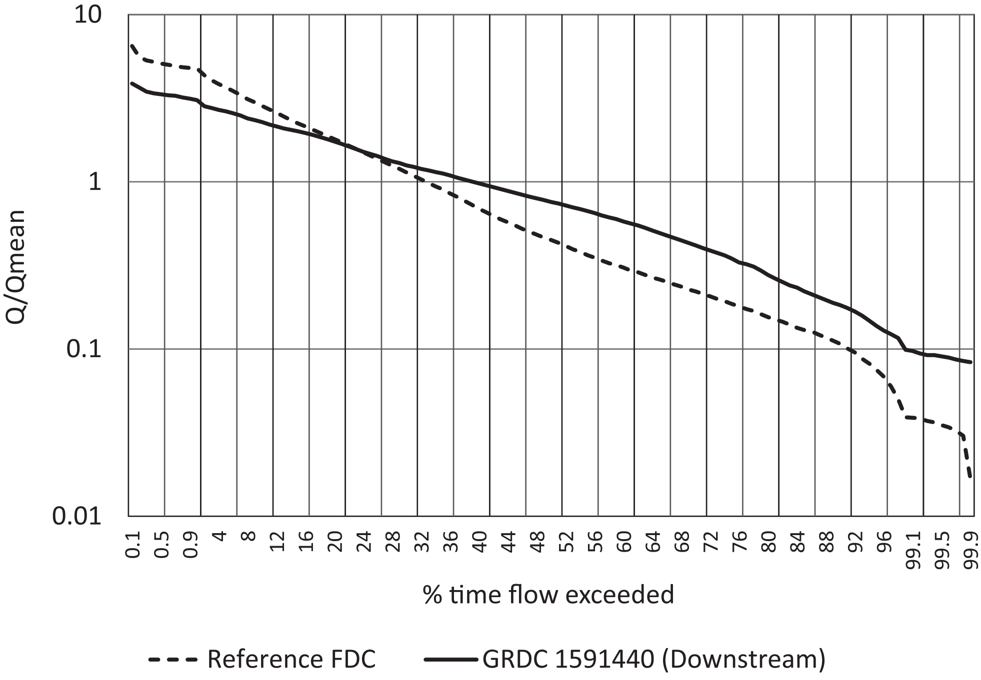


FIGURE 5. Comparison of the ‘reference’ FDC and the observed FDC at the gauge downstream of the Luwishi floodplain.



altered by the presence of the ecosystem; all that changes is the distribution of flow within the year.

Generating the Reference Flow Time Series

The observed and the reference FDC for the downstream location are suitable for comparative analysis of “no wetland” and “with wetland” catchment flow responses. However, analysis of specific flow events (and derivation of flood frequency curves – see section, *Comparison of Flow Series*) requires the actual daily streamflow time series. Hence, it is necessary to generate a reference time series. The generation of this time series was accomplished using the spatial interpolation technique of Hughes and Smakhtin (1996). The main assumption of the method is that flows occurring simultaneously at sites in reasonably close proximity to each other correspond to similar percentage points on their respective FDCs.

The location for which the streamflow time series generation is required is called the “destination” site(s). The sites from which the time series are used for generation is referred to as the “source” site(s). The above assumption implies that the source and destination flow regimes will display similarity in the sequence of flows (i.e., if there is a peak flow at the source site, there is also a high flow at the destination site). This may be ensured if the source sites are selected from within the surrounding area, in close proximity to the destination. Examples include two sites on the same river or two sites in adjacent similarly-sized catchments. The degree of similarity between each source and a destination flow regime is ranked arbitrarily by assigning a weighting factor to each source site. If only one source site is used, the weighting factor is always 1. If more than one source site is used and the destination site is either in the adjacent catchment or on the same stream, the weighting factors may be set equal (Hughes and Smakhtin 1996).

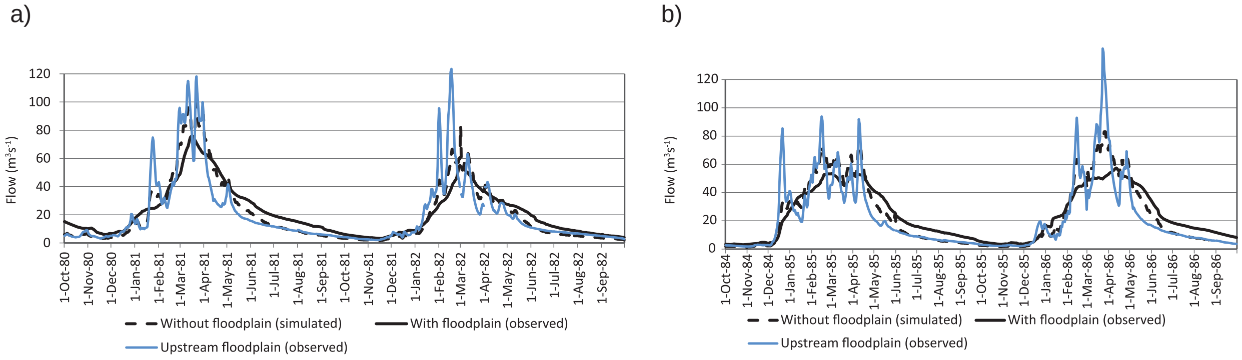
If only one source site is used, the computational procedure for each day comprises i) identification of the percentage point position of the source site’s streamflow on the source site’s FDC; and ii) reading off the flow value for the equivalent percentage point from the destination site's FDC. If more than one source site is used, the two steps above are repeated for each source site. This obviously leads to more than one estimate of the destination site flow on the same day (i.e., if two source sites are used, there will be two estimates). The final destination site flow value on each day is estimated as the weighted average of all estimated destination site flow values. The weights are assigned based on the degree of similarity between each source and the destination flow regime (Hughes and Smakhtin 1996).

The procedure is repeated for each day. For streamflow time series generation at the destination site, it is recommended to use, where possible, more than one source site. The use of several source sites is an attempt to account for the fact that a destination site time series may be the result of several influences, which may not be reflected in a single source site time series. Also, part of an individual source site time series may be missing and the use of several should decrease the number of missing values in the resultant time series at the destination site. More details about the computational procedure are available in Hughes and Smakhtin 1996; and Smakhtin 2000.

In the case of the Luwishi River floodplain, the source sites were the upstream and downstream flow gauges. Both were weighted equally. The location of the destination "site" was naturally the same as that of the downstream gauge. The fact that the downstream observed flow record, affected by the floodplain, is used as a "source" time series is not significant. The use of this record, however, allows a sequentially similar destination flow time series to be simulated. The simulated time series will at the same time reflect the "no floodplain" condition in its upstream catchment because the destination FDC was generated from the reference FDC (which excludes the presence of the floodplain). The conversion of the reference FDC into a continuous time series of mean daily flow completes the generation of reference flow conditions. The comparison between reference and actual catchment responses can now be done in terms of observed (with floodplain) and simulated (without floodplain) flows.

Figure 6 illustrates the results for the Liwushi River floodplain for two periods. The results indicate that without the floodplain there would still be attenuation of flow between the upstream and downstream gauges; flood peaks are reduced and the recession limb on the hydrographs slightly extended. However, the impact on low flows is very small. In contrast, the floodplain not only enhances the flood attenuation significantly, reducing flood peaks much more than in the absence of the floodplain, but also increases low flows substantially.

FIGURE 6. Comparison of the flow at GRDC gauging site 1591440 with and without the floodplain and upstream of the floodplain for two periods: a) hydrological years 1980 and 1981, and b) hydrological years 1984 and 1985.



Note: In contrast to the calendar year, in southern Africa the hydrological year (which better reflects the correspondence between rainfall and flow) is conventionally taken from October 1 to September 30. Thus, hydrological year 1982 (HY1982) runs from October 1, 1982 to September 30, 1983.

Modifications to the Method

One of the complications of the analyses for the Zambezi River Basin is that in this part of southern Africa the landscape naturally comprises a patchwork of headwater wetlands, floodplains and forest ecosystems. Consequently, it is impossible to isolate catchments with one ecosystem type and not the others. Furthermore, for both headwater wetlands and forests it proved very difficult to find locations with upstream flow gauging stations. Consequently, a slightly modified approach was adopted. In some instances, only a gauge downstream of the ecosystem was used and this station effectively became the sole "source" site as well as the "destination" site. Two disadvantages of this are that i) the full range of factors influencing flow within a region may not be taken into account and ii) there is no way to infill missing values, so the simulated "no ecosystem" time series cannot be extended and is only as long as that of the downstream gauge (i.e., there is no way to extend the time series or infill missing values).

In addition, very few catchments had no forest or headwater wetlands. Consequently, deriving reference FDCs was difficult and in many instances it was necessary to use catchments a long distance from the catchment under investigation. This increased the likelihood that the reference catchments were from a dissimilar region and influenced by factors different from those of the investigated catchment. In some instances rather than relying solely on catchments a long way away, closer catchments were used that included some forest or headwater wetlands, but where they covered a much smaller proportion of the catchment than the investigated catchment.

Comparison of Flow Series

The method simulates time series of flow in the absence of the ecosystem. Hence, it is possible to quantify hydrological functions using standard analyses to evaluate flood frequency and low flow statistics. In the current study, the "with" and "without" ecosystem flow series were analyzed to determine and compare baseflow indices and mean annual 1-day and 10-day flow minima. In addition, flood frequency curves were derived.

The baseflow index (BFI) (i.e., the ratio of the baseflow volume to the total volume of flow from a catchment) was derived using a two parameter baseflow filtering technique, with the parameters fixed at. 0.995 and 0.5, respectivly (Hughes et al. 2003). The baseflow index ranges from zero (no baseflow) to one (all baseflow). In natural catchments, high BFIs indicate significant storage (i.e., in groundwater, lakes and wetlands).

The annual minima were computed from the time series using 1-day flows and flows averaged over a 10-day period. In each case, the average annual minimum was determined.

Flood frequency analysis entails the estimation of the peak discharge that is likely to be equalled or exceeded on average once in a specified period, T years. This is the T-year event and the peak, Q_T is said to have a return period or recurrence interval of T years. The return period, T years, is the long-term average interval between successive exceedances of a specified flood magnitude, Q_T. However, the actual intervals may vary considerably around the average. Thus a given record may show a 25-year event, Q_{25}, occurring at intervals both much more and much fewer than 25 years. Analysis of flood frequency involves fitting a statistical distribution to the series of annual maximum flows, ranked by the magnitude of flow.

In this study, instantaneous maximum discharges were not available and so the maximum mean daily discharges were used. A number of probability distributions have been investigated for application to maximum flood series in different parts of the world. In southern Africa, Pearson type 3 (P3) and log-Pearson type 3 (LP3) have been found to be the most suitable for flood flows (Mkhandi et al. 2000). In this study, the P3 distribution fitted using the method of moments was used and, where sufficient data were available, extrapolated to T = 200 years.

Results

The results for each site are presented in Appendix C. They illustrate the differences in flow regime between the "with" and "without" ecosystems. For each catchment the following are presented:

- FDCs
- Example hydrographs
- BFI and low flow statistics
- Flood frequency curves

On the following pages the results of regression analyses conducted to evaluate the impact of each ecosystem type on different aspects of flow are presented.

Headwater Wetlands

The results for sites 4, 5, 6, 7 and 11 indicate that the headwater wetlands in the Zambezi River Basin have very variable impacts on flow regimes. In four out of five of the catchments they increase the maximum one-day floods by between 12 and 300%. It is only in the catchment with the largest proportion of headwater wetlands (i.e., site 4, in which headwater wetlands comprise 17.2% of the catchment) that flood flows are reduced (i.e., between 40 and 70%, depending on the return period). Generally, there is little correlation between the proportion of the catchment that comprises headwater wetlands and the impact on flood flows (Figure 7).

The impact of the headwater wetlands on low flows is also variable. The impact on BFI varies between -36% (site 6) and +5% (site 5) (Figure 8a). There is seemingly no correlation between the impact on BFI and the proportion of the catchment that comprises headwater wetlands (Figure 8a). The one phenomenon that is consistent for all the catchments is that the headwater wetlands decrease the 1-day and 10-day flow minima by between 20 and 90%. However, again there is no correlation between percentage decrease and the proportion of the catchment comprising headwater wetlands (Figure 8b).

Floodplains

The results for sites 1, 2, 3, 8 and 9 confirm that the Zambezi floodplains do regulate flows. The results from site 10 (the Kafue Flats) were felt to be unrepresentative because they are generated from too short a time series. Consequently, results of site 10 were not included in the analyses reported here.

FIGURE 7. Reduction in flood flows as a function of the proportion of the catchment that is floodplain (negative values indicate an increase in flood flows).

