IWMI Research Report

166

Evaluating the Flow Regulating Effects of Ecosystems in the Mekong and Volta River Basins

Guillaume Lacombe and Matthew McCartney

International Water Management Institute

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Research Program on Water, Land and Ecosystems

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Front cover photograph shows rice fields and forest near Vang Vieng, Lao PDR (*photo*: Matthew McCartney, IWMI).

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Project

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Contents

Acronyms

CRU	Climatic Research Unit
FDC	Flow Duration Curve
ITCZ	Inter-Tropical Convergence Zone
MRC	Mekong River Commission

Summary

Natural and agrarian ecosystems regulate river flows by storing and releasing water between seasons. By smoothing flood peaks and enhancing dry-season flows, they protect human populations against the destruction and hardship caused by floods and water shortage. A method to quantify the impact of ecosystems on flow regimes has been developed and tested in the Volta and Mekong river basins: two basins in which people's livelihoods are particularly dependent on river water. Instead of complex physical models, the approach utilizes weighted least square regressions to derive multivariate power-law models that predict a range of flow percentiles from catchment characteristics, including geographic, geomorphologic, climatic, soil and land cover features. Step-wise and best subset regressions were used concurrently to select the model variables that best predict flow metrics observed in several gauged sub-catchments. Maximizing the prediction R-squared (R^2_{pred}), computed by leave-one-out cross-validations, ensured parsimonious, yet accurate, relationships. In a general context of data scarcity, typical of tropical areas, these power-law models enable the derivation of flow duration curves anywhere along the tributaries of the Mekong and Volta rivers. The models, which perform reasonably well (most R^2_{pred} > 90%), allow the hydrological consequences of modified paddy area and forest cover to be determined. In the Mekong River Basin, extending paddy areas results in a decrease in downstream low flows. In the Volta River Basin, the conversion of forests to crops induces greater downstream flood flows. A physical interpretation of the model structure was possible for most of the resulting relationships, thus providing an opportunity to increase our understanding of the effects of different ecosystems on flow. Basin development planners, who tend to neglect flow-related ecosystem services, should take these relationships into account. Data limitations meant that the effect of wetlands on downstream river flow could not be determined in either basin. There is a need for more data collection and research for this particular ecosystem.

Evaluating the Flow Regulating Effects of Ecosystems in the Mekong and Volta River Basins

Guillaume Lacombe and Matthew McCartney

Introduction

Research has been conducted to determine the flow regulating effects of ecosystems in the Mekong and Volta river basins. The research conducted built on an earlier study, *Factoring the role of ecosystems in the decision-support system of the Zambezi River Basin*, which developed a method for quantifying the flow regulating effects of wetlands, floodplains and forests in the Zambezi River Basin (McCartney et al. 2013).

The research was predicated on the fact that ecosystems, such as wetlands and forests, influence the hydrological cycle by affecting rates of infiltration and evapotranspiration, and by modifying how water is transmitted and stored in a basin (Bruijnzeel 1996; Bullock and Acreman 2003). Although with little scientific verification, a function widely attributed to forests and wetlands is the natural regulation of river flow: reducing floods and increasing dry-season baseflows. This 'natural' flow regulation is widely perceived as an 'ecosystem service' that brings significant benefits to people and society: reducing flood damage and increasing water availability during dry periods. In recent years, this has led to the suggestion that natural ecosystems should be considered as 'natural infrastructure', and more closely incorporated into decision-making processes pertaining to water resources planning and management (Emerton and Bos 2004). However, the lack of a trusted evidence base, and uncertainty in quantifying either a reduction in flood risk or increases in baseflow at a given location are key constraints to incorporating natural solutions into water resources planning and management.

The hydrological research conducted in the previous study (McCartney et al. 2013) was a first attempt to develop a pragmatic method for quantifying the flow regulating functions of floodplains, forests and headwater wetlands. Combining elements of hydrological regionalization with spatial interpolation of streamflow records, the method developed utilized observed streamflow records and flow duration curves[1] (FDCs) to derive a simulated time series of flow in the hypothetical situation that an ecosystem is absent. This can then be compared (using standard hydrological techniques) with an observed time series (measured downstream of the ecosystem) to evaluate the impact of that particular ecosystem on both high and low flows.

The method was developed using data obtained from 102 flow gauging stations with more than 25 years of daily flow data, and applied at 16 locations in the Zambezi River Basin. Results were generally consistent with other research in southern Africa, and indicate that the different ecosystems of the Zambezi affect flows in different and complex ways. Broadly: i) floodplains decrease flood flows and increase low flows; ii) headwater wetlands increase flood flows and decrease low flows; iii) forests of indigenous '*miombo*' trees, when covering more than 70% of the catchment, decrease flood flows and decrease low flows. However, in all the cases, there were examples which produced contrary results, and simple relationships between the extent of an ecosystem type within a catchment and the impact on the flow regime were not found.

As acknowledged in McCartney et al. (2013), there are several limitations in the method developed:

1. The method attempts to determine the flow regime in the absence of specific

[1] A flow duration curve (FDC) shows the relationship between any given discharge and the percentage of time that flow is equalled or exceeded (Shaw 1984).

ecosystems as if this was the only difference between the catchments 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.

2. Lack of data meant that an arbitrary, rather *ad hoc,* approach had to be used to determine the reference conditions on a case-by-case basis. As a result, the method is ultimately subjective.
3. The method makes no allowance for changes in mean annual discharge. The mean discharge of the simulated 'without ecosystem' approach was assumed to be the same as that of the 'with ecosystem' approach. 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. However, without knowledge of how the mean flow is affected by the presence of the ecosystem, it was not possible to modify the mean flow.

Overall, the previous study concluded:

> *"…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."* (McCartney et al. 2013).

Against this background, the original intention of the research conducted for the current study was to verify the applicability of the method derived in the Zambezi, through application in the Mekong and Volta river basins. However, soon after initiating the study it became clear that, in comparison to the Zambezi, there are relatively few gauging stations with long daily flow records in either the Mekong or the Volta river basin. Consequently, it was decided to modify the approach.

One option considered was the application of a rainfall-runoff model. Such models can be used in different ways. One possibility is to calibrate the model using data prior to land-use change and then use the model as a 'virtual control' in conjunction with rainfall observed after the land-use change, in order to reconstitute runoff as if no change in the catchment had occurred (e.g., Lacombe et al. 2010). Underlying assumptions of this approach are that the model adequately simulates the full range of available rainfall-runoff responses, and that the catchment is stationary before and after the land-use change. Another approach involves the application of a spatially-distributed, physically-based model, in which land use is explicitly incorporated in the model parameterization. It is then possible to evaluate the effect of any change in land cover by modifying the model parameters. In this way, different land-use scenarios can be simulated directly (e.g., Homdee et al. 2011). However, this requires a very good understanding of the hydrological processes occurring under different land covers, including the effect of land conversion on soil surface properties (Lacombe et al. 2015).

Both approaches are constrained, if there are limited data for model calibration and validation. In our case studies, land-use data were scarce and understanding of the biophysical processes affecting flow generation is very limited. Consequently, it was not possible to undertake such detailed hydrological modelling. The most reliable data are flow and rainfall. For this reason, the approach developed relies predominantly on these data, and attempts to detect relationships with other environmental characteristics without pre-assumptions.

As with the previous Zambezi study, the method is based on the derivation of FDCs. However, in the current study, rather than basing FDCs on 'reference catchments' (see McCartney et al. 2013), the FDCs were derived from statistical relationships that linked different flow percentiles to specific catchment characteristics. In this way, it was possible to derive FDCs at ungauged sites, and the equations developed were then used to determine the FDCs in situations ‘without’ the ecosystem of interest. Such techniques rely on the fact that the shape of any FDC is largely a function of the catchment characteristics that govern the partitioning of precipitation into interception, infiltration and rapid runoff, as well as subsurface storage, delayed drainage and evaporation.

Such approaches have been used elsewhere (Homa et al. 2013; Castellarin et al. 2013), and empirical evidence from around the world indicates that the catchment characteristics that determine the shape of the FDC typically relate to climate, geology, soil depth and permeability, vegetation cover dynamics and catchment geomorphology. Of particular interest to the current study is that the presence and absence of specific landscape features (e.g., wetlands) have been shown to affect the shape of the FDC in some circumstances. Past studies developed in other parts of the world (Blöschl et al. 2013; Salinas et al. 2013) have demonstrated that such features can be incorporated into statistical tools, linking points on the FDC to catchment characteristics.

Compared to the method developed in the Zambezi River Basin, the current study has two advantages (i.e., points 2 and 3 above): (i) reference catchments are not required; and (ii) the impact of an ecosystem on mean annual flow can be evaluated. For these reasons, the new approach is considered to be less subjective.

This report summarizes the research conducted. To provide context, both the Mekong and the Volta river basins are described briefly in the next section. The report then provides a detailed description of the method developed to estimate the impact of catchment features/ ecosystems on river flow. The results obtained for both basins are presented. The strengths and weaknesses of the method are discussed.

Description of the Basins

The Mekong

The Mekong is the world’s 12th longest river, flowing approximately 4,350 km through three provinces of China, and continuing into Myanmar, Lao People’s Democratic Republic (Lao PDR), Thailand, Cambodia and Vietnam before discharging into the South China Sea. The basin of the Mekong River drains a total land area of 795,000 km^2 from the eastern watershed of the Tibetan Plateau to the Mekong Delta. Mean annual flow is 457 km^3, which is equivalent to a runoff depth of 600 mm y^{-1} (MRC 2005).

The climate of the Mekong River Basin is dominated by the monsoon, which generates wet and dry seasons of more or less equal lengths. The southwest monsoon generates the wet season, which usually lasts from May until late September or early October. Tropical cyclones occur over much of the area during August and September, and even October (in the Mekong Delta). The northeast monsoon brings lower temperatures from China and causes dry weather in the Lower Mekong River Basin (i.e., the portion of the Mekong River Basin south of China) from late October until April. Mean annual rainfall is significantly different between the east and west banks of the Lower Mekong River. Rainfall of more than 2,500 mm y^{-1} occurs in the western mountain regions of Lao PDR. In contrast, typically, less than 1,000 mm y^{-1} of rainfall occurs in the Khorat Plateau in Northeast Thailand.