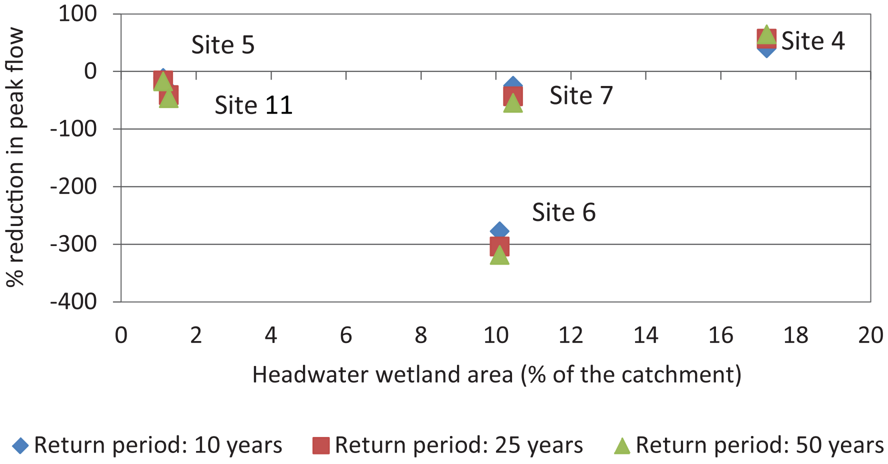
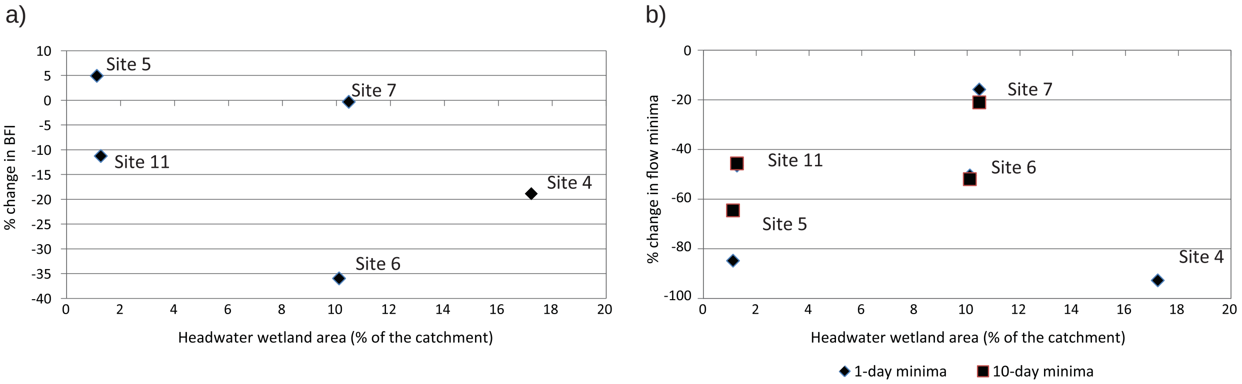


FIGURE 8. Change in a) BFI and b) 1-day and 10-day flow minima, as a function of the proportion of the catchment that is headwater wetlands (negative values indicate a decrease).



Flood flows are generally reduced very significantly (i.e., of the order of 10 to 60%) as a consequence of the presence of the floodplain. Furthermore, it seems that in most cases (the exception being site 9) the absolute reduction in 1-day maximum flows increases with increasing return periods (i.e., the greater the flood, the greater the effectiveness of the floodplain in reducing the flood magnitude). This may simply be because at higher flows a greater proportion of the volume of the flood hydrograph is "spread" across the floodplain (rather than in the river channel). Of the five sites, the site 9 floodplain represents the smallest proportion of the catchment and, as might be expected, has the least impact on flood flows. Conversely, site 8 floodplain represents the largest proportion of the catchment and has the greatest impact on flood flows. However, generally there is little correlation between the proportion of the catchment that comprises floodplain and the reduction in flood flows (Figure 9).

The impact of the floodplains on low flows is also clear. In all cases the floodplains increase the BFI and 1-day and 10-day flow minima. However, as with reductions in flood peaks, there is no statistically significant correlation between the percentage increase and the proportion of the catchment that the floodplain constitutes (Figure 10).

FIGURE 9. Reduction in flood flows as a function of the proportion of the catchment that is floodplain.

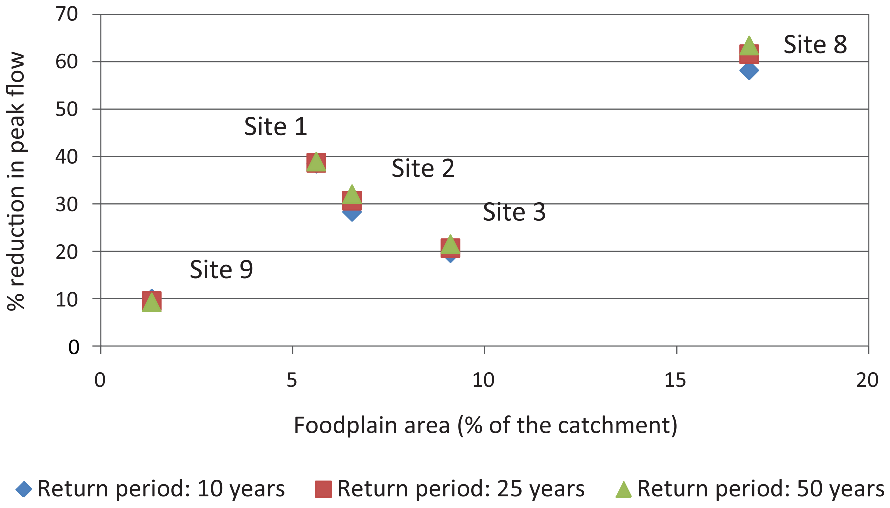
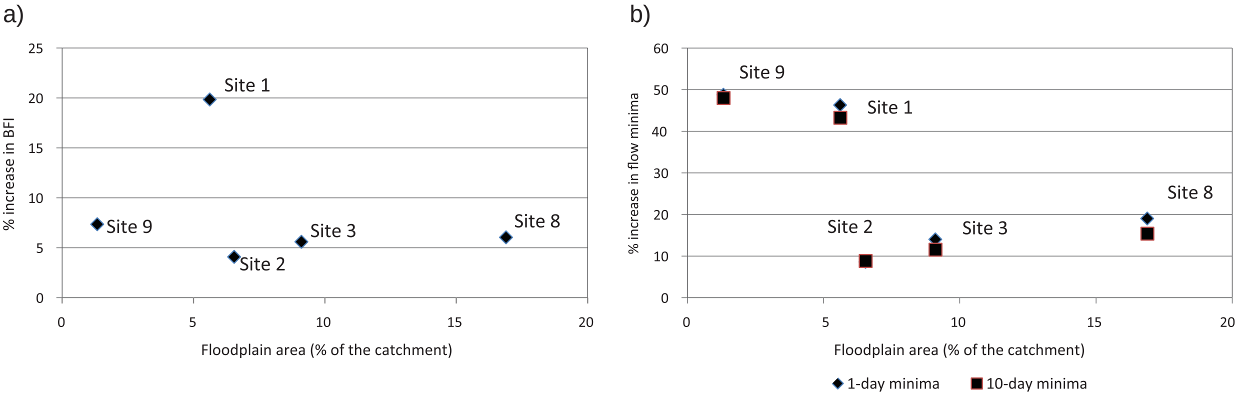


FIGURE 10. Change in a) BFI and b) 1-day and 10-day flow minima, as a function of the proportion of the catchment that is floodplain.



Forests

The results for sites 12, 13, 14 and 17 indicate that the forests in the Zambezi River Basin have variable impacts on flow regimes. In the three catchments with greater than 70% forest cover (i.e., 13, 14 and 17) they reduce the maximum 1-day maximum flows by between 37 and 68%. Furthermore, in these three catchments the proportional reduction in peak flows increases with increasing return period (i.e., the greater the flood, the greater the effectiveness of the forests in reducing the flood magnitude). It is only in the catchment with the smallest proportion of forest cover (i.e., site 12, in which forest covers just 10.1% of the catchment) that floods are seemingly increased by the presence of the forest (Figure 11).

The impact of the forests on low flows is also variable. In the three catchments with greater than 70% forest cover the change in BFI is between -6° (site 14) and +21% (site 13). At site 12, the catchment with just 10% forest cover, BFI is reduced by 36% (Figure 12a). The impact of the forest on annual minimum flows is variable. The presence of forest seemingly reduces both 1- and 10-day annual minima, by between 14 and 83%, in three of the catchments (i.e., 12, 14 and 17) but increases them, by ca. 72%, in the fourth (i.e., site 13) (Figure 12b).

FIGURE 11. Reduction in flood flows as a function of the proportion of the catchment that is forest (negative values indicate an increase in flood flows).

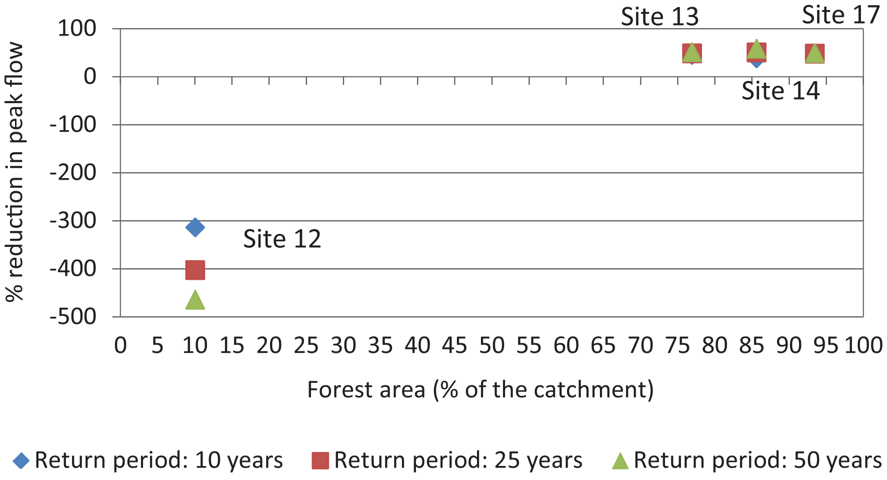
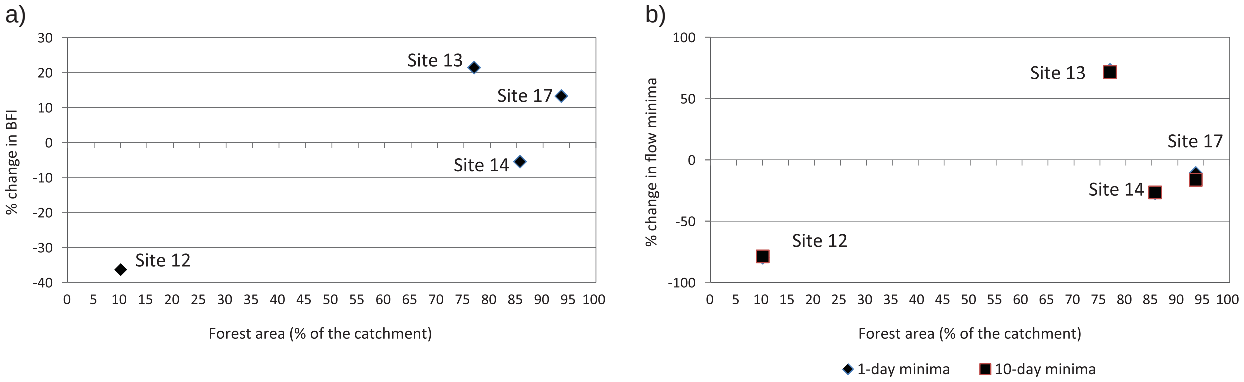


FIGURE 12. Change in a) BFI and b) 1-day and 10-day flow minima, as a function of the proportion of the catchment that is forest (negative values indicate a decrease).



Discussion

There are a number of limitations in the method as applied in this study. First, the method attempts to determine the flow regime in the absence of specific ecosystems as if this were the only difference in the catchment of interest. This ignores the fact that in all cases the presence of the ecosystem is dependent on the wider geological and climatic setting: they are a function of the landscape in which they are located. Although there is no way to mitigate this limitation it is important to remember that the simulated “without ecosystem” flow regime is not strictly what would occur in its absence, since in reality the catchment characteristics would necessarily be different. This is effectively the same limitation that arises when comparing paired catchments with and without ecosystems (see Table 2).

Second, since it affects all the subsequent analyses, a critical part of the approach is the development of reliable reference conditions. The method relies on determining deviations from pooled dimensionless regional FDCs. However, as noted previously, this was not easy in the Zambezi River Basin and it was necessary to resort to an ad hoc approach in which the reference conditions were evaluated on a case-by-case basis using whichever flow stations were available as references. This is arbitrary and so not ideal. A possible improvement to the method would be to develop robust regional FDCs corresponding to natural regions in the basin, perhaps the upper, middle and lower Zambezi. By their nature such regional FDCs would integrate the effects of all the ecosystems in the region for which they were developed. Consequently, it would be necessary to define the average cover of forests, headwater wetlands and floodplains in the catchments used to develop these regional FDCs. The analyses could then be conducted for catchments with a greater or lesser extent of a particular ecosystem to determine the impact of different proportions of that ecosystem relative to the average condition within the region.

Such an approach would obviate the need to identify reference catchments separately for each site of interest and would avoid the need to select reference catchments that, in some cases, are located a long distance from the site of interest. However, this methodology will not work if the sample of individual dimensionless FDCs has such a wide scatter at a given percentile that the impact attributable to a particular ecosystem falls within the variability of the individual FDCs used in the pooling. Since in this part of Africa there is indeed high inherent variability, even between closely located catchments of similar size and rainfall (Andrew Bullock, Independent Consultant, pers. comm., April 20, 2012) the value in creating geographically pooled FDCs may be limited. More research is required to determine the best way of developing the reference FDC.

Third, the method makes no allowance for changes in mean annual discharge; the mean discharge of the simulated “without ecosystem” is the same as that of the “with ecosystem.” Given that the presence of the ecosystem causes changes in flood flows as well as low flows, both of which affect mean flow, this is unlikely to be the case. It is, therefore, a simplification to rescale the dimensionless FDCs using an unaltered mean flow. However, without knowledge of how the mean flow has been affected by the presence of the ecosystem it is not possible to modify the mean flow prior to rescaling. Again, more research is required to quantify the effect of different ecosystems on mean flow – something which is likely to be location-specific – and improve the method.

Fourth, in this study restrictions in both time and financial resources meant it was not possible to obtain aerial photographs or very high resolution satellite data. Consequently, to determine the areal extent of the different ecosystem types within each catchment the land cover map and Google Earth images were used. As a result, it is probable that there are errors in the estimates of ecosystem extent, particularly of forest cover and headwater wetlands, within each catchment. Although this does not affect the applicability of the method developed, clearly it affects interpretation of the results obtained.

Finally, BFI is not strictly a measure of low flows but, because it is computed as a ratio, it is a compound measure affected by both high flows and baseflow. Even if baseflow volumes remain the same in absolute terms, BFI can be higher or lower depending on the absolute volume of storm flow. Consequently, unlike the mean annual minima, BFI is not a rigorous measure of low flow conditions. Other flow statistics (e.g., those based on recession rates) may be more appropriate indicators of low flow characteristics but are more difficult to compute and are less easily understood. This is not a limitation of the method generally, but rather a limitation of its application in this particular study. In fact, one of the primary strengths of the method is that because time series are simulated any desired flow statistics can be determined.

Notwithstanding the limitations of the method, the results obtained in this study appear to confirm that different ecosystems in the Zambezi Rivdr Basin do, as expected, affect flow regimes in different ways. The results for the floodplains are fairly unequivocal and indicate that they significantly reduce flood flows (i.e., between 10 and 60%), increase annual minimum flows (i.e., between 10 and 50%) and increase baseflow indices (i.e., between 4 and 20%). The results are consistent with those of previous research both in the Zambezi and elsewhere in the world, which have indicated that floodplains attenuate floods largely as a consequence of overspill into topographic depressions (see section, *Review of the Regulating Functions of the Major Ecosystems*).

For the headwater wetlands the results are more ambiguous. The majority of the headwater wetlands appear to increase 1-day flood flows (by up to 300%). This is consistent with research conducted in southern Africa, which indicates that once saturated, headwater wetlands often act as locations of rapid runoff and source sites for flow (see section, *Review of the Regulating Functions of the Major Ecosystems*). However, in the current study the catchment with the highest proportion of headwater wetlands (site 4) reduced flood flows with return periods greater than 5 years. This is the largest of the catchments and it is possible that the headwater wetlands in this catchment lie along and adjacent to the river and so, at least in relation to flood flows, function in a manner more akin to floodplains.

The impacts of the headwater wetlands on low flows are also variable but, with the exception of one site (i.e., site 7), the majority of the sites investigated reduce the average annual minima. This is again consistent with previous research in the region which indicates that headwater wetlands promote evapotranspiration and hence tend to reduce dry-season low flows (see section, *Review of the Regulating Functions of the Major Ecosystems*).

The results obtained for the forested catchments are, like those of the headwater wetlands, variable. The results from all three sites with greater than 70% miombo forest cover indicate that the forest significantly reduces flood flows (i.e., 40-60%). However, changes in BFI are variable with two sites (i.e., 13 and 17) indicating an increase and one (i.e., 14) a decrease. Similarly, changes in annual minima are more variable with two sites (i.e., 14 and 17) indicating the forest decreases the minima by 14-28% and one (i.e., site 13) indicating the forest increases the minima by about 70%. The one catchment analyzed with only 10% forest cover indicates that the presence of the forest greatly increases flood peaks (up to 500%), reduces BFI (36%) and reduces the annual minima (80%). These results are broadly consistent with the view that by increasing interception and infiltration miombo forest reduces flood flows and, as a consequence of high evapotranspiration, also reduces low flows (see section, *Review of the Regulating Functions of the Major Ecosystems*). However, it is clear from the wide scatter of results that the impacts are far from uniform.

Overall, these results confirm that, as might be expected, there is great variability in the way different ecosystems affect flows in the Zambezi River Basin. Impacts are dependent not just on the presence/absence of different ecosystem types, but also on a range of other biophysical factors including topography, climate, soil and geology (Calder 2006; Bullock 1992a, 1992b). In particular, the hydrogeological setting (i.e., surface water-groundwater interactions) seems to play a very significant role in hydrological functioning and is perhaps the most important driver in the conversion of rainfall to river flow in the Zambezi River Basin and southern Africa generally (Andrew Bullock, Independent Consultant, pers. comm., April 20, 2012).

The hydrological response of well-weathered crystalline basement, which is dominated by deep regional flow of groundwater, has been shown to be very different to that of less weathered regolith, with lower absorptive capacities (Bullock 1992b). In this context, the extent to which the hydrological functioning of different ecosystems varies from that of the surrounding landscape is location-specific and highly dependent on the hydrogeology. For example, where headwater wetlands comprising superficial clay aquifers with little storage capacity occur in association with well-weathered, more permeable regolith, the hydrological functions may differ markedly from their surroundings. Thus, in relation to floods, saturation-overland flow generation of the wetlands contrasts with the more permeable character of the surrounding regolith. In addition, in relation to baseflows, depletion by evaporation and lack of contribution to dry-season recession flows differ from the greater baseflow contributions from the surrounding regolith (Bullock 1992b). In comparison, where the headwater wetlands occur in association with less-weathered, less-permeable regolith the contrast in hydrological response is different, but not as significantly different, from the surrounding catchment (Bullock 1992b).

Against this background, to really quantify hydrological effects a more rigorous approach, taking into account wider geographic variability, is required. Indeed, it is only when this other variability (e.g., in geology/soil water capacity) has been rigorously discounted that meaningful results about natural ecosystem functions emerge (Bullock 1992b). To obtain such differentiated results – especially ones with statistical significance – much larger datasets, that enable wider hydrological processes to be taken into account, need to be used.

This is not to say that the method developed in this study is not of value. The method provides an extremely useful tool for quantifying the impacts of individual ecosystems on flow regimes and, as such, is useful for water planners and managers. However, in order to gain insights into the processes that cause the impacts and to be able to generalize on the basis of geographic characteristics much more rigorous and detailed research is essential.

Conclusion

A relatively simple method for quantifying the impact of natural ecosystems on river flows has been tested in the Zambezi River Basin. Although it is not as sophisticated as hydrological modelling, the method is in some ways superior because analyses can be undertaken rapidly and, unlike most modelling studies, it is not necessary to make assumptions about ecosystem functions. The method enables the construction of time series of flow in the absence of a particular ecosystem. Standard hydrological techniques can then be used to compare this time series with the observed flow series and, hence, quantify the impact of the ecosystem of interest on any aspect of the flow regime.

Application of the method to headwater wetlands, floodplains and miombo forest in the Zambezi River Basin has confirmed that these ecosystems affect river flow in different ways. In this study, analyses were conducted for only a small number of each ecosystem type which constrains the statistical analyses. Nevertheless, the results broadly confirm the findings of past research, indicating the following:

i) Floodplains decrease the magnitude of flood flows and increase low flows.

ii) Headwater wetlands increase the magnitude of flood flows and decrease low flows.

iii) Miombo forest, when covering more than 70% of the catchment, decreases the magnitude of flood flows and also decreases low flows.

However, in all cases there are examples which produce contrary results. Simple relationships between the areal coverage of a particular ecosystem type within a catchment and the impact on the flow regime were not found. This confirms that effects on flow are a function not just of the presence/absence of different ecosystem types, but also of a range of other biophysical factors, including topography, climate, soil, vegetation and geology. Not surprisingly, the hydrological functions of natural ecosystems depend to a large extent on location-specific characteristics that make it difficult to generalize. To identify distinctive functions much more detailed research that takes into account the full range of biophysical factors affecting flow is required.

The concept of the green economy is beginning to permeate water planning and it is increasingly recognized that within any river basin water resources development can no longer be considered a matter of simply expanding the endowment of built water infrastructure. Because they are widely perceived to deliver beneficial services, the idea of considering natural ecosystems as “natural infrastructure” and the need to consider built infrastructure in conjunction with natural infrastructure is gaining credence. However, the hydrological functions of natural ecosystems are multifaceted. As this study has demonstrated, in different circumstances natural ecosystems both attenuate and increase flood flows and both augment and reduce low flows. Notwithstanding the other ecosystems services that they provide, it is incorrect to assume that natural ecosystems will necessarily regulate flows to the benefit of people.

Although there are limitations and considerable scope for improvement, the method developed in this study is a useful tool. The strength of the method is that it enables the impacts of natural ecosystems on flow to be made explicit and quantified without the need to resort to complex computer models. As such, it provides a way for water resource planners and managers to deduce the impacts of natural ecosystems on flows and assess the implications (positive or negative) for communities living downstream. The method is a useful contribution to the better incorporation of natural ecosystems into water planning and management.

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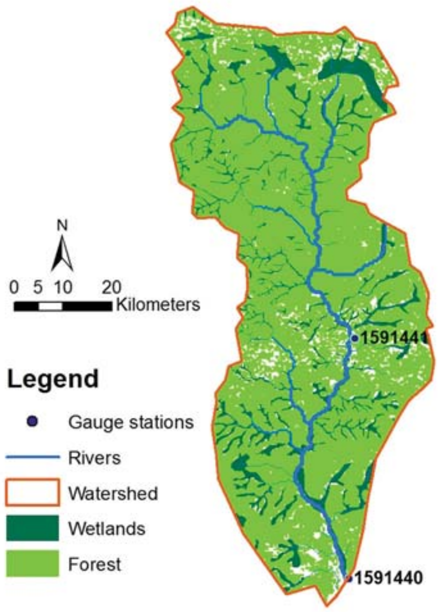
Appendix A. Land Use in the 13 Major Sub-catchments of the Zambezi River Basin.

Land use	Zambezi Delta	Tete	Shire	Mupata	Luangwa	Kariba	Kafue	Cuando/ Chobe	Barotse	Luanginga	Lungue Bungo	Upper Zambezi	Kabompa	Total
Rain-fed croplands	196	12	720	8	20	6.9	58	0	0	0	0	0	0	1,020
Mosaic cropland (50-70%) / vegetation (grass/shrub/forest) (20-50%)	189	18	593	3.5	5	2.2	64	0	0	0	0	0	0	874
Mosaic vegetation (grass/shrub/forest) (50-70%) / cropland (20-50%)	1,816	39,374	30,737	5,643	25,869	33,016	7,419	21,704	8,558	1,839	1,167	2,024	544	179,710
Closed to open (>15%) broad-leaved semi-deciduous forest (>5 m)	522	18	1,948	0	7	0	2.7	0.9	2.8	103	2.7	52	11	2,669
Closed (>40%) broad-leaved deciduous forest (>5 m) (miombo)	6,454	25,054	32,641	4,891	25,290	5,292	36,153	11,135	5,366	7,781	18,486	34,230	40,563	253,336
Open (15-40%) broad-leaved deciduous forest (>5 m) (miombo)	1,888	49,092	17,851	11,590	53,309	36,553	49,989	25,945	40,416	7,043	10,036	35,925	14,552	354,187
Closed (>40%) needle-leaved evergreen forest (>5 m)	0	0	1	0	0	0	0	0	0	0	0	0	0	1
Open (15-40%) needle-leaved deciduous forest (>5 m)	156	24	1,705	1.9	41	0.1	0.8	0.4	0	0	0	0	0	1,929
Closed to open (>15%) mixed broad-leaved forest (>5 m)	0	0.5	2.2	0	0	0.1	0.1	0	0	0	0	0	0	3
Mosaic forest or shrubland (50-70%) / grassland (20-50%)	2.3	1,586	869	244	829	5,248	2,179	6,421	3,869	2,851	4,647	4,846	389	33,981
Mosaic grassland (50-70%) / forest or shrubland (20-50%)	0.6	1,007	566	49	504	690	259	3,627	2,179	289	105	314	62	9,650
Closed/open (>15%) (broad-leaved deciduous) shrubland (<5 m)	1,057	47,658	18,971	10,022	34,347	41,999	31,529	31,877	26,815	5,299	6,409	7,481	10,634	274,098
Closed/open (>15%) herbaceous vegetation (grassland)	13	18,031	2,668	1,878	4,694	29,707	8,094	28,920	12,417	4,871	4,064	2,107	400	117,863
Sparse (<15%) vegetation	0.1	29	2	1.1	43	19	59	0	0.4	0.1	0	0.2	4	157
Closed/open (>15%) broad-leaved forest regularly flooded	0	0	32	0	17	0	110	0	0	0	0	49	18	226
Closed/open (>15%) grassland/woody vegetation regularly flooded	0	25	75	0	252	0	0.9	25	746	538	2,571	3,332	107	7,672
Artificial surfaces and associated areas (urban areas >50%)	0	603	209	59	29	452	512	0	0	0	0	0	0	1,864
Bare areas	0	0.2	0	0	0.2	1.6	0.6	0.2	0.2	0	0	0	0	3
Water bodies	270	4,949	29,573	215	198	5,003	1,763	17	268	40	3.2	119	9.7	42,428
Wetland	2,123	978	4,251	0	2,156	0	15,520	11,993	13,177	5,424	2,499	3,538	1,608	63,266
Total	14,687	188,458	143,412	34,605	147,610	157,990	153,712	141,665	113,815	36,075	49,989	94,017	68,902	1,344,936

Appendix B. Maps.