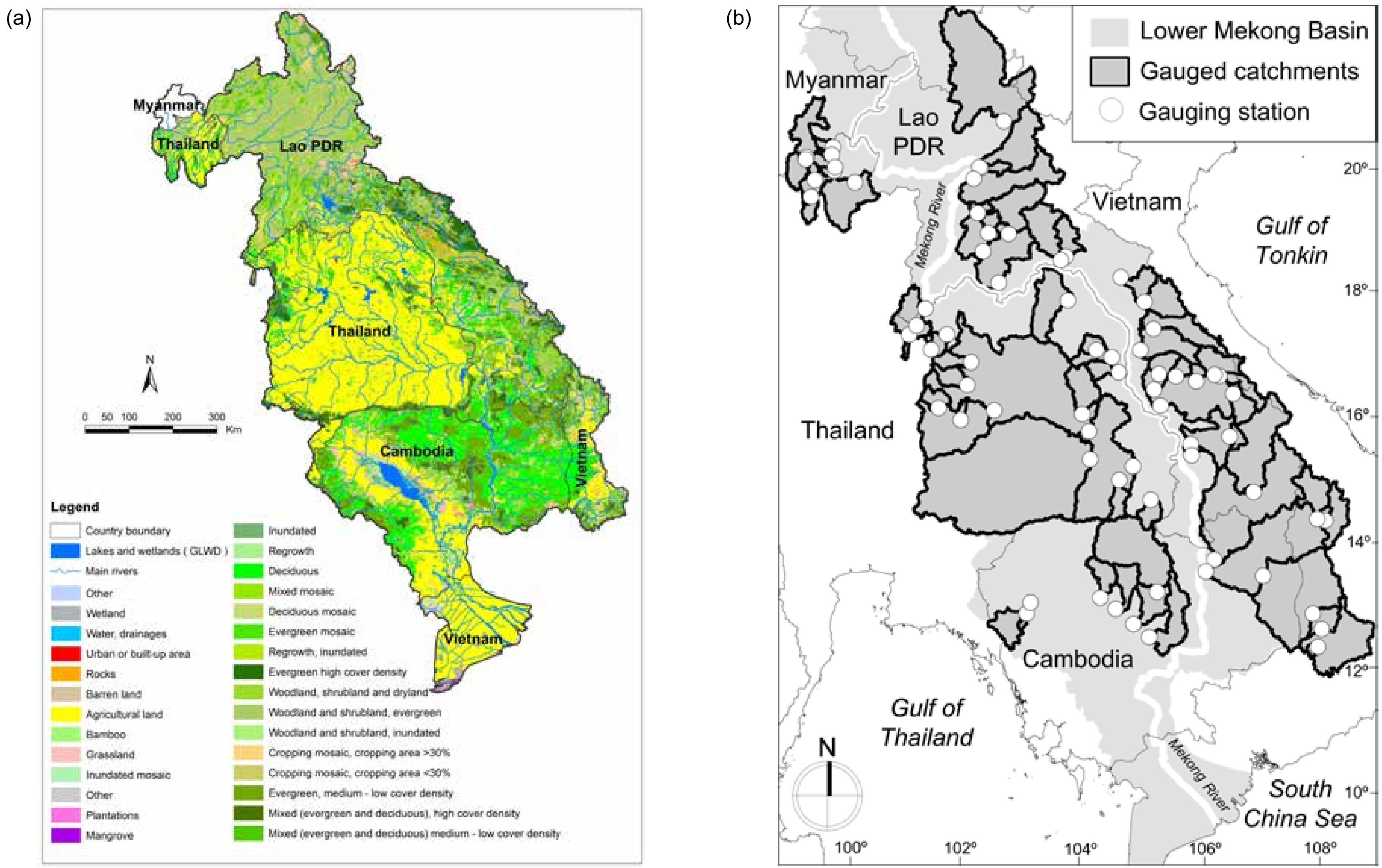
The Tibetan Plateau, where the Mekong River originates, is predominantly covered by alpine grass and rangeland. Below the tree line, at approximately 4,000 m, needle-leaved forest formations and shrubland become dominant, which increasingly give way to broad-leaved, evergreen forests and woodlands from elevations of 2,000-2,500 m downwards (Figure 1). However, in the more densely populated southern part of Yunnan Province and northern Lao PDR, in particular, large extents of these evergreen forests have been degraded by practices of shifting cultivation and other large-scale human disturbance, resulting in very heterogenic patterns of forests and forest regrowth interspersed with patches of shrubland, grassland and cropland. The land cover distribution in the lowlands of Lao PDR and Cambodia shows lower proportions of evergreen vegetation, but higher distributions of cropland, cropland/vegetation mosaics, and dry-deciduous, broad-leaved wood and scrublands. Intensively cultivated areas, mainly rice, are concentrated in the Mekong Delta, lowlands surrounding the Tonle Sap Lake and in the extensive plains of the Khorat Plateau in Thailand. In the Mekong Delta, double- and triple-season rice paddies, orchard cultivation, aquaculture, coastal mangrove forests and a mixture of the latter, known as integrated shrimp-mangrove farming systems, dominate (Leinenkugel et al. 2013).

Across much of the Mekong region, investment in land, including foreign direct investment, has been promoted as an effective development tool by several governments. For example, in Lao PDR, the establishment of policies and regulatory frameworks that are favorable to land- and resource-intensive investment has resulted in a rapid increase in the area of land granted for development. Excluding mining, land deals totalling 1.1 million hectares (Mha) (ca. 5% of the national territory of Lao PDR and an area greater than the total area under rice cultivation) have been recorded (Schönweger et al. 2012). A range of products are cultivated or extracted from lands under investment: rubber, teak, eucalyptus, cassava and sugarcane. Hence, large-scale land cover changes are occurring throughout the region. Many secondary forest formations and shrublands in the highlands of Lao PDR, which play an important role in securing the livelihoods of local people (Heinimann 2006), have been converted to mono-species rubber plantations which compete with food crops and only provide a fraction of the ecosystem services associated with natural forests.

Water resources of the Mekong region are undergoing significant development, particularly for hydropower, and also for water diversion, water supply and irrigation. Besides hydropower dams, many of the weirs and dams that already exist on the rivers in the Mekong region are for irrigation. Countries in the Mekong region continue to see irrigated agriculture as a central pillar of rural development, and withdrawals for this purpose dominate water use in the region. In the Lower Mekong River Basin, the irrigated area (ca. 1.2 Mha) is currently less than 10% of the total agricultural area (15 Mha). There are plans to increase dry-season irrigation by 50% (i.e., to 1.8 Mha) over the next 20 years. Lao PDR plans to expand irrigation from about 100,000 ha (i.e., 4,000 small- to medium-scale schemes, mostly pumping water directly from rivers) to over 300,000 ha. Major irrigation expansion is being studied in Cambodia, linked to investments in flood control in the undeveloped Cambodian delta and to hydropower development elsewhere. Mainstream water transfers have long been considered by Thailand to complement national approaches to alleviate drought in the northeast of the country.

The Mekong River Basin supports the livelihoods of a population of over 70 million people. Climate variability and, in particular, floods and droughts have a major effect on the livelihoods of many of these people. The severe economic, social and environmental impacts of droughts are confirmed by a growing level of vulnerability among people living in the affected areas. For example, millions of farmers and low-income earners were affected by the drought in 2004, which caused considerable agricultural losses in Northeast Thailand and Cambodia, a significant reduction in rice crop in Lao PDR and critical levels of saline intrusion in the Mekong Delta.

FIGURE 1. (a) Land use, and (b) location of the 65 gauging stations in the Lower Mekong River Basin.



Source: (a) GlobCover 2009 (Bontemps et al. 2011), and (b) Lacombe et al. 2014b.

Note: GLWD – from the Global Lakes and Wetlands Database (GLWD).

Unlike floods, which reach a high level of severity within relatively short time periods, droughts develop more slowly over periods of several months and within certain regional areas. However, once established, the economic, social and environmental consequences of droughts pose a serious threat to those who rely on secure water supplies, including farmers, fisherfolk and domestic households.

The role of floods is much more complex than that of droughts, because, in addition to costs, floods also bring significant benefits for both ecology and agriculture. For example, in the Lower Mekong River Basin, the annual costs of flooding (mainly related to damage to infrastructure and crops) equates to an annual average of USD 60-70 million. In contrast, the benefits of floods (associated primarily with fisheries and agriculture) are estimated to average approximately USD 8-10 billion annually (MRC 2009). Of course, the spatial distribution of costs and benefits is very uneven, with benefits, to a large extent, being realized in the lower part of the basin (i.e., the delta and the Cambodian floodplain). The costs are generally associated with flooding further upstream, particularly as a consequence of flash floods on tributaries (MRC 2009).

The impact of floods and droughts (positive and negative) are influenced by natural ecosystems in the basin. The significant seasonal variation in water levels in the river (typically wet-season levels are 8-10 m higher than that in the dry season along the main stem and main tributaries) creates a rich and extensive series of floodplains, backwaters, swamps and other wetlands in the basin. Many rural livelihoods are founded on the integrated use of a wide range of natural resources, adapting to the seasonal changes of flooding and recession. Consequently, the hydrological functioning of natural ecosystems is intimately tied to people's livelihoods. As built infrastructure in the basin increases, particularly as more hydropower dams are constructed, and flow regimes are altered, many of these important ecosystems are under threat.