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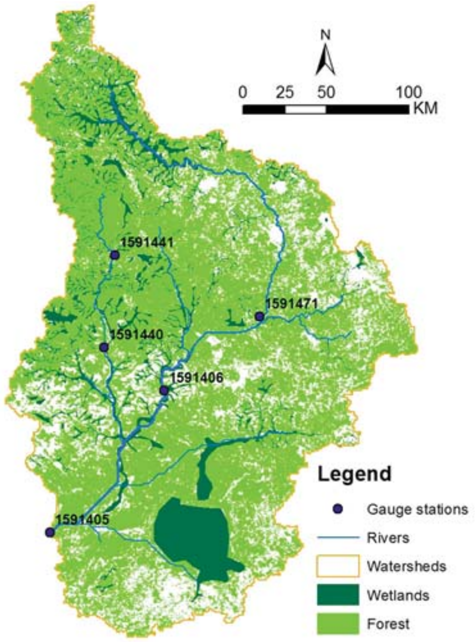

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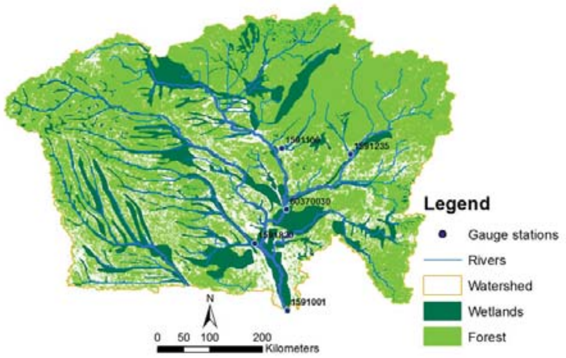

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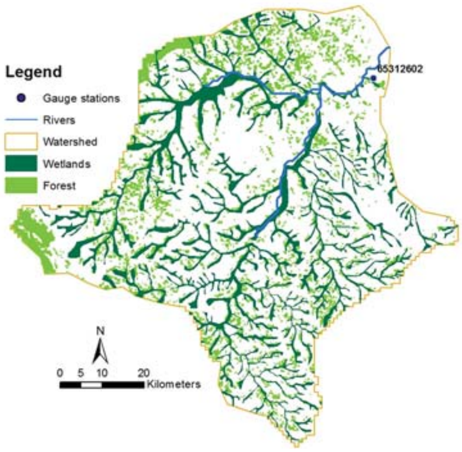

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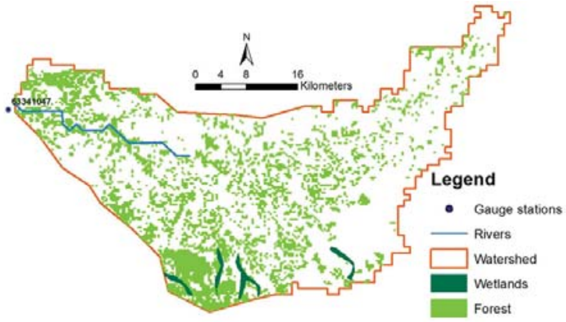

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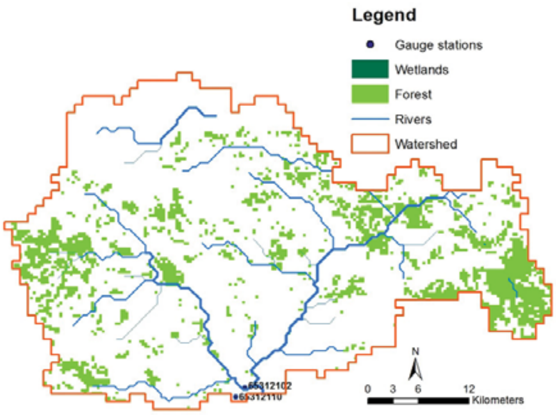

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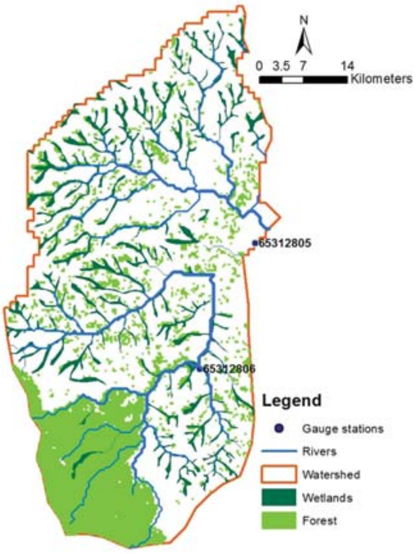
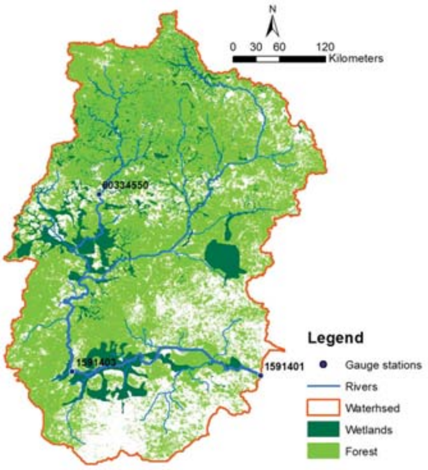


Site 7

Site 8

Site 9



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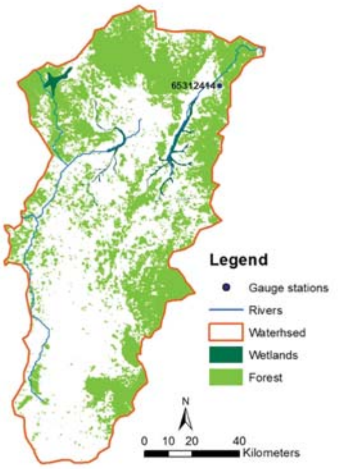

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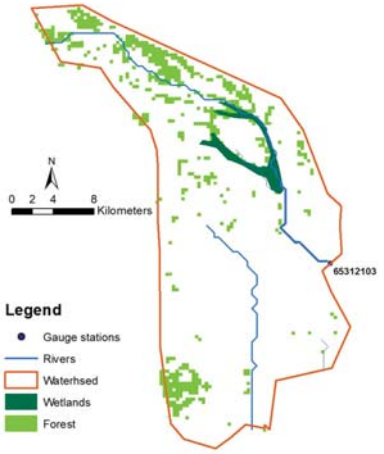

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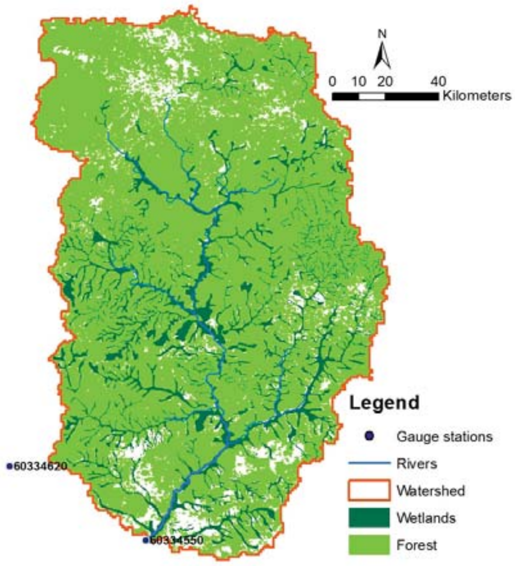

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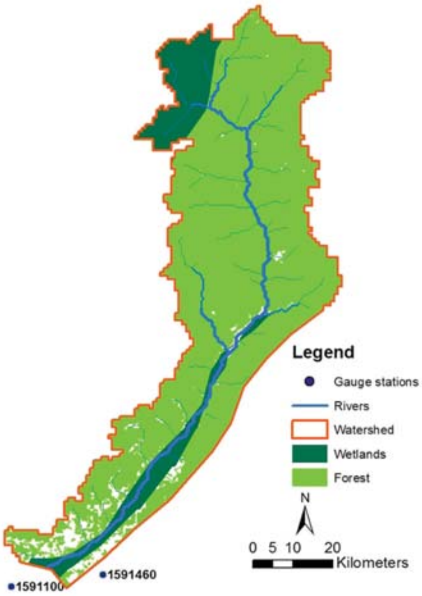

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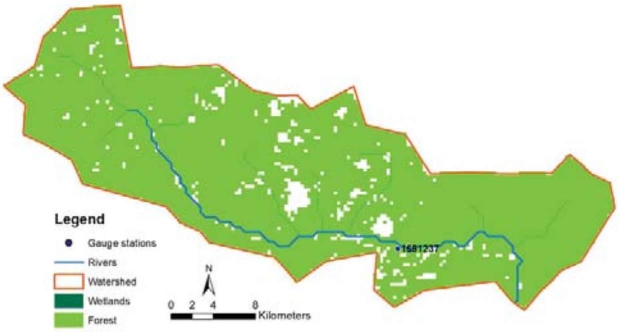

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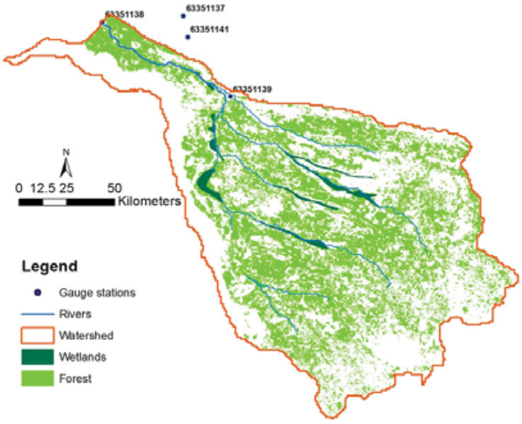

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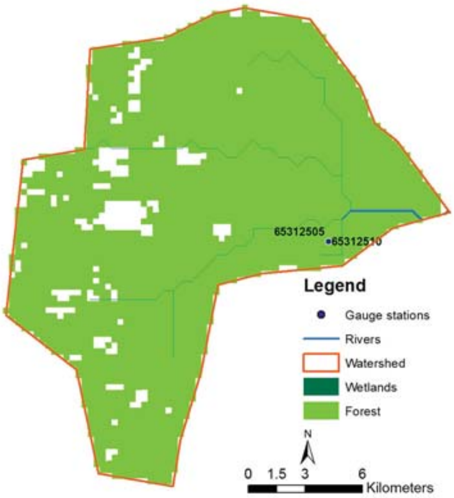

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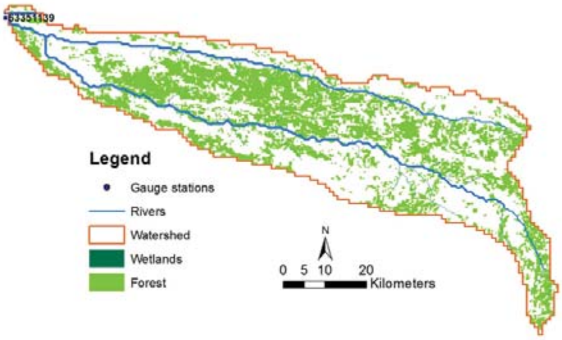


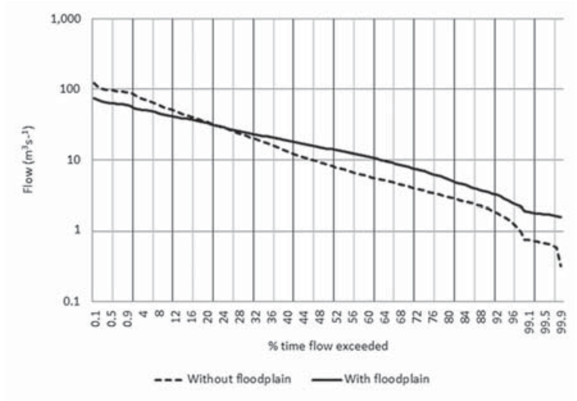
Site 18

Appendix C. Results for the Individual Catchments.

Site 1. Floodplain on the Luswishi River in Zambia. Comparison with and without the floodplain at the location of GRDC flow gauge 1591440 (i.e., the Luswishi at Kangondi).

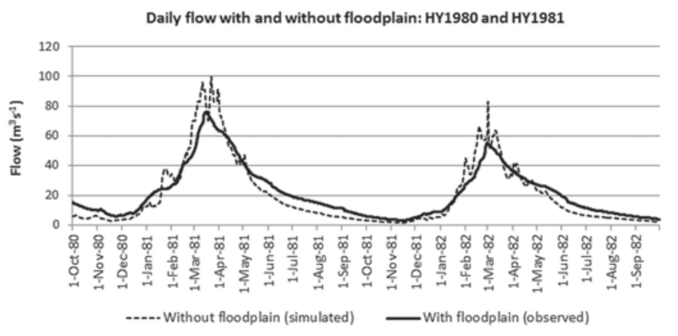
Total catchment area:	3,756 km^2
Catchment area between upstream and downstream gauge:	1,502 km^2
Area of floodplain	211 km^2 (5.9% of total catchment)

Comparison of FDCs



Perecentile	Flow (m^{3}s^{-1})%		% difference
	with floodplain	without floodplain	
99	1.90	0.75	-60.5
95	2.63	1.41	-45.3
90	3.51	2.06	-41.4
75	6.64	3.53	-46.4
50	14.81	8.59	-40.6
25	28.04	27.42	-2.2
10	43.51	54.41	25.1
5	50.40	70.06	39.0
1	60.15	91.85	52.7

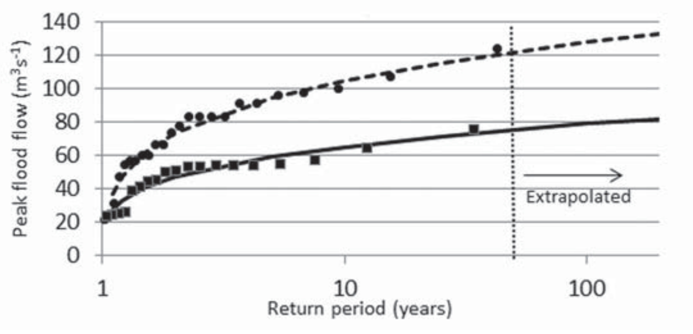
Example hydrographs



Comparison of low-flow statistics

	BFI	Mean annual minimum (m^{3}s^{-1})	
		1-day	10-day
With floodplain	0.526	2.96	3.04
Without floodplain	0.439	2.02	2.13

Comparison of flood frequency curves

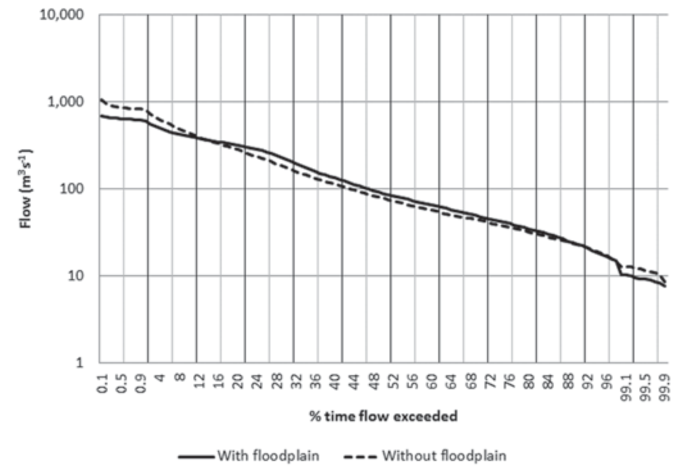


Return period (years)	Flood magnitude (m^{3}s^{-1})		% reduction
	with floodplain	without floodplain	
1.1	27.3	37.0	26.3
1.5	41.0	62.0	33.9
2	47.3	73.3	35.5
5	56.2	94.3	37.2
10	65.2	104.6	37.7
25	71.4	115.3	38.0
50	75.4	121.9	38.2
100	78.9	127.8	38.3
200	82.0	133.0	38.3

Site 2. Floodplain on the Kafue River in Zambia. Comparison with and without the floodplain at the location of GRDC flow gauge 1591405 (i.e., the Kafue at Mswebi).

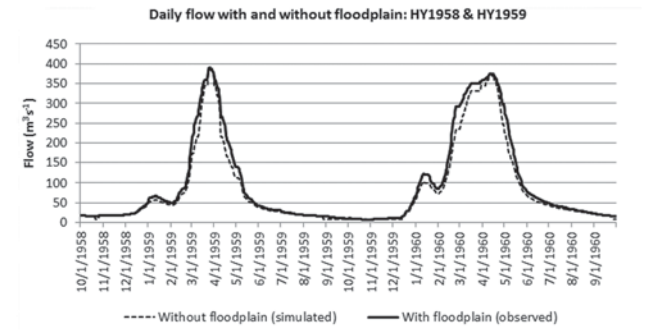
Total catchment area:	45,939 km^2
Catchment area between upstream and downstream gauge:	21,607 km^2
Area of floodplain	3,009 km^2 (6.6% of total catchment)

Comparison of FDCs



Perecentile	Flow (m^{3}s^{-1})%		% difference
	with floodplain	without floodplain	
99	10.3	12.9	25.2
95	17.8	18.3	2.7
90	22.8	22.8	-0.1
75	41.1	37.5	-8.8
50	88.5	77.9	-12.0
25	274.4	225.6	-17.8
10	404.1	431.0	6.6
5	466.9	588.6	26.1
1	605.4	815.6	34.7

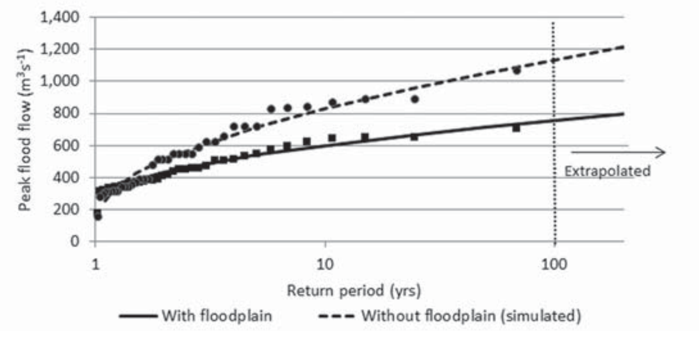
Example hydrographs



Comparison of low-flow statistics

	BFI	Mean annual minimum (m^{3}s^{-1})	
		1-day	10-day
With floodplain	0.458	21.0	21.6
Without floodplain	0.440	19.4	19.9

Comparison of flood frequency curves

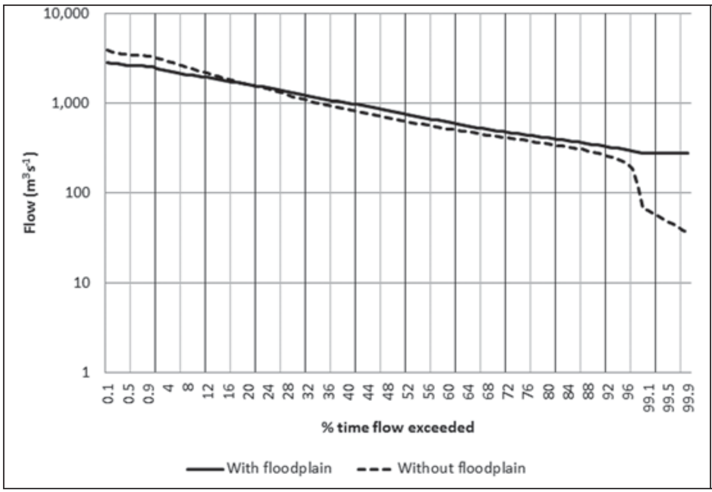


Return period (years)	Flood magnitude (m^{3}s^{-1})		% reduction
	with floodplain	without floodplain	
1.1	295.6	258.8	-14.2
1.5	387.6	427.0	9.2
2	436.1	517.3	15.7
5	540.3	714.1	24.3
10	599.9	828.3	27.6
25	667.6	958.8	30.4
50	713.5	1,048.2	31.9
100	756.5	1,132.1	33.2
200	797.1	1,211.8	34.2

Site 3. Floodplain (Barotse) on the Zambezi River in Zambia. Comparison with and without the floodplain at the location of GRDC flow gauge 1591001 (i.e., the Zambezi at Senanga).

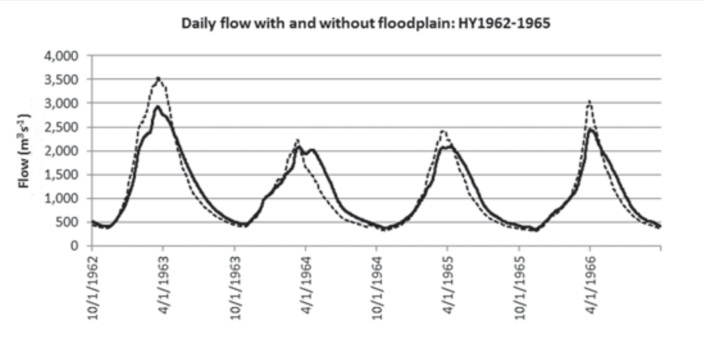
Total catchment area:	299,492 km^2
Catchment area between upstream and downstream gauge:	123,159 km^2
Area of floodplain	27,284 km^2 (9.1% of total catchment)

Comparison of FDCs



Perecentile	Flow (m^3s^{-1})%		% difference
	with floodplain	without floodplain	
99	280	67	-76.1
95	306	223	-27.2
90	339	276	-18.4
75	444	389	-12.5
50	787	657	-16.6
25	1,443	1,395	-3.3
10	2,000	2,321	16.0
5	2,237	2,819	26.0
1	2,552	3,349	31.2

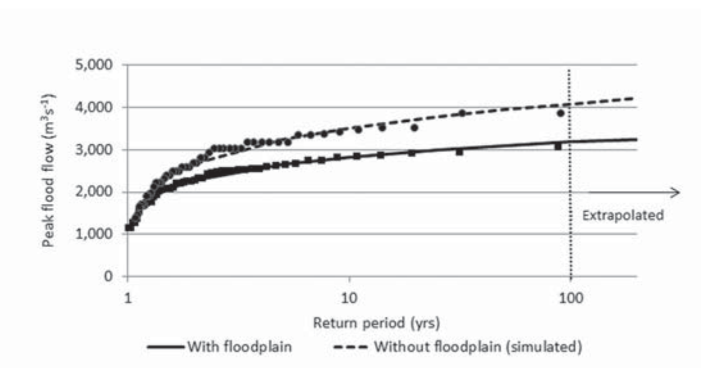
Example hydrographs



Comparison of low-flow statistics

	BFI	Mean annual minimum (m^3s^{-1})	
		1-day	10-day
With floodplain	0.568	301	303
Without floodplain	0.538	262	271

Comparison of flood frequency curves

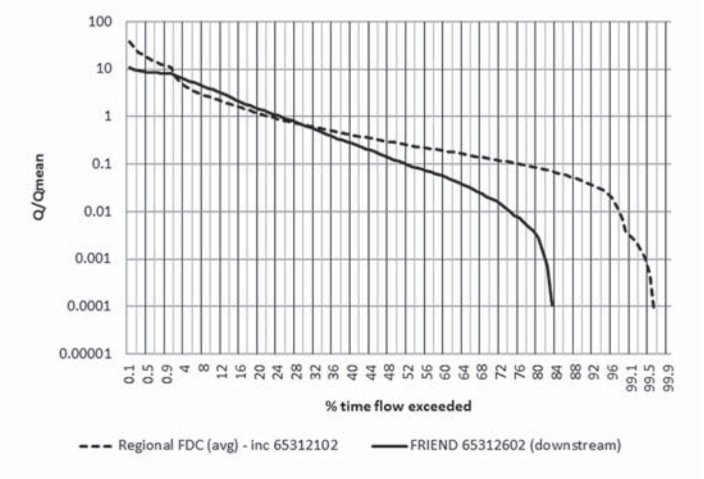


Return period (years)	Flood magnitude (m^3s^{-1})		% reduction
	with floodplain	without floodplain	
1.1	1,546	1,652	6.4
1.5	2,061	2,357	12.6
2	2,278	2,667	14.6
5	2,655	3,228	17.8
10	2,828	3,498	19.2
25	2,995	3,769	20.5
50	3,094	3,935	21.4
100	3,177	4,078	22.1
200	3,249	4,205	22.7

Site 4. Headwater wetlands on the Bua River in Malawi. Comparison with and without the wetlands at the location of FRIEND flow gauge 65312602 (i.e., Old Bua Bridge at Kasese).

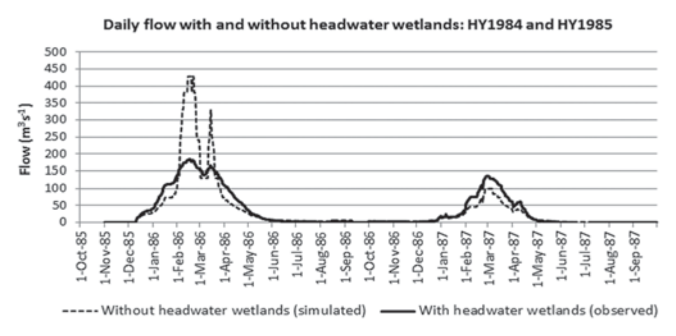
Total catchment area:	4,777 km^2
Area of headwater wetlands:	823 km^2 (17.2% of total catchment)

Comparison of FDCs



Perecentile	Flow (m^{3}s^{-1})%		% difference
	with floodplain	without floodplain	
99	0.0	0.1	-
95	0.0	0.5	-
90	0.0	0.8	-
75	0.2	2.1	980.4
50	2.2	5.3	142.1
25	20.1	17.1	-15.3
10	70.3	46.2	-34.3
5	107.0	73.5	-31.4
1	152.9	208.2	36.2

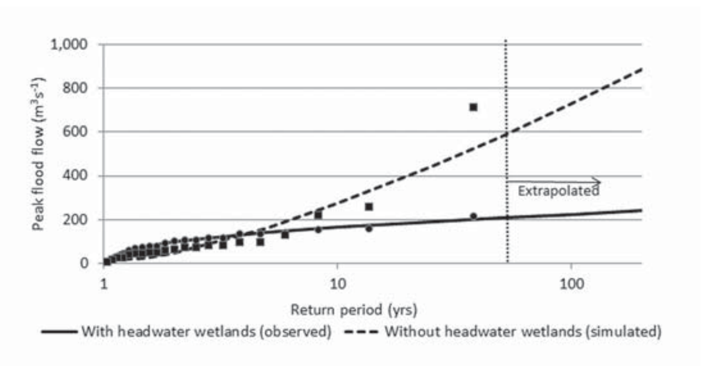
Example hydrographs



Comparison of low-flow statistics

	BFI	Mean annual minimum (m^{3}s^{-1})	
		1-day	10-day
With headwater wetlands	0.290	0.028	0.032
Without headwater wetlands	0.358	0.389	0.443

Comparison of flood frequency curves

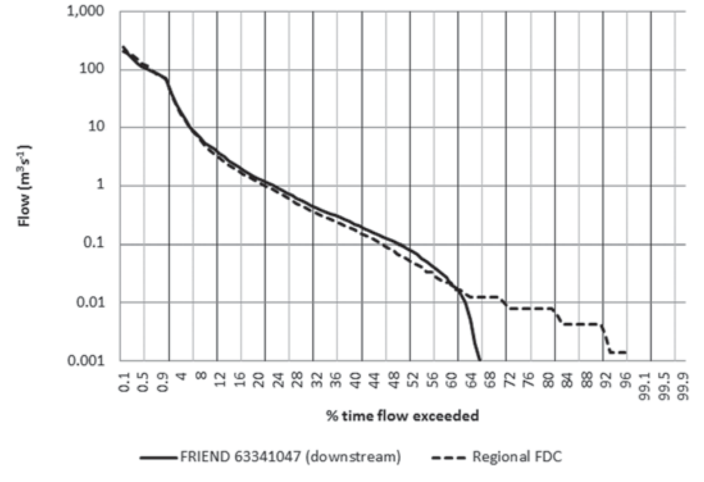


Return period (years)	Flood magnitude (m^{3}s^{-1})		% reduction
	with floodplain	without floodplain	
1.1	31.9	15.0	-112.7
1.5	75.0	24.8	-202.4
2	96.5	47.8	-101.9
5	140.5	161.8	13.2
10	164.4	272.2	39.6
25	190.8	439.6	56.6
50	208.3	579.2	64.0
100	224.3	728.3	69.2
200	239.2	885.9	73.0

Site 5. Headwater wetlands on the Sebakwe River in Zimbabwe. Comparison with and without the wetlands at the location of FRIEND flow gauge 63341047 (i.e., upstream Sebakwe Dam).