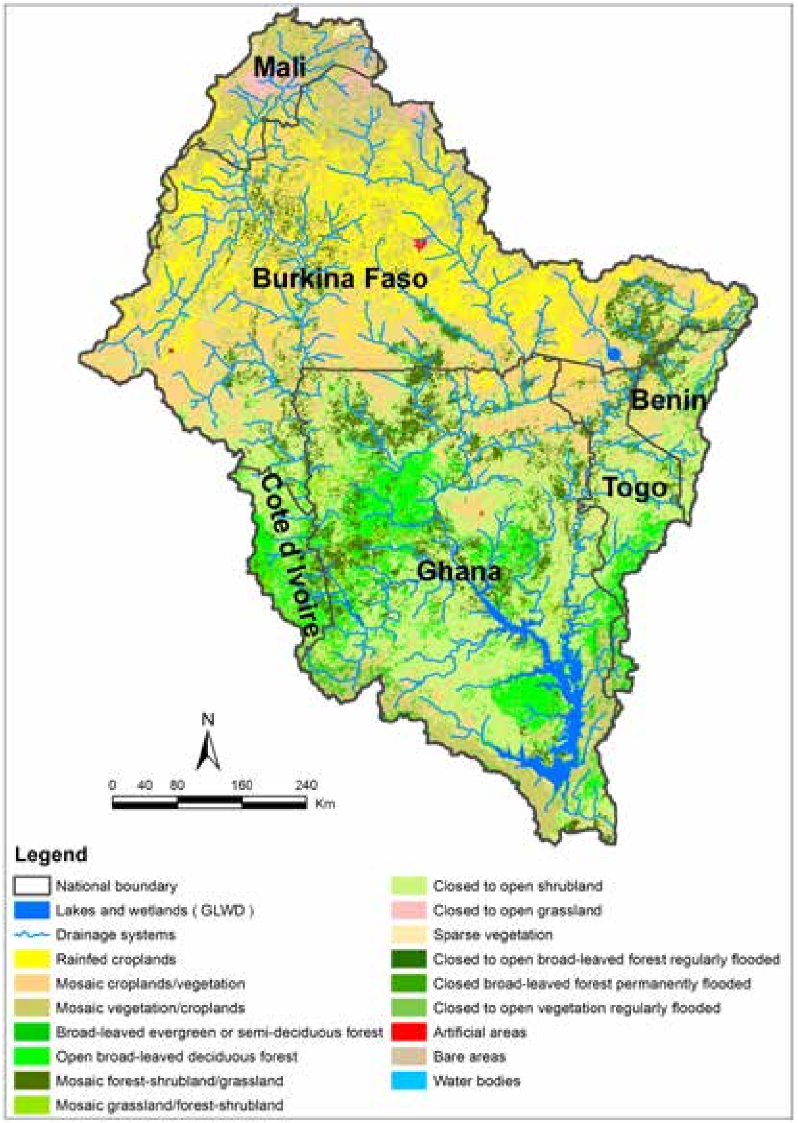
The Volta

Although just one-third of the Mekong River in terms of length, the Volta River (1,600 km) drains an area of 403,000 km^2, which represents half of the surface area of the Mekong River Basin. The Volta River Basin is shared by six countries in West Africa. It lies mainly in Ghana (42%) and Burkina Faso (43%) with the remainder in Benin, Cote d'Ivoire, Mali and Togo (Figure 2). The river, one of Africa's most important in terms of length and discharge, comprises three major tributaries corresponding to large sub-catchments: the Black Volta (147,000 km^2), White Volta (106,000 km^2) and the Oti (72,000 km^2), which come together to form the Lower Volta (325,000 km^2). The total annual flow varies considerably, but is approximately 40,400 Mm^3, on average (Andah et al. 2004), which is equivalent to a runoff depth of 100 mm y^{-1}.

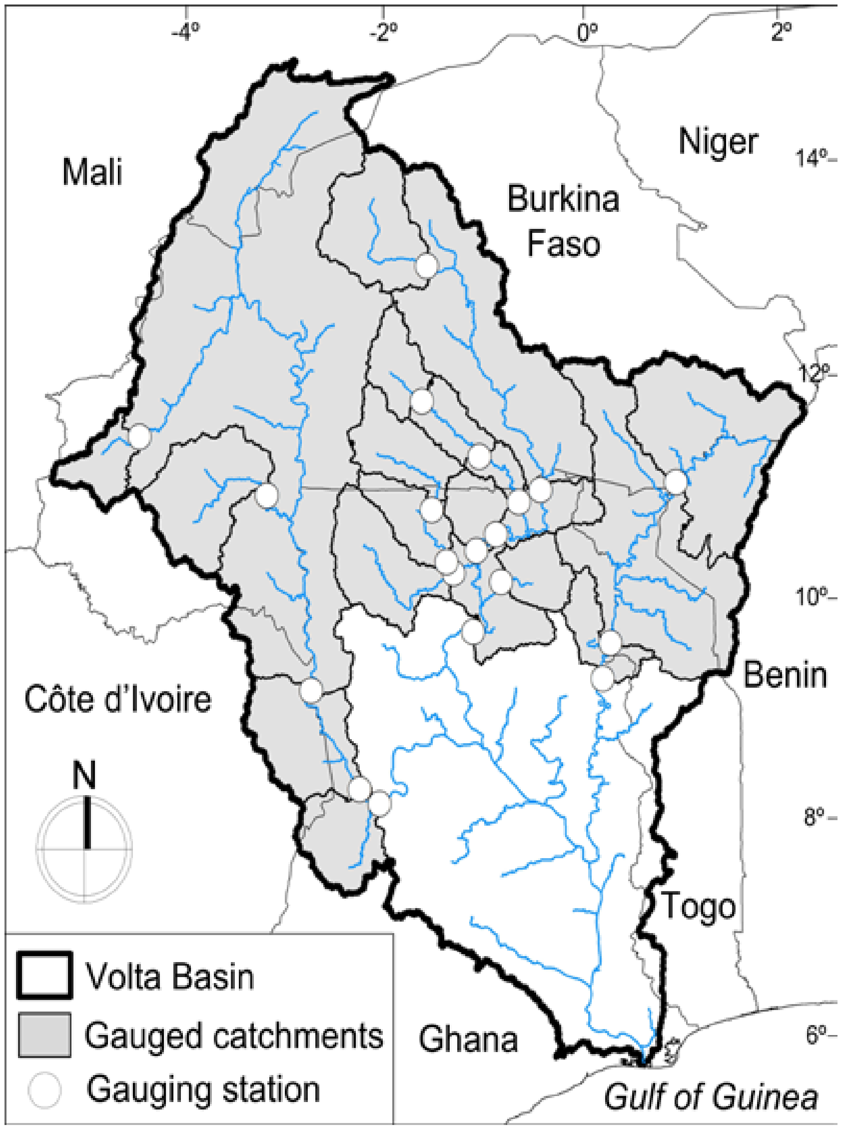
Climatically, the basin is dominated by the rain-bearing, southwesterly tropical maritime air mass and the dry, northeasterly tropical continental air mass (Dickson and Benneh 1988). The two air masses meet at the Inter-Tropical Convergence Zone (ITCZ). At any location, the rainy season begins when ITCZ has passed overhead moving north and ends with its southwards retreat. Consequently, there is a general tendency for rainfall to decrease from the south to the north, though this general effect is disrupted in a few places as a consequence of local relief. Between May and August (i.e., the West African monsoon), the ITCZ moves to the north and the entire basin lies under the influence of the tropical maritime. These months yield approximately 75% of the total annual rainfall. In the vicinity of the coast, rainfall is approximately 1,500 mm y^{-1} and bimodal, falling between May and October, with a short dry season in July/August, separating two peaks (Dickson and Benneh 1988). The two rainfall peaks tend to disappear northward, and in the northern part of Ghana, the rainfall distribution is uni-modal and averages approximately 500 mm y^{-1}. In addition to seasonality, inter-annual variability is considerable (Nicholson 2005).

Figure 2. (a) Land use, and (b) location of the 20 gauging stations in the Volta River Basin.

(a)



(b)



Source: (a) GlobCover 2009 (Bontemps et al. 2011), and (b) created as part of this study.

Note: GLWD – from the Global Lakes and Wetlands Database (GLWD).

Grassland is the dominant land cover throughout the basin, ranging from 76% of the delta catchment in the south to 98% of the Arly catchment in the north. As in the Mekong, natural ecosystems, wetlands, floodplains and forests (though much degraded) influence the basin hydrology. Within Burkina Faso, wetland areas are not extensive, but there are floodplains along the major tributaries of the Volta River. It is estimated that, within Ghana, there are at least 238,600 ha of swamps and floodplains on tributaries flowing into Lake Volta (Hughes and Hughes 1992).

Water resources in the basin have come under increasing pressure in recent years. Population growth in Ghana and Burkina Faso has resulted in larger abstractions to meet increasing water demand (van de Giesen et al. 2001). Population is projected to reach 34 million in 2025, up from 18.6 million in 2000 (Biney 2010). As in the Mekong, much of the agriculture in the basin is rainfed, and thus highly susceptible to rainfall variability, floods and droughts. River flows are extremely sensitive to precipitation (Andreini et al. 2000).

Floods in northern Ghana in 2007, particularly along the White Volta, are reported to have affected more than 275,000 people with many of them being displaced from their homes. The flooding also damaged farmland and resulted in the loss of crops. It is estimated that more than 12,200 ha of farmland were ‘washed away’, and some 160,000 metric tonnes of food was lost as a consequence of the flooding and the drought that immediately preceded it (IRIN 2007). The vagaries of rainfall influence not only livelihoods and food security but also economic development. It is anticipated that climate change, in conjunction with increasing population, may aggravate the situation (Lacombe et al. 2012). Against this background, there are plans to build more dams to increase electricity production and expand irrigation in the basin.

Method

Detecting and quantifying the flow regulating effects of ecosystems is challenging in data-scarce areas such as the Mekong and Volta river basins, where accurate and sufficiently long records of land use and land cover are limited. In most cases, only one remote sensing product is available for a particular date, making time comparison of land use and flow for correlation analyses impossible. An alternative option is to use a statistical approach to assess the relationship between human basin modifications and the resulting impact on flow. Instead of exploring basin modifications over time, it can be easier to make the comparison between gauged basins – with different land cover – over the same period. Then, if the statistical relationships are valid and sufficiently strong, the spatial variability of flow (i.e., inter-basin variability) can be attributed to the differences in the catchment characteristics.

Multiple regression analyses determine linear or log-linear relationships between a dependent variable (in this case, flow percentiles) and independent variables (in this case, catchment characteristics). Flow variables can be correlated to more than one explanatory variable at the same time. For example, mean annual flow may be positively correlated to rainfall, catchment area and the mean catchment slope. Consequently, it is in correct to derive simple correlations between the variable and a single catchment characteristic. Rather, multiple regression techniques, which enable variables with statistically significant explanatory power to be identified, must be applied. Multiple linear regressions enable the statistical characterization of these correlations, and provide the opportunity to identify the causal links between catchment characteristics and catchment hydrology. Knowing that catchment alterations, such as land cover change, will affect low flow and high flow differently, it is important to apply the multiple regression analyses to a wide range of flow percentiles. This way, it is possible to observe how the environmental characteristics of a catchment determine the shape of the corresponding FDC. Following the method proposed by Homa et al. (2013), we developed a two-step approach:

- Derivation of a set of multiple linear regression models to estimate a range of daily flow percentiles from a number of catchment characteristics, including the area of natural ecosystems and land cover types (i.e., forests, crops).
- Use of these relationships to determine what the FDC would have been if the catchment areas covered by each land cover type were modified by setting the relevant area to different values in the regression models.