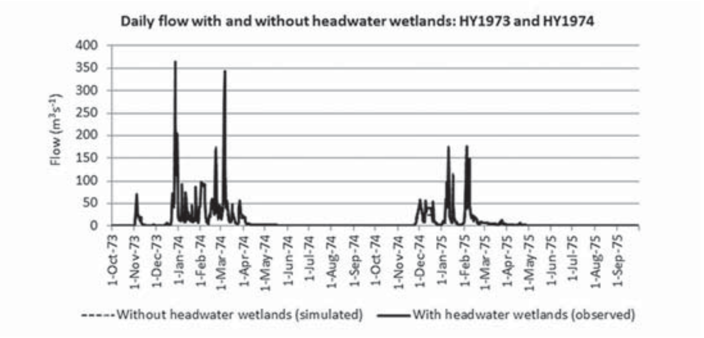
Total catchment area:	1,533 km^2
Area of headwater wetlands:	17.2 km^2 (1.1% of total catchment)

Comparison of FDCs



Perecentile	Flow (m^{3}s^{-1})%		% difference
	with floodplain	without floodplain	
99	0.0	0.0	-
95	0.0	0.01	-
90	0.0	0.0043	-
75	0.0	0.008	-
50	0.10	0.07	-33.6
25	0.84	0.71	-16.0
10	4.77	4.07	-14.54
5	13.74	12.94	-5.8
1	66.97	71.96	7.5

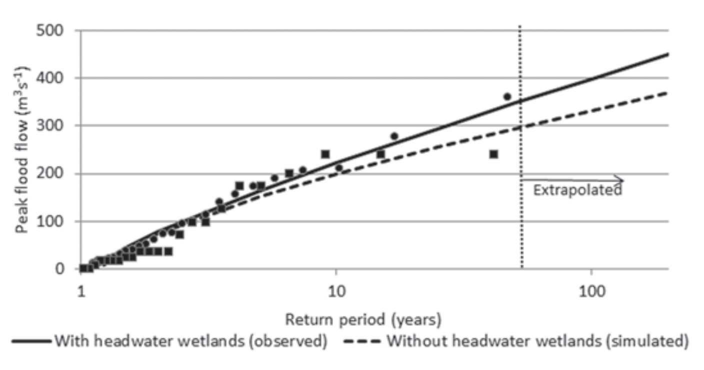
Example hydrographs



Comparison of low-flow statistics

	BFI	Mean annual minimum (m^{3}s^{-1})	
		1-day	10-day
With headwater wetlands	0.160	0.002	0.005
Without headwater wetlands	0.150	0.013	0.014

Comparison of flood frequency curves

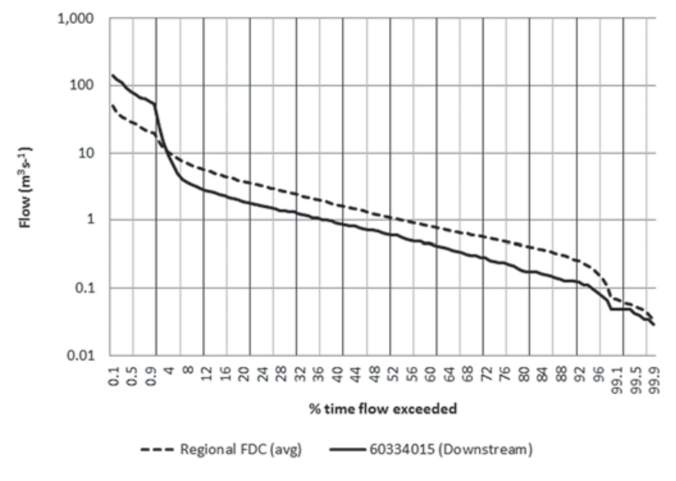


Return period (years)	Flood magnitude (m^{3}s^{-1})		% reduction
	with floodplain	without floodplain	
1.1	-	-	-
1.5	43.5	40.6	-7.1
2	77.2	73.9	-4.5
5	164.2	151.3	-8.5
10	222.2	198.7	-11.8
25	294.5	255.0	-15.5
50	347.3	294.6	-17.9
100	399.2	332.5	-20.1
200	450.4	369.2	-22.0

Site 6. Headwater wetlands on the Muchindamu River in Zambia. Comparison with and without the wetlands at the location of FRIEND flow gauge 60334015 (i.e., Muchindamu at Muchindamu).

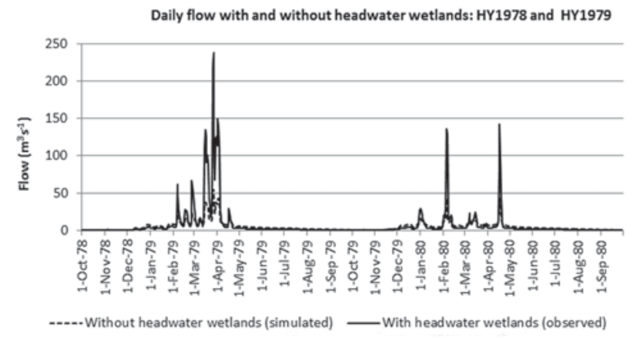
Total catchment area:	198 km^2
Area of headwater wetlands:	20 km^2 (10.2% of total catchment)

Comparison of FDCs



Perecentile	Flow (m^{3}s^{-1})%		% difference
	with floodplain	without floodplain	
99	0.05	0.07	46.6
95	0.10	0.19	95.1
90	0.13	0.28	122.6
75	0.24	0.51	113.5
50	0.65	1.18	81.9
25	1.6	3.1	96.7
10	3.1	6.2	97.6
5	6.5	9.1	39.0
1	53.2	19.7	-63.0

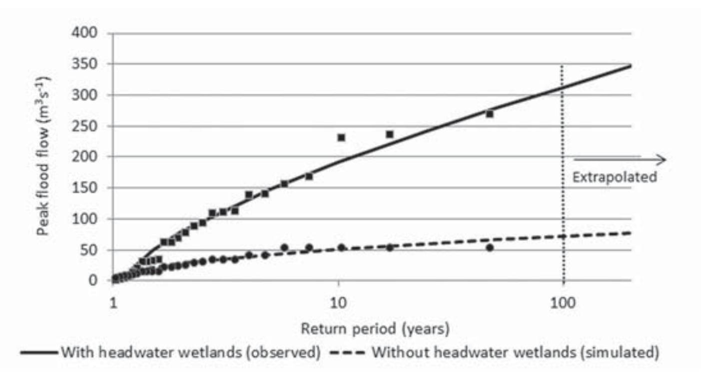
Example hydrographs



Comparison of low-flow statistics

	BFI	Mean annual minimum (m^{3}s^{-1})	
		1-day	10-day
With headwater wetlands	0.284	0.12	0.13
Without headwater wetlands	0.444	0.24	0.27

Comparison of flood frequency curves

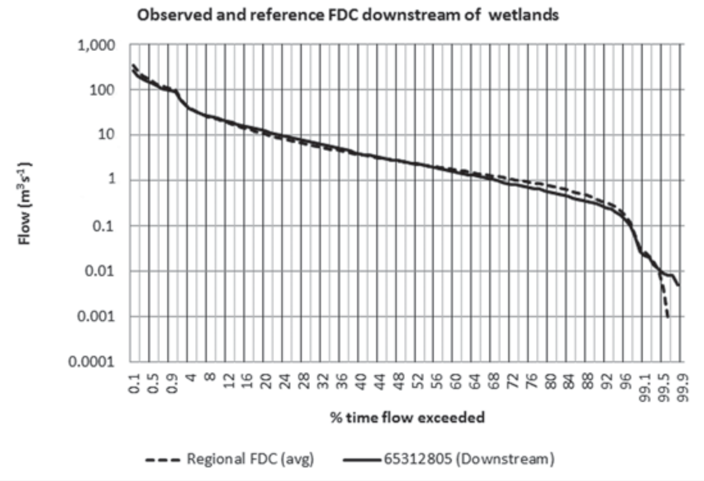


Return period (years)	Flood magnitude (m^{3}s^{-1})		% reduction
	with floodplain	without floodplain	
1.1	-	7.3	-
1.5	49.5	20.7	-139.1
2	79.2	27.7	-185.9
5	148.7	42.4	250.7
10	191.5	50.7	-277.7
25	242.5	60.1	-303.5
50	278.4	66.4	-319.3
100	312.9	72.3	-332.8
200	346.2	77.8	-345.0

Site 7. Headwater wetlands on the Lilongwe River in Malawi. Comparison with and without the wetlands at the location of FRIEND flow gauge 65312805 (i.e., at Lilongwe Old Town).

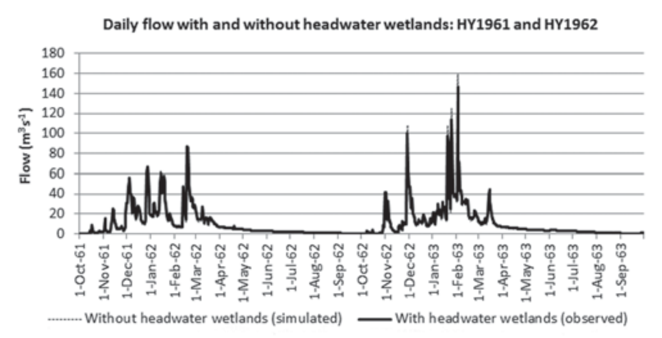
Total catchment area:	2,285 km^2
Area of headwater wetlands:	239 km^2 10.5% of total catchment)

Comparison of FDCs



Perecentile	Flow (m^{3}s^{-1})%		% difference
	with floodplain	without floodplain	
99	0.03	0.03	15.9
95	0.17	0.22	26.4
90	0.3	0.4	28.2
75	0.8	1.0	31.0
50	2.6	2.5	-0.8
25	9.1	7.7	-14.5
10	23.4	22.2	-5.1
5	35.0	35.4	1.2
1	93.6	100.3	7.2

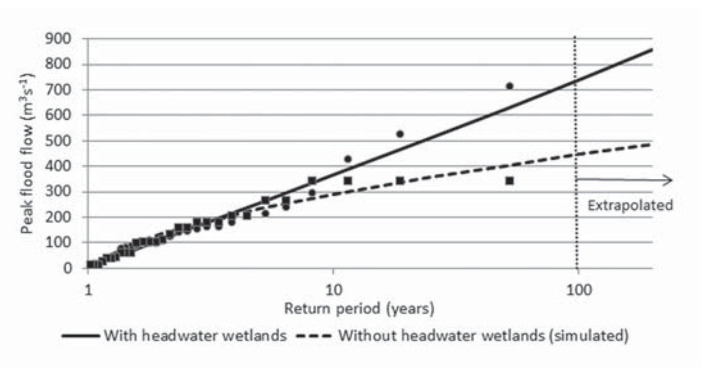
Example hydrographs



Comparison of low-flow statistics

	BFI	Mean annual minimum (m^{3}s^{-1})	
		1-day	10-day
With headwater wetlands	0.332	0.18	0.23
Without headwater wetlands	0.334	0.21	0.29

Comparison of flood frequency curves

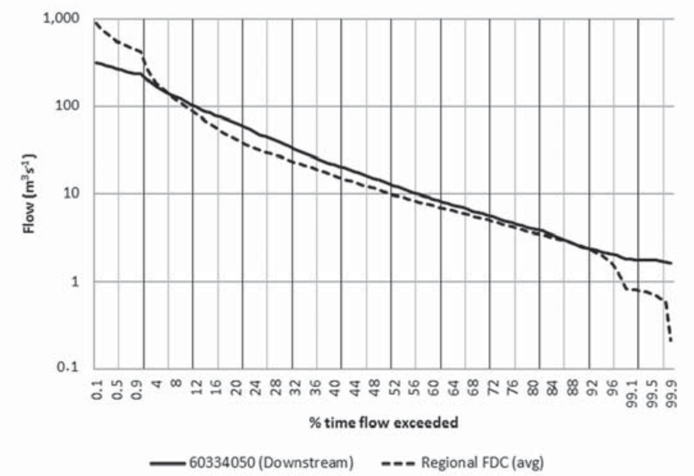


Return period (years)	Flood magnitude (m^{3}s^{-1})		% reduction
	with floodplain	without floodplain	
1.1	19.3	14.3	-35.0
1.5	69.1	92.9	25.6
2	114.1	136.3	16.3
5	256.0	233.0	-9.9
10	364.5	290.2	-25.6
25	510.9	356.5	-43.3
50	623.9	402.3	-55.1
100	739.1	445.7	-65.8
200	856.3	487.1	-75.8

Site 8. Floodplain on the Kafue River in Zambia. Comparison with and without the floodplain at the location of FRIEND flow gauge 60334050 (i.e., the Kafue at Reglan Farm).