Relatively simple regression approaches have shown value for determining flow percentiles in data-scarce regions of the world (Hrachowitz et al. 2013). Since a power-law is more suitable for environmental processes (hydrological variables are not normally distributed and highly skewed) than a linear relationship, we used equation (1) to estimate a flow metric *q* from m catchments with characteristics X_i (i=1,…, m). A logarithmic transformation of equation (1) results in a log-linear model (equation [2]), where coefficients β_i (i=1,…, m) can be determined by multiple linear regressions. It should be noted that the original linear form of the equation (without logarithmic transformation) was first tested and proved to underperform, compared to the multiplicative version requiring logarithmic transformation.

$$q = \exp^{\beta_0} \cdot X_1^{\beta_1} \cdot X_2^{\beta_2} \cdots X_m^{\beta_m} \cdot v \qquad (1)$$

$$\ln(q) = \beta_0 + \beta_1 \cdot \ln(X_1) + \beta_2 \cdot \ln(X_2) + \\ ... + \beta_m \cdot \ln(X_m) + \varepsilon \qquad (2)$$

β_0 is a constant. v (equation [1]) and ε (equation [2]) are the log-normal and normally distributed errors (or residual) of the models, respectively. The natural logarithm (ln) being defined for strictly positive values only, catchment characteristics X_i and flow q with possible zero values are incremented by one prior to being used in the regression analysis (Homa et al. 2013). In these cases, X_i and/or q should be replaced by X_i+1 and/or q+1, respectively, in equations (1) and (2). For each predicted flow percentile q of the FDC, selection of the variables X_i (i.e., catchment characteristics) with the highest explanatory power and calculation of their respective coefficients β_i was performed by weighted least squares regressions applied to n observations q_j (j = 1, ..., n) of q and their respective m catchment characteristics X_{ij}. A description of the approaches used to calculate the dependent variables q_j and the independent variables X_{ij} is presented in the section *Data*.

Unlike ordinary least square regressions treating the n observations of q_j equally, weighted least square regression (Tasker 1980) enables the varying number k_j of hydrological years (April 1 - March 31 for both basins) used to calculate each flow statistic q_j and its associated climate characteristics to be taken into account. Values of q_j derived from a greater number of hydrological years are more precise (have lower variance) and thus should have a greater weight in the regression. However, this reliability decreases as the variance of q_j increases. To account for these two counteracting factors, the multiple regression analysis was performed by weighted least square regressions (Tasker 1980) using two different formulae for the Mekong and the Volta regions. In the Mekong, the following equation was used:

$$w_j = \frac{\sqrt{k_j}}{Stdev(q_j)} \qquad (3)$$

Where: $Stdev(q_j)$ is the standard deviation of q_j.

In the Volta, the computation of the weight w_j using equation (3) would have resulted in high bias caused by the high disparity in the number k_j of observations between different stations. k_j varies between 1 and 45 with a median value of 4. In addition, w_j is not computable when k_j = 1, because $Stdev(q_j)$ becomes null. For these reasons, an alternative equation was set up as follows: $w_j = k_j$. This way, the increased reliability of q_j, as the number of k_j observations increases, is taken into account.

For each estimated flow metric q_j, selection of the best set of explanatory variables X_i was guided by the combined use of the selection algorithms known as 'best subsets regression' and 'step-wise regression', both of which are widely available in statistical packages. This selection was intended to maximize the prediction R-squared (R^2_{pred}) calculated by leave-one-out cross-validations. Unlike the classical R-squared, the maximization of which can lead to model over-fitting and loss of robustness, R^2_{pred} reflects the ability of the model to predict observations which were not used in the model calibration. Maximizing R^2_{pred} generally leads to greater parsimony in the number of explanatory variables. An explanatory variable was considered to be statistically significantly different from zero if its p-value, derived from Student's t-test, was lower than 0.05.

The required homoscedasticity (homogeneity of variance) of the model residuals ε was verified by visual inspection of the residual plots. Possible multi-collinearity among the explanatory variables was controlled with the variance inflation factor (VIF), which should never exceed 8. VIFs for all explanatory variables of our models were found to never and rarely exceed 3 and 2, respectively. The influence statistic Cooks D (Cook and Weisberg 1982) was used to identify and remove outlier catchments exhibiting high influence on the estimation of the model coefficients. Removal of these outliers (between 2 and 5, depending on the flow metrics) was found to systematically increase the performance of the models. For further background on R-squared, VIF and influence statistics, refer to Helsel and Hirsch (2002).

For each gauged sub-catchment, the predicted FDC was refined using a scaling factor α ($q_{pred} = a \times q_{obs}$). The value of α was optimized to minimize the deviation between q_{obs} and q_{pred} for each flow percentile predicted with a power-law equation, where q_{obs} and q_{pred} are the observed and predicted flow variables, respectively. The value of α was optimized by maximizing the Nash-Sutcliffe efficiency criteria. This scaling factor was not intended to 'artificially' improve the predictive power of the power-law models, but rather to reduce possible bias while assessing the effect of land-use changes on FDC by altering values taken by the explanatory variables X_i of the power-law equations.

The FDCs produced using the methodology described above provide a useful overview of the impact of ecosystems/land cover on the flow regime at any given location. However, analysis of specific flow events, and determination of the cumulative impact on flow volumes, requires comparison of actual streamflow time series 'with' and 'without' specific ecosystems. To generate these time series, we took the daily flow at locations where it had been measured and converted all flows to a flow percentile. Each flow percentile was then converted back to a daily flow value using the regression models: once with the ecosystem set to the coverage actually present and once with it set to zero (e.g., rice area) or alternatively to a maximal value (e.g., forest or crop area). This approach assumes that there is no change in the frequency of specific flow events as a consequence of land-use change.

Depending on the FDCs, two types of interpolations were used to assess flow values corresponding to flow percentiles positioned between two modelled values (e.g., flow value associated with the 0.85 flow percentile was calculated by interpolating flow values corresponding to the 0.80 and 0.90 flow percentiles): fifth-order polynomial interpolation or exponential interpolation. Comparison of the two time series enabled quantification of the impact of land-use change on the catchment hydrology.

Data

It should be noted that the set of candidate explanatory variables were not exactly the same in the two river basins (cf. data on geomorphology, geography, climate, soil and land cover characteristics) – Mekong (Table 1) and Volta (Table 2). The reason for this is that data for each basin were collected over different periods of time and data availability varied between the basins. The discrepancies do not affect the results because the main objective was to observe how different classes of land cover have an impact on the flow metrics. As indicated in the section *Land Cover*, particular care was devoted to ensuring that representative land cover classes were selected as explanatory variables in each basin.

TABLE 1. List of the candidate explanatory variables (catchment characteristics) used in the multiple regression analyses for the Mekong River Basin.

Variable name	Definition	Unit	Minimum value	Median value	Maximum value
Climatic characteristics					
Rain	Median annual rainfall	mm/year	880	1,416	2,093
Geomorphological characteristics					
Area	Drainage area	km^2	207	3,278	106,748
Peri	Perimeter	km	76	401	2,090
Slop	Mean slope	%	2	15	32
Elev	Mean elevation	m	84	562	1,168
Drai	Drainage density = total stream lengths/drainage area	km^{-1}	0.09	0.13	0.17
S	Ratio of area draining south	%	21	37	45
SW	Ratio of area draining southwest	%	26	44	62
W	Ratio of area draining west	%	16	35	52
NW	Ratio of area draining northwest	%	28	41	51
Geographic characteristics (coordinates of the flow gauging stations)					
Lati	Latitude	Decimal	12.33	16.70	20.70
Long	Longitude	Degree	99.35	104.03	108.00
Soil characteristics (averaged over catchment area)					
Sdep	Mean soil depth	4-unit scale	0.00	3.07	4.00
Sste	Mean top soil texture		0.00	2.08	2.91
Land cover characteristics (ratio of catchment area coverage)					
Fore	Forest	%	3	75	98
Padd	Paddy	%	0	4	77
Wetl	Wetlands (marsh and swamp)	%	0	0	1.23

Source: Lacombe et al. 2014b.

TABLE 2. List of the candidate explanatory variables (catchment characteristics) used in the multiple regression analyses for the Volta River Basin.

Variable name	Definition	Unit	Minimum value	Median value	Maximum value
Climatic characteristics					
Temp	Median annual temperature	Degrees Celcius	27.0	28.1	29.0
Rain	Median annual rainfall	mm/year	601	917	1,075
Geomorphological characteristics					
Area	Drainage area	km^2	4,419	17,863	138,086
Peri	Perimeter	km	338	869	3,261
Slop	Mean slope	%	1.2	1.6	2.8
Elev	Mean elevation	m	184	299	416
Reli	Relief	m	16	52	99
Drai	Drainage density = total stream lengths/drainage area	km^{-1}	0.10	0.11	0.14
DDir	Drainage direction	%	0.70	0.86	1.27
Land cover characteristics (ratio of catchment area coverage)					
Fore	Forest		1.4	12.4	45.6
Shru	Shrubland		0.1	22.0	45.6
Herb	Herbaceous		0.0	0.1	10.5
NoVe	No vegetation	%	0.0	0.0	1.0
Flood	Flooded vegetation		0.0	0.0	0.2
Wate	Water bodies		0.0	0.1	0.6
Crop	Cultivated and managed lands		8.9	62.9	93.5

Discharge

The power-law models were parameterized using flow records provided by the Mekong River Commission (MRC) for the Lower Mekong River Basin, and downloaded from the GLOWA Volta databases for the Volta River Basin. In the two regions, the study sub-catchments were selected based on data availability and reliability, and on the basis that they provide records which were not subject to dam regulation.