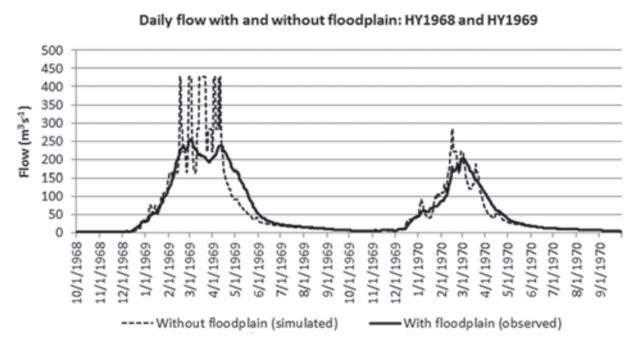
Total catchment area:	4,321 km^2
Catchment area between upstream and downstream gauge:	3,756 km^2
Area of floodplain	730 km^2 (17% of total catchment)

Comparison of FDCs



Perecentile	Flow (m^3s^{-1})%		% difference
	with floodplain	without floodplain	
99	1.8	0.8	-54.4
95	2.1	1.8	-14.3
90	2.52	2.55	1.3
75	4.9	4.4	-10.5
50	13.8	10.7	-22.6
25	47.9	31.6	-33.9
10	113.8	100.4	-11.1
5	158.0	164.5	4.1
1	233.4	427.0	82.9

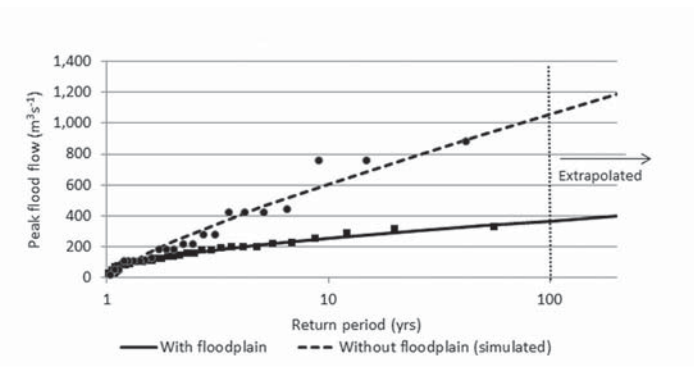
Example hydrographs



Comparison of low-flow statistics

	BFI	Mean annual minimum (m^3s^{-1})	
		1-day	10-day
With floodplain	0.384	2.48	2.58
Without floodplain	0.362	2.09	2.26

Comparison of flood frequency curves

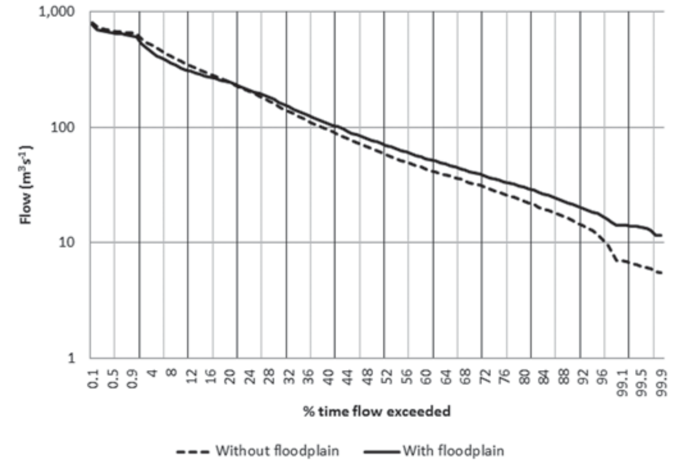


Return period (years)	Flood magnitude (m^3s^{-1})		% reduction
	with floodplain	without floodplain	
1.1	62	18	-239
1.5	117	150	22
2	148	237	38
5	216	460	53
10	257	607	58
25	304	790	62
50	337	924	64
100	368	1,055	65
200	398	1,185	66

Site 9. Floodplain on the Kafue River in Zambia. Comparison with and without the floodplain at the location of GRDC flow gauge 1591470 (i.e., the Kafue at Ndubeni).

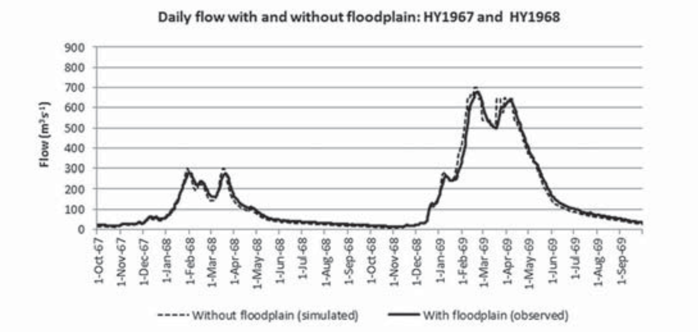
Total catchment area:	16,638 km^2
Catchment area between upstream and downstream gauge:	2,631 km^2
Area of floodplain	222 km^2 (1.3% of total catchment)

Comparison of FDCs



Perecentile	Flow (m^3s^{-1})%		% difference
	with floodplain	without floodplain	
99	14	7	-50.7
95	18	12	-34.0
90	22	16	-27.3
75	35	27	-21.5
50	75	63	-16.2
25	202	195	-3.6
10	326	371	13.9
5	417	485	16.5
1	606	643	6.2

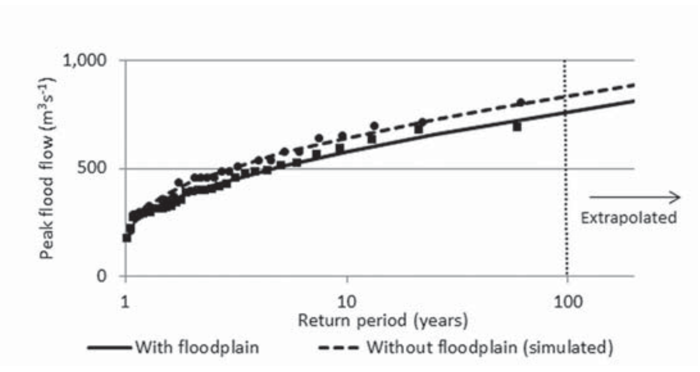
Example hydrographs



Comparison of low-flow statistics

	BFI	Mean annual minimum (m^3s^{-1})	
		1-day	10-day
With floodplain	0.466	19.9	20.8
Without floodplain	0.434	13.4	14.1

Comparison of flood frequency curves



Return period (years)	Flood magnitude (m^3s^{-1})		% reduction
	with floodplain	without floodplain	
1.1	251	263	4.5
1.5	338	379	10.7
2	393	439	10.6
5	508	569	10.7
10	576	643	10.3
25	655	726	9.8
50	710	783	9.4
100	761	836	9.0
200	810	886	8.5

Site 10. Floodplain (Kafue Flats) on the Kafue River in Zambia. Comparison with and without the floodplain at the location of GRDC flow gauge 1591401 (i.e., the Kafue at Kasaka).

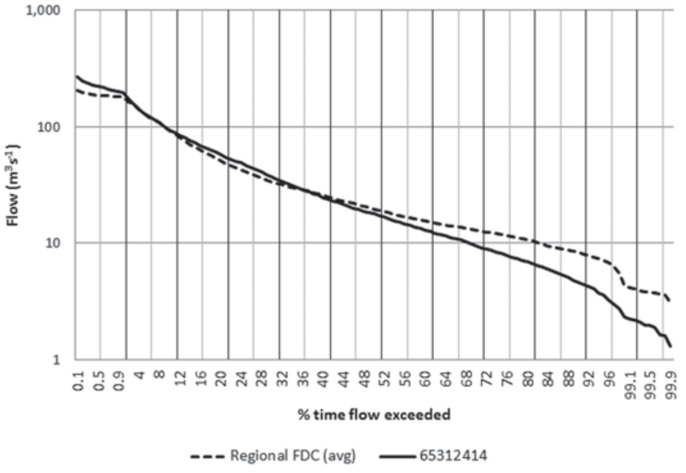
Total catchment area: 137,970 km^2
Catchment area between upstream and downstream gauge: 39,874 km^2
Area of floodplain 4,363 km^2 (3.2% of total catchment)

Flow in the Kafue Flats has been altered by the construction of dams (i.e., Kafue Gorge downstream in 1971 and Itezhi-tezhi upstream in 1979). Hence, only short flow records were available and this station was dropped from the final analyses.

Site 11. Headwater wetlands on the South Rukuru River in Malawi. Comparison with and without the wetlands at the location of FRIEND flow gauge 65312414 (i.e., South Rukuru at Phewzi).

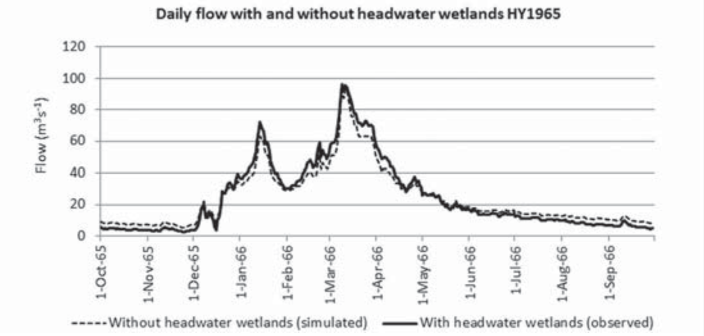
Total catchment area:	10,386 km^2
Area of headwater wetlands:	132 km^2 (1.3% of total catchment)

Comparison of FDCs



Perecentile	Flow (m^3s^{-1})%		% difference
	with floodplain	without floodplain	
99	2.4	4.3	83.6
95	3.6	7.2	99.0
90	4.7	8.3	78.2
75	8.2	11.9	45.4
50	17.9	19.6	9.7
25	46.8	40.8	-12.9
10	94.3	92.9	-1.5
5	130.0	130.4	0.3
1	197.7	179.6	-9.1

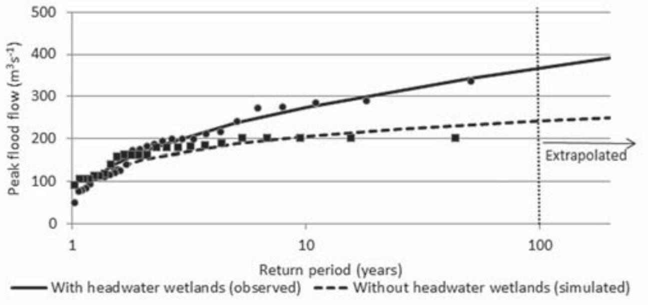
Example hydrographs



Comparison of low-flow statistics

	BFI	Mean annual minimum (m^3s^{-1})	
		1-day	10-day
With headwater wetlands	0.430	3.08	3.51
Without headwater wetlands	0.485	5.77	6.44

Comparison of flood frequency curves

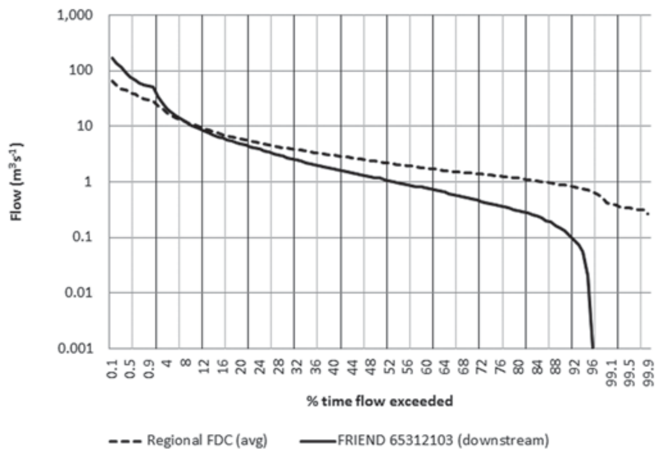


Return period (years)	Flood magnitude (m^3s^{-1})		% reduction
	with floodplain	without floodplain	
1.1	78.2	79.9	2.1
1.5	139.2	129.4	-7.6
2	170.6	150.7	-13.2
5	236.4	188.0	-25.7
10	273.3	205.4	-33.1
25	314.5	222.5	-41.3
50	342.2	232.8	-47.0
100	367.9	241.5	-52.3
200	392.0	249.0	-57.4

Site 12. Forest in the catchment of the Rivi Rivi River in Malawi. Comparison with and without the forest at the location of FRIEND flow gauge 65312103 (Rivi Rivi at Balaka).

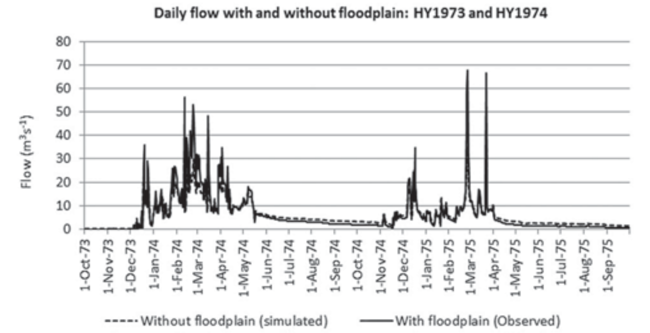
Total catchment area:	534 km^2
Area of forest:	53.8 km^2 (10.1% of total catchment)

Comparison of FDCs



Perecentile	Flow (m^{3}s^{-1})%		% difference
	with forest	without forest	
99	0.00	0.41	-
95	0.02	0.71	3293
90	0.13	0.87	569
75	0.39	1.29	231
50	1.16	2.29	97.8
25	3.6	4.8	33.5
10	9.8	10.4	6.0
5	17.7	15.6	-12.1
1	49.9	28.9	-42.1

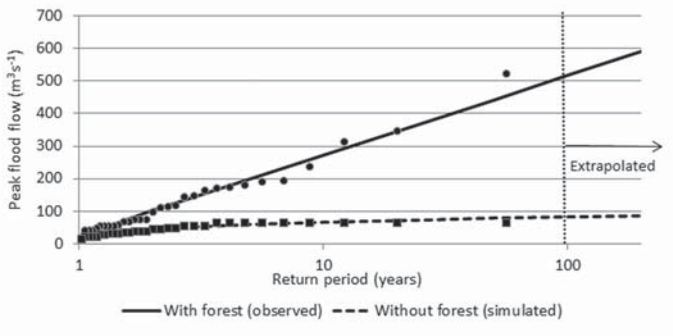
Example hydrographs



Comparison of low-flow statistics

	BFI	Mean annual minimum (m^{3}s^{-1})	
		1-day	10-day
With forest	0.311	0.12	0.14
Without forest	0.489	0.72	0.77

Comparison of flood frequency curves

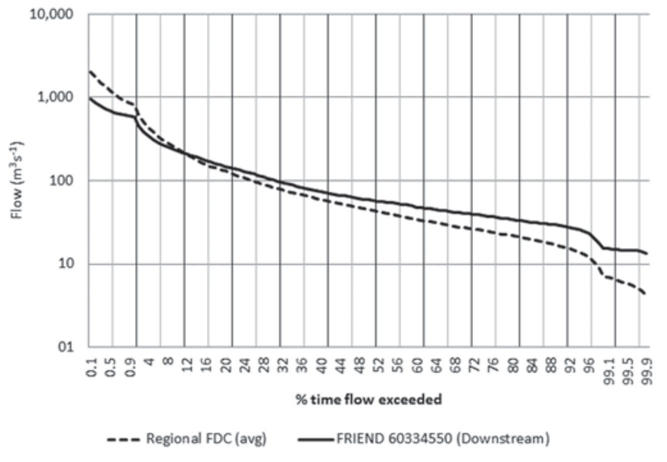


Return period (years)	Flood magnitude (m^{3}s^{-1})		% reduction
	with forest	without forest	
1.1	30.0	22.8	-31.6
1.5	68.6	37.5	-82.9
2	101.1	44.5	-127.2
5	198.9	58.3	-241.2
10	271.7	65.5	-314.8
25	368.3	73.2	-403.1
50	442.2	78.2	-465.5
100	519.9	82.6	-525.8
200	592.5	86.7	-583.4

Site 13. Forest in the catchment of the Lunga River in Zambia. Comparison with and without the forest at the location of FRIEND flow gauge 60334550 (i.e., Lunga at Kelongwa School).