In the Volta River Basin, out of 23 gauged sites, 20 stations were selected, based on data-quality control and data gaps. These stations had between 1 and 45 years of records, and have been maintained by either the Office de la Recherche Scientifique et Technique d'Outre-Mer (ORSTOM) (former name of the Institut de Recherche pour le Développement [IRD]) or the Council for Scientific and Industrial Research - Water Research Institute (CSIR-WRI), Ghana. In the Mekong River Basin, out of 71 gauged sites, 65 stations were selected. The streamflow time series comprised between 1 and 41 years of records with a median value of 17 years. In the two basins, records are available between 1951 and 2007. The full list of the stations with their characteristics is available in Annex A.

In order to best represent and estimate FDC, 11 flow percentiles (i.e., exceedance probabilities) were selected for prediction with the power-law models in the Lower Mekong River Basin: 0.05, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90 and 0.95. Additionally, we computed the annual minimum, maximum and mean flow - henceforth referred to as Min, Max and Mean, respectively. Since daily flow values below 1 $m^3.s^{-1}$ are not provided in the MRC database, regression models had to be computed using sub-catchments with median values of flow percentiles greater than 1 $m^3.s^{-1}$. This resulted in the removal of 15, 11, 10, 7 and 5 sub-catchments from the datasets used to compute the Min, 0.95, 0.90, 0.80 and 0.70 flow percentiles, respectively. For the Volta River Basin, 13 flow percentiles were selected for prediction with the power-law models: 0.01, 0.05, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 0.95 and 0.99. Additionally, we computed the annual mean flow.

For each sub-catchment *j* in the Volta and Mekong river basins, the value of each of these flow percentiles, and the Min, Max and Mean values were obtained by selecting the median of the k_j annual values as suggested by Vogel and Fennessey (1994). Compared to the period-of-record FDC, which indicates the percentage of time (duration) a particular value of streamflow is exceeded over a historical period, the median FDC reflects the percentage of time a particular value of streamflow is exceeded in a typical year. This second approach is particularly relevant when the start and end dates of the flow time series used to compute the flow percentiles vary a lot between the study sub-catchments. All these flow metrics (flow percentiles and Min, Max and Mean flow values) are the dependent variables *q* in equations (1) and (2).

Rainfall

Two different gridded precipitation databases were used in the Mekong and Volta river basins to derive areal daily rainfall time series for each study sub-catchment. In the Mekong, we used the high-resolution (0.25° × 0.25°), daily gridded precipitation database 'Asian Precipitation - Highly Resolved Observational Data Integration Towards Evaluation of Water Resources' (APHRODITE) (Yatagai et al. 2012) (freely available at http://www.chikyu.ac.jp/precip/ - accessed February 03, 2014), covering the period 1951-2007. In the Volta, we used the medium resolution (0.50° × 0.50°), monthly gridded precipitation database from the Climatic Research Unit (CRU) at the University of East Anglia (Harris et al. 2014), covering the period 1901-2009 and provided free by the Consortium for Spatial Information (CGIAR-CSI) (available at http://www.cgiar-csi.org/data/uea-cru-ts-v3-10-01-historic-climate-database - accessed on March 15, 2014).

Several rainfall variables were tested for correlation with each of the 11 selected flow percentiles: annual and monthly rainfall depths, rainfall depth cumulated over the n-day rainiest periods of the hydrological year (n=5, 10 and 15). Annual rainfall was found to exhibit the greatest correlation coefficients with all the flow metrics q in the Volta and Mekong river basins, and was included as the only candidate explanatory rainfall variable in the power-law models for both the Mekong and Volta river basins. Median rainfall and median flow values used in the regression analyses were derived from the same hydrological years (Tables A1 and A2 in Annex A).

Temperature

Areal temperature variables were generated following the same procedure as for rainfall using the CRU database (Harris et al. 2014). Through several correlation analyses, only annual temperature was finally selected as a candidate explanatory variable in the Volta River Basin. Temperature was not studied in the Mekong, because the new CRU database (used for the Volta) was not available at the time of the analysis.

Geomorphological and Geographic Characteristics

Several geomorphological catchment characteristics, likely to influence hydrology, were derived from the United States Geological Survey (USGS) **Hydro**logical data and maps based on **SH**uttle **E**levation **D**erivatives at multiple **S**cales (HydroSHEDS), a quality-controlled 90-meter digital elevation model (Lehner et al. 2006) (freely available at http://hydrosheds.cr.usgs.gov/index.php (accessed on March 15, 2014). These characteristics include drainage area, perimeter, mean slope, mean elevation, drainage density, drainage direction and relief. The drainage density is the cumulative length of all streams within the catchment, normalized by the drainage area of the catchment. The stream network consists of all outlet points draining an area greater than 40 km^2. This threshold value was selected to best capture the variability of drainage densities among the study sub-catchments. For the Mekong River Basin, four variables representing mean drainage directions were calculated - South, Southwest, West and Northwest. A value of 1 (or zero) meant that the sub-catchment was draining toward the named direction (or opposite to the named direction). For the Volta River Basin, drainage direction was defined slightly differently: only one variable was defined - the ratio of the number of pixels draining to the northeast divided by the number of pixels draining to the southwest. Relief is the standard deviation of all pixel elevations within each sub-catchment. A value of zero corresponds to perfectly flat, horizontal land.

The geographic coordinates of the flow gauging stations (latitude and longitude) were selected as two additional candidate explanatory variables for the Mekong River Basin (Table 1). These geospatial variables may control solar radiation that has an effect on evapotranspiration and local climate patterns influenced by the regional topography, not only in the sub-catchment itself, but also in its neighborhood.

Soil Characteristics

Due to the lack of available data for the Volta, we included soil characteristics only in the Mekong. Two soil characteristics, likely to control hydrological processes, were selected from the MRC soil database (MRC 2011): soil depth and top soil texture. A four-unit scale suggested by MRC was used for quantification. Average values for each soil characteristic and each sub-catchment were averaged by weighting each scale unit by the respective area covered in the sub-catchment.

Land Cover

Land cover percentages for land cover types in each of the study basins were derived from two different remote sensing products. In the Mekong River Basin, we used a digitized 2003 land cover map prepared by MRC (2011). Forest cover was produced by merging four forest types available as separate land cover classes in the published map: coniferous forest, deciduous forest, evergreen forest and forest plantation. The other land cover classes (wetlands and paddy) were directly available, because they correspond to distinct land cover classes on the published map.

In the Volta River Basin, we used the global land cover map GlobCover 2009 (Bontemps et al. 2011). This is a 300-m resolution global land cover map produced from an automated classification of the MEdium Resolution Imaging Spectrometer (MERIS) Full resolution (FR) time series, with 22 land cover classes. We defined seven land cover types as candidate explanatory variables: 'Crop' was produced by merging three land cover classes: rainfed crops, mosaic croplands/vegetation and mosaic vegetation/croplands. 'Forest' was the result of merging four land cover classes: closed to open broad-leaved evergreen or semi-deciduous forest, open broad-leaved deciduous forest, mosaic forest-shrubland/grassland and mosaic grassland/forest-shrubland. 'Herbaceous' resulted from merging two land cover classes: 'closed to open grassland' and 'sparse vegetation'. The land cover type 'No vegetation' was produced by merging two land cover classes: 'artificial areas' and 'bare areas'. The three other land cover types – 'flooded vegetation', 'water bodies' and 'shrubland' – correspond to single land cover classes already available in the original database: 'closed to open vegetation regularly flooded', 'water bodies' and 'closed to open shrubland', respectively.

The multiple regression analyses enabled the flow regulating effect of the land cover types that have a significant explanatory power on the flow metrics (i.e., p-value < 5%) to be selected and their associated coefficient (i.e., exponent) to be calculated. If a selected land-use type (variable X_i in equations [1] and [2]) has a positive exponent (coefficient β_i in equation [1]), it means that the flow metric q will increase as the spatial extent of that land cover type increases. A negative coefficient means that the flow metric q will decrease as the spatial extent of the land cover type increases. The absence of any land cover type as an explanatory variable in the model signifies that this (land cover type) has a negligible hydrological effect compared to other candidate explanatory variables listed in Tables 1 and 2. It is also possible to compare the respective effects of various land cover types by comparing the values of their associated coefficients in the power-law models.

Results and Discussion

The Power-law Models

Tables 3 and 4 present the results of the multiple regression analyses for the 14 flow metrics (listed in column 1) in the Lower Mekong River Basin and the Volta River Basin, respectively. Column 2 provides the value of the intercept term β_o. Columns 3 to 11 (in Table 3) and columns 3 to 12 (in Table 4) provide the coefficients β_i associated with each explanatory variable X_i included in the power-law models (cf. equations [1] and [2]). The last column of the tables indicates the performance of the models. The model performance is good in the Mekong River Basin for any flow metric: R^2_{pred}>89%. In the Volta River Basin, the model performs well for flow percentiles lower than 80%: R^2_{pred}>80%. In the two basins, the predictive power of the models declines for low flows, indicating that the explanatory variables tested in this study do not correspond to the catchment characteristics that predominantly control low flows. This suggests that more effort is needed to generate catchment characteristics suitable for multivariate low flow predictions. For the Lower Mekong River Basin, values of the explanatory variable 'Padd', and of the flow metrics 0.50, 0.60, 0.70, 0.80, 0.90, 0.95 and Min (Table 3) should be incremented by 1 for inclusion in equation (1). For the Volta River Basin, only the values of the flow metrics 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 0.95 and 0.99 (Table 4) should be incremented by 1 for inclusion in equation (1) (cf. section *Method*). As examples for the Lower Mekong River Basin, equations (4) and (5) show how to predict the 0.95 flow percentile ($q_{0.95}$) and mean annual flow (q_{mean}) using the coefficients provided in Table 3.

$$q_{0.95} = \exp^{-27.857} \times \text{Rain}^{2.698} \times \text{Peri}^{1.436} \times \text{Elev}^{0.966} \times \text{Lati}^{-1.291} \times (\text{Padd}+1)^{-0.285} - 1 \quad (4)$$

$$q_{mean} = \exp^{-18.989} \times \text{Rain}^{2.543} \times \text{Area}^{0.883} \times \text{Drai}^{1.089} \quad (5)$$

Figure 3 illustrates the performance of the power-law models by comparing observed and predicted flows in each gauged sub-catchment *j* (one plot = one sub-catchment) for some flow metrics: mean annual flow in the Mekong and the Volta river basins (Figures 3[a] and 3[c], respectively); the 0.95 and 0.05 flow percentiles in the Lower Mekong River Basin (Figure 3[b]) and the Volta River Basin (Figure 3[d]), respectively. Refer to Lacombe et al. (2014b) for further interpretations of Figures 3(a) and 3(b).

TABLE 3. Coefficients and performance of the power-law models predicting the flow metrics *q* in the Lower Mekong River Basin (cf. Table 1 for the full names of the variables). No coefficient value means that the corresponding variable was found not to have statistically significant explanatory power to predict the flow metric and therefore should not be included in the equation predicting q.

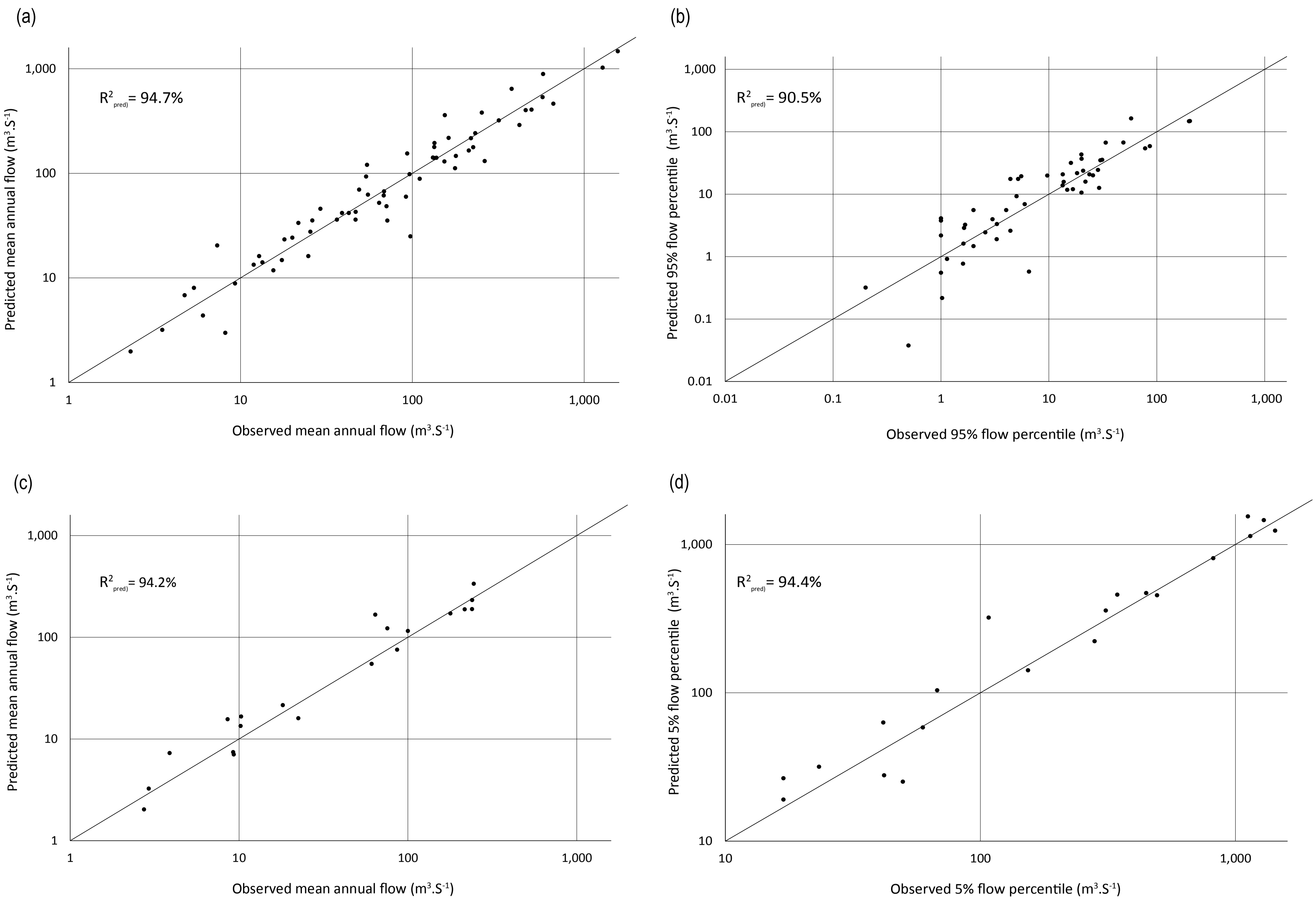
q (m^3/s)	β_0	Explanatory variables (βi, *i>0*)									R^2_{pred} (%)
		Rain	Peri	Elev	Area	Drai	Slop	Lati	Padd	Fore	
Max		1.870		-0.796	0.668	2.694	0.798	-1.423			89.1
0.05	-14.434	2.376			0.862	2.016					94.1
0.10	-21.435	2.608			0.970						93.5
0.20	-23.087	2.742			0.988						94.3
0.30	-24.135	2.519		0.335	0.992						91.8
0.40	-29.234	2.603	1.789	0.566							92.5
0.50	-31.247	2.529	1.798	0.714						0.262	92.1
0.60	-24.521	2.289	1.600	0.963				-1.526	-0.155		92.4
0.70	-24.023	2.307	1.469	1.074				-1.820	-0.155		90.7
0.80	-25.761	2.582	1.411	1.080				-1.852	-0.189		92.2
0.90	-28.562	2.613	1.467	0.844		-1.706	0.587	-2.503			89.5
0.95	-27.857	2.698	1.436	0.966				-1.291	-0.285		90.5
Min	-32.951	3.027	1.416	0.803		-2.684	0.535	-2.598			89.1
Mean	-18.989	2.543			0.883	1.089					94.7

Source: Adapted from Lacombe et al. 2014b.

TABLE 4. Coefficients and performance of the power-law models predicting the flow metrics *q* in the Volta River Basin (cf. Table 2 for the full names of the variables). No coefficient value means that the corresponding variable was found not to have statistically significant explanatory power to predict the flow metric and therefore should not be included in the equation predicting q.

q (m^3/s)	β_0	Explanatory variables (*βi, i>0*)										R^2_{pred} (%)
		Fore	Crop	Area	Peri	Reli	Slop	Drai	Elev	Rain	Temp	
Mean	-23.09	-0.354		1.223					-2.487	4.074		94.22
0.01	172	-0.694		1.132					-7.552		-40.97	91.77
0.05	186.1	-0.583		1.243					-7.371		-45.87	94.39
0.10	202.3	-0.584		1.313					-7.611		-50.67	93.74
0.20	-28.62	-0.342		1.302					-2.738	5.047		92.13
0.30	-8.622	-0.387			1.989	1.370			-1.467			96.04
0.40	88.49	-0.416		1.303		0.814			-2.512		-26.73	92.36
0.50			0.516	1.047			2.452	4.445				95.61
0.60	-5.218	0.867	2.421	0.791			3.815					91.21
0.70	-3.567	0.888	1.522		0.912		2.681					80.52
0.80		1.226	3.067	0.388			3.056					73.07
0.90	5.590	1.732	4.550				3.541					54.84
0.95	5.325	1.608	4.145				2.818					45.6
0.99	4.504	1.340	3.440				2.233					33.75

FIGURE 3. Comparison of observed and predicted flows. (a) and (b): Lower Mekong River Basin. (c) and (d): Volta River Basin.



Interpretation of the Explanatory Variables

Physical Variables

In the Lower Mekong River Basin, annual rainfall is an explanatory variable in all the models (Table 3). Coefficient values are much greater than unity (average = 2.59), indicating that an increase of x% in annual rainfall would induce a greater than x% increase in any of the studied flow metrics. Drainage area is an explanatory variable for mean annual flow and high-flow variables. The coefficients for this variable are slightly lower than 1, depicting a slight tendency for a reduction in runoff depth (i.e., specific runoff) as catchment size increases, reflecting the tendency for increased seepage in larger catchments (Pilgrim et al. 1982). In contrast, low-flow variables are better explained by the catchment perimeter rather than the catchment area. The perimeter provides information related to the shape of the catchment. For a given catchment area, a greater perimeter implies a longer time for water to reach the catchment outlet, thus explaining the positive correlation with low-flow variables. The drainage density quantifies the level of catchment drainage by stream channels. Lower drainage density corresponds to flatter land with less differentiated drainage paths. High values imply steep-sided valleys, shorter flow transfer time and a flashy (i.e., steeper) hydrograph. As would be anticipated, the coefficients of the drainage density are consistently positive and negative for high and low flows, respectively. Flow percentiles of intermediate magnitude are not influenced by the drainage density (Lacombe et al. 2014b).

In the Volta River Basin, elevation and slope are the predominant controls on high and low flows, respectively. According to the signs of these coefficients, high flows tend to decrease as elevation increases, while low flows tend to increase in steeper catchments. It is difficult to provide a physical interpretation for these behaviors. While rainfall is always an explanatory variable in the Mekong River Basin, it is only used to predict mean flow and the 20% flow percentile in the Volta River Basin, suggesting that rainfall is not the main discriminatory variable that differentiates catchment hydrology in the gauged sub-catchments of the Volta River Basin used in this study. The coefficient of other explanatory variables, not related to land cover change (i.e., drainage area, perimeter, relief, drainage density and temperature), are also difficult to explain and suggest that further research is required to better understand how the climate and the geomorphology controls flow production in the sub-catchments of the Volta River Basin.