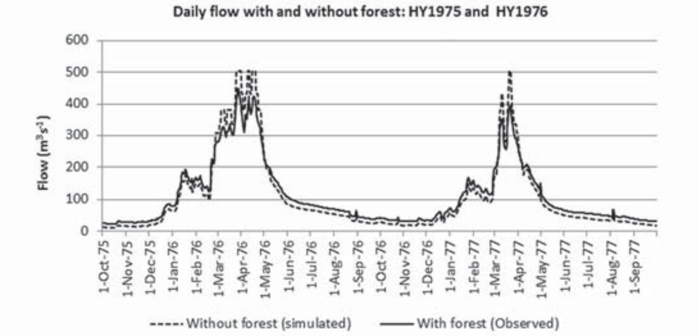
Total catchment area:	17,742 km^2
Area of forest:	13,652 km^2 (75.9% of total catchment)

Comparison of FDCs



Perecentile	Flow (m^{3}s^{-1})%		% difference
	with forest	without forest	
99	15.6	7.1	-54.1
95	24.5	13.1	-46.6
90	28.9	16.4	-43.2
75	37.4	24.4	-34.8
50	59.0	44.8	-24.1
25	125.2	102.8	-17.9
10	229.7	240.7	4.8
5	312.0	381.3	22.2
1	590.1	815.6	38.2

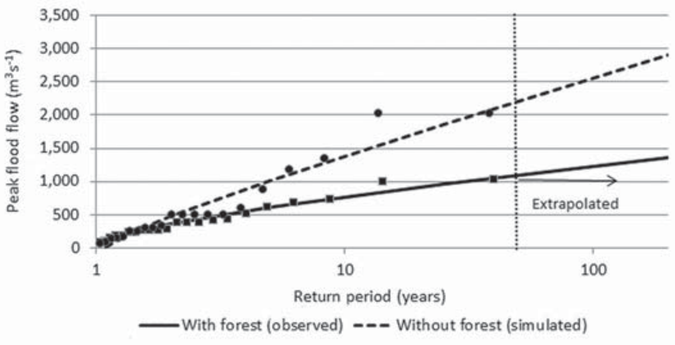
Example hydrographs



Comparison of low-flow statistics

	BFI	Mean annual minimum (m^{3}s^{-1})	
		1-day	10-day
With forest	0.543	28.4	29.1
Without forest	0.448	16.4	17.0

Comparison of flood frequency curves

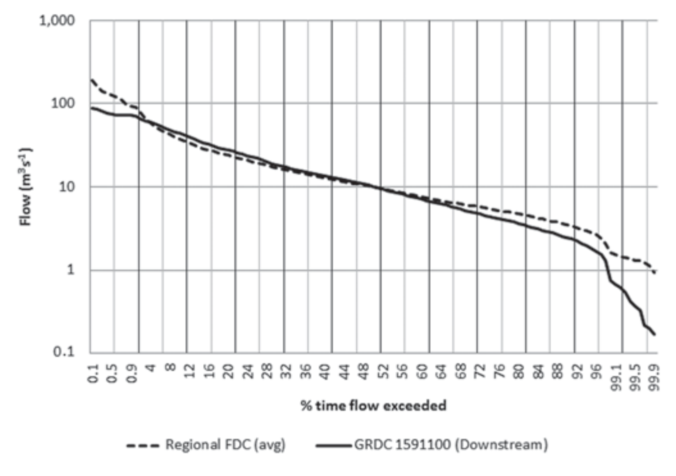


Return period (years)	Flood magnitude (m^{3}s^{-1})		% reduction
	with forest	without forest	
1.1	113.7	4.2	-2607
1.5	268.9	276.6	2.8
2	366.6	472.6	22.4
5	608.5	1,007.3	39.6
10	764.7	1,378.4	44.5
25	955.9	1,852.6	48.4
50	1,093.8	2,205.4	50.4
100	1,228.0	2,555.9	52.0
200	1,359.5	2,905.4	53.2

Site 14. Forest in the catchment of the Mokondu River in Zambia. Comparison with and without the forest at the location of GRDC flow gauge 1591100 (i.e., Mokondu at Chivata Village).

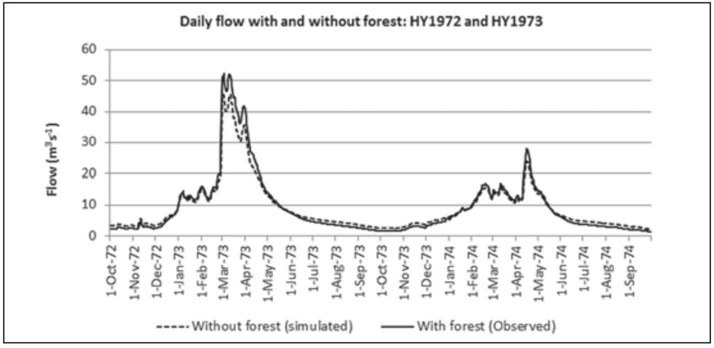
Total catchment area:	3,699 km^2
Area of forest:	3,168 km^2 (58.6% of total catchment)

Comparison of FDCs



Perecentile	Flow (m^{3}s^{-1})%		% difference
	with forest	without forest	
99	0.7	1.6	117.1
95	1.8	2.8	56.9
90	2.5	3.5	41.3
75	4.3	5.3	24.6
50	10.1	9.9	-1.7
25	22.9	20.1	-12.1
10	43.9	37.9	-13.7
5	56.2	52.8	-6.2
1	71.5	91.9	28.6

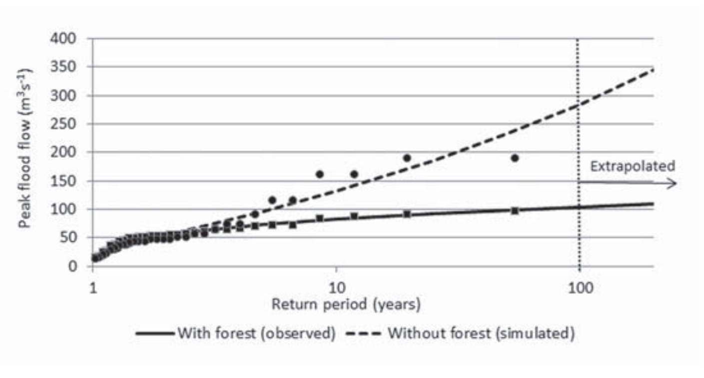
Example hydrographs



Comparison of low-flow statistics

	BFI	Mean annual minimum (m^{3}s^{-1})	
		1-day	10-day
With forest	0.475	2.18	2.35
Without forest	0.502	3.03	3.23

Comparison of flood frequency curves



Return period (years)	Flood magnitude (m^{3}s^{-1})		% reduction
	with forest	without forest	
1.1	29.5	15.4	-91.6
1.5	48.0	40.8	-17.6
2	56.8	54.4	-5.0
5	74.0	96.7	23.5
10	82.9	132.0	37.2
25	92.5	185.6	50.3
50	98.7	232.4	57.5
100	104.2	285.4	63.5
200	109.3	345.3	68.3

Site 15. Forest in the catchment of the Luakela River in Zambia. Comparison with and without the forest at the location of GRDC flow gauge 1591237 (Luakela at Sacibondo).

Total catchment area: 632 km^2
Area of forest: 51.3 km^2 (8% of total catchment)

This site was dropped from the final analyses.

Site 16. Forest in the catchment of the Gwayi River in Zimbabwe. Comparison with and without the forest at the location of FRIEND flow gauge 63351138 (Gwayi at Dahalia Control Section).

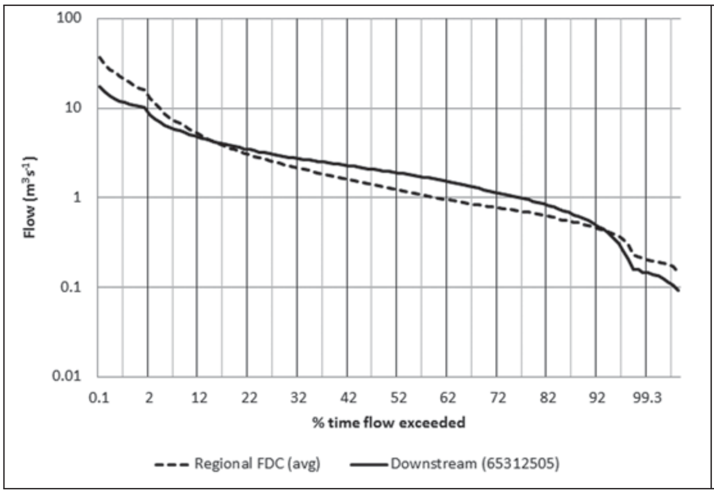
Total catchment area: 20,371 km^2
Area of forest: 7,248.5 km^2 (35.8% of total catchment)

This site was dropped from the final analyses.

Site 17. Forest in the catchment of the Luchelemu River in Malawi. Comparison with and without the forest at the location of FRIEND flow gauge 65312505 (i.e., Luchelemu at Mazambe).

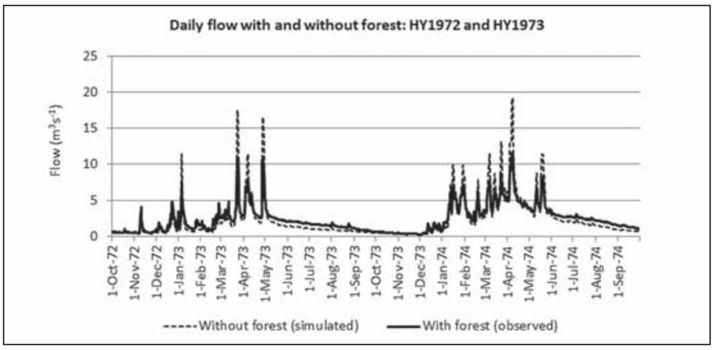
Total catchment area:	261 km^2
Area of forest:	244 km^2 (93.5% of total catchment)

Comparison of FDCs



Perecentile	Flow (m^3s^{-1})%		% difference
	with forest	without forest	
99	0.16	0.23	45.7
95	0.36	0.40	11.1
90	0.57	0.49	-13.6
75	1.05	0.73	-30.6
50	1.96	1.28	-34.4
25	3.17	2.70	-14.7
10	5.08	5.81	14.4
5	6.51	8.73	34.0
1	10.3	16.2	57.4

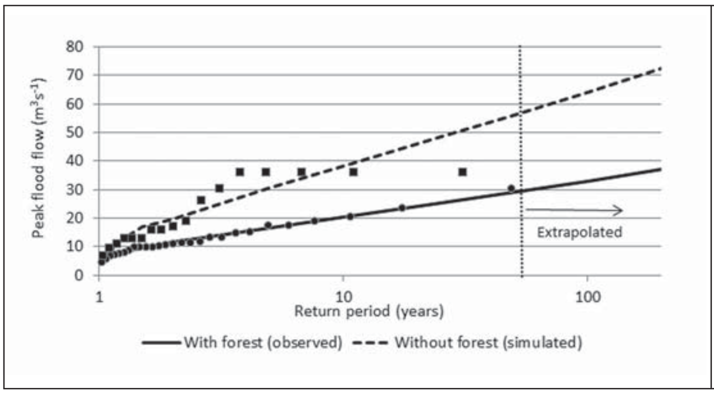
Example hydrographs



Comparison of low-flow statistics

	BFI	Mean annual minimum (m^3s^{-1})	
		1-day	10-day
With forest	0.589	0.552	0.628
Without forest	0.521	0.465	0.508

Comparison of flood frequency curves



Return period (years)	Flood magnitude (m^3s^{-1})		% reduction
	with forest	without forest	
1.1	6.5	7.9	17.7
1.5	9.6	17.0	43.3
2	11.7	19.7	40.6
5	16.8	30.6	45.1
10	20.4	38.3	46.7
25	25.3	48.5	47.8
50	29.1	56.2	48.2
100	33.1	64.2	48.4
200	37.3	72.4	48.5

Site 18. Forest in the catchment of the Bubi River in Zimbabwe. Comparison with and without the forest at the location of FRIEND flow gauge 63351139 (i.e., Bubi at Lupane).

Total catchment area: 2,906 km^2
Area of forest: 1,041 km^2 (35.8% of total catchment)

This site was dropped from the final analyses.

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