In both the Lower Mekong and the Volta river basins, the high values of R^2_{pred} (Tables 3 and 4) could largely be attributed to mass balance considerations, i.e., they indicate that a larger catchment produces more flow. To verify if this scaling behavior actually magnifies the performance of the models, we carried out the multiple regression analyses for the Lower Mekong River Basin again, using specific runoff (in mm y^{-1}) as a dependent variable and computed the Nash-Sutcliffe efficiency coefficient based on volumetric runoff (m^3 s^{-1}) for the two sets of power-law models predicting either specific or volumetric runoff. According to this efficiency coefficient, the models predicting specific runoff were found not to outperform those described in this report. In addition, homoscedasticity of the residual of the models predicting specific runoff was more difficult to obtain compared to the models predicting volumetric runoff. The values of the variance inflation factor (VIF) associated with each explanatory variable were higher for the models predicting specific runoff compared to the models predicting volumetric runoff, revealing greater dependency between the explanatory variables. Finally, the explanatory variables of the model predicting specific runoff were found to vary a lot depending on the flow percentiles considered, thus hampering the physical interpretation of the set of equations. For all these reasons, the models predicting volumetric runoff (reported in Tables 3 and 4) were found to be more reliable than those predicting specific runoff (not included in this report). Furthermore, multiple regression, including drainage area as an independent variable, has been shown to better account for the heterogeneity of those basin attributes which are correlated to drainage area and thus reduces omitted variable bias (Farmer et al. 2015). This scaling behavior is reflected in the exponent values of the variable 'drainage area', which are different from 1 (cf. Tables 3 and 4), and by the fact that this variable is replaced by the variable 'perimeter' in the models predicting low-flow percentiles.

Ecosystem-related Variables

In both the Volta and Mekong river basins, the unavoidable time discrepancy between the dates of the flow record and the land cover maps probably weakens the relationship between hydrology and land cover. However, a few notable correlations are worth highlighting and are discussed in the following subsections.

i. Paddy fields in the Mekong River Basin

The surface ratio of paddy rice is negatively correlated to four low-flow variables (flow percentiles 0.60, 0.70, 0.80 and 0.95). One possible explanation is that the rice is irrigated and dry-season abstractions are reducing low flows. However, only a small proportion of the lowland rice in the Lower Mekong River Basin is irrigated. In this case, an alternative explanation is that the traditional practice of puddling (i.e., churning of the soil prior to transplanting) creates a hardpan layer of rice below the rice root zone, which reduces groundwater recharge, and contributes to the maintenance of ponded water and hence increased evapotranspiration from the bunded rice fields (Bouman et al. 2007).

Figures 4(a), (c) and (e) illustrate the accuracy of the power-law models to predict the FDC. Figures 4(b), (d) and (f) show the effect of paddy on low flows. When the paddy area is set to zero (this case is equivalent to replacing paddy by a land cover equal to a weighted average of all other land covers included in the studied sample of sub-catchments), low flows increase. In these examples, the difference in low flow is large because the three selected sub-catchments in Figure 4, i.e., Nam Mun, Nam Chi and Nam Mae Ing rivers, were covered by 60%, 50% and 39% of the paddy area, respectively. It should be noted that the 0.90 flow percentile is an outlier in the FDC corresponding to actual paddy coverage in figures 4(b), (d) and (f). This is likely to be attributed to the lower performance of the power-law model predicting this flow percentile, which has the second lowest value of R^2_{pred} in Table 3.

Figure 5 illustrates the effect of an expansion in the rice area on low flows at Tha Ngon in Lao PDR. Figure 5(b) compares estimated FDCs with current paddy areas to a hypothetical FDC that would correspond to an increase in the paddy area from 6% (current paddy coverage in the Nam Ngum River Basin at Tha Ngon) to 25% (projection for the next 25 years). The Nam Ngum River Basin is particularly relevant for projecting expansion in the paddy area: it is one of the most populated catchments in Lao PDR with easily accessible flat and fertile lands, including potential for paddy expansion (Lacombe et al. 2014a). Figure 5(b) shows that, even in the case of an extreme scenario of expansion in the paddy area in the Nam Ngum catchment, the effect on low flow would remain moderate.

FIGURE 4. FDC at three stations along the main tributaries of the Mekong River in Thailand. (a), (c) and (e): comparison of observed and predicted FDC in actual conditions of paddy coverage (as of 2003, date of the land cover map used in this analysis). (b), (d) and (f): comparison of FDC predicted under actual paddy coverage and no paddy coverage.

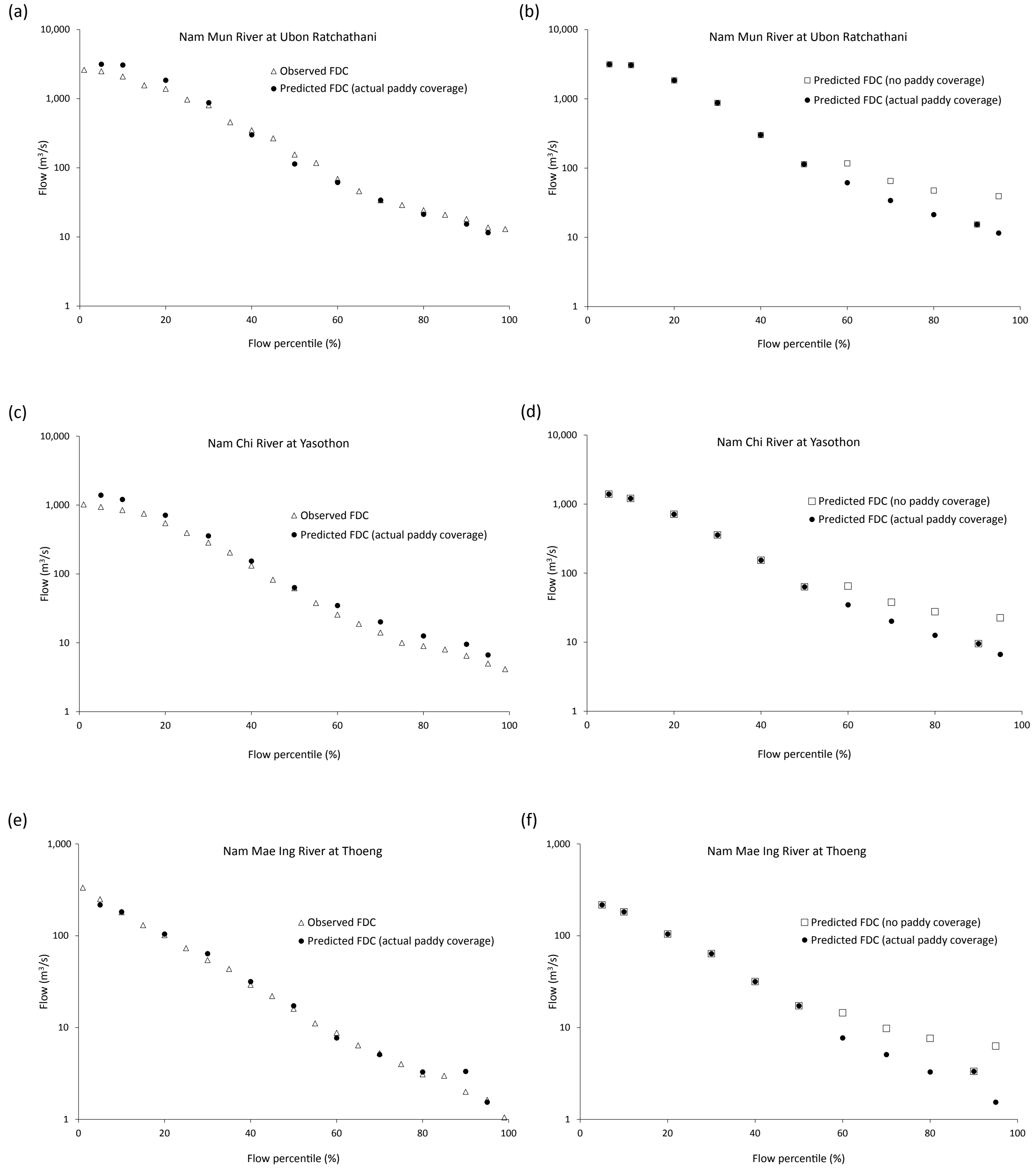
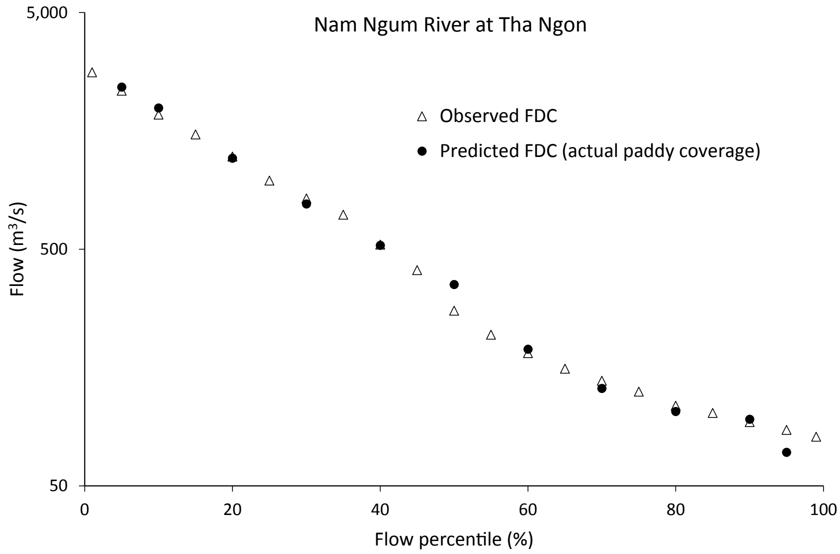
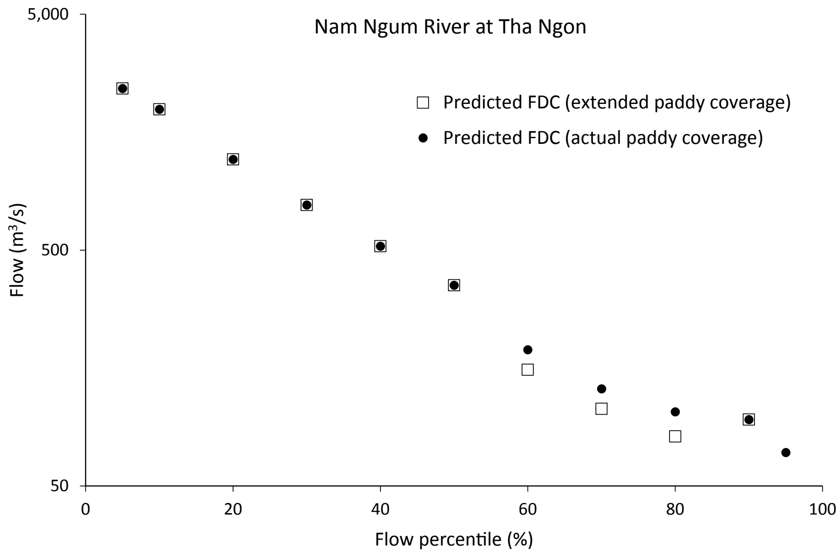


FIGURE 5. FDC of the Nam Ngum River at Tha Ngon, Lao PDR. (a) comparison of observed and predicted FDC under actual paddy coverage; and (b) comparison of FDC predicted under actual paddy coverage (6% of the sub-catchment area) and extended paddy coverage (25% of the sub-catchment area).

(a)

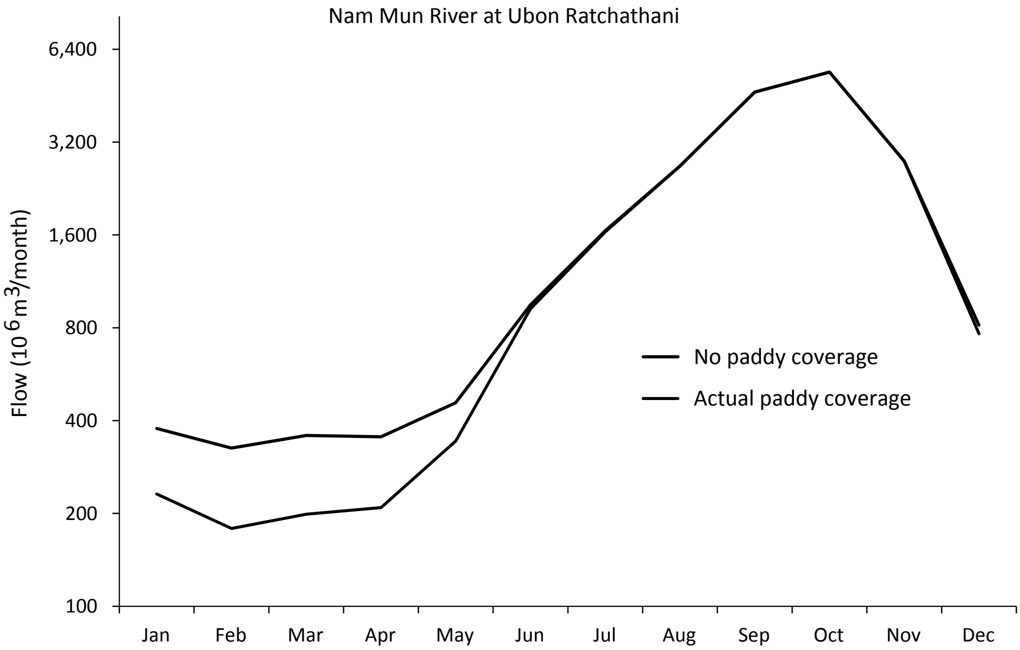


(b)



In Figure 6, the impact of lowland rainfed rice on seasonal flows is estimated in the sub-catchment of the Nam Mun River at Ubon Ratchathani in Thailand. Currently, 60% of the sub-catchment is covered with rice. Without any paddy fields in this sub-catchment, low flows would be about 200 × 10^6 m^3/month higher from January to April. Over a full year, rainfed paddy causes a flow reduction of about 800 × 10^6 m^3, which is equivalent to 12 mm over the portion of the sub-catchment covered with rice (64,049 km^2). This difference is equivalent to the difference between evapotranspiration of rice and the combined evapotranspiration of other land covers in the sub-catchment. This low value remains negligible compared to average annual evapotranspiration rates in the region (about 1,300 mmy^{-1}) (Tanaka et al. 2008). However, the hydrological effect is significant (Figure 6), due to the large size of the sub-catchment.

FIGURE 6. Average hydrograph of the Nam Mun River at Ubon Ratchathani under current conditions (with paddy) and calculated assuming the absence of paddy fields in the sub-catchment.



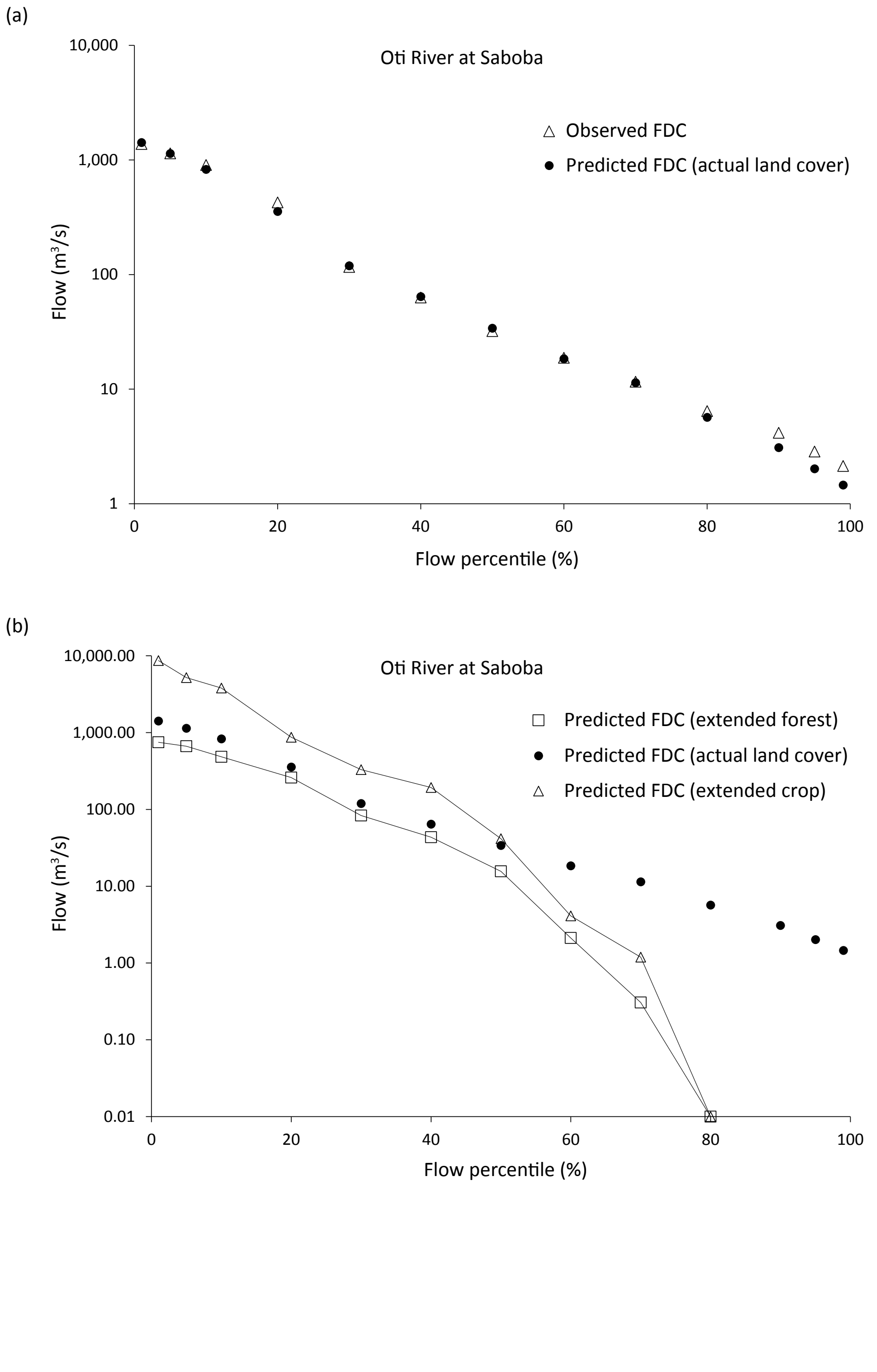
ii. Forest and crops in the Volta River Basin

Table 4 shows that the only two explanatory variables selected from the land cover types investigated to predict the flow metrics *q* are 'crop' and 'forest'. According to the signs of the associated coefficients, increasing forest cover reduces high flow and increases low flow. It is possible that, by increasing infiltration and evapotranspiration, surface runoff is reduced, thereby reducing high flows. Furthermore, by favoring infiltration and protecting soil against erosion, forest increases the water storage capacity of the soil, thus increasing water table drainage into the stream during the dry season, which increases low flows. However, these suppositions need to be confirmed by process studies and plot-level experiments.

The percentage of area covered by crops alters the low flow only: according to the relationships resulting from the regression analysis, this land cover type has no effect on high flows. The positive coefficients indicate that low flows tend to increase as crop coverage increases. It is difficult to interpret these results because many causes are possible through changes in evapotranspiration, infiltration, soil water storage capacity, velocity of water transfers, etc. It is also possible that crops are grown in areas which are generally wetter, and therefore the results reflect a relationship but not a causative one. Further analyses and research are required to understand the observed relationship.

Figure 7 illustrates the effect of land cover changes on FDC at Saboba along the Oti River in Ghana. Two cases are compared to the original situation: a substitution of forest by crops - changing the areal proportions of these two land-use types from 19% and 38% to 1.4% and 55.4%, respectively, and a substitution of crops by forests - changing the areal proportions of these two land-use types from 38% and 19% to 8.9% and 47.9%, respectively. These extreme cases were bounded by the extreme values of crop and forest coverage reported in Table 2, because the predictive power of all models may reduce if they are applied to catchments with characteristics outside the range of values reported in Table 2. The relative positions of the original, forest and crop FDC in Figure 7(b) indicate that the substitution of crop by forest reduces high flows slightly, while the opposite change (replacement of forest by crop) increases high flow. Due to the much lower predictive power of the low flow models (Table 4), low flow changes in Figure 7(b) should be interpreted with caution. As mentioned above, low flow modelling, especially in the Volta River Basin, would require further effort to improve the accuracy of predictions. Another confounding factor is the way the vegetation cover is managed. This was not taken into account here. It is possible that two land cover changes, apparently opposite in direction, both result in a drastic reduction of low flows. It depends on how the new vegetation cover is managed, and the impacts of land conversion on soil surface properties and infiltration (e.g., Lacombe et al. 2015). Less ambiguity is observed for high flows, and our results should be used to anticipate the possible risk of enhanced floods in response to deforestation in the Volta River Basin.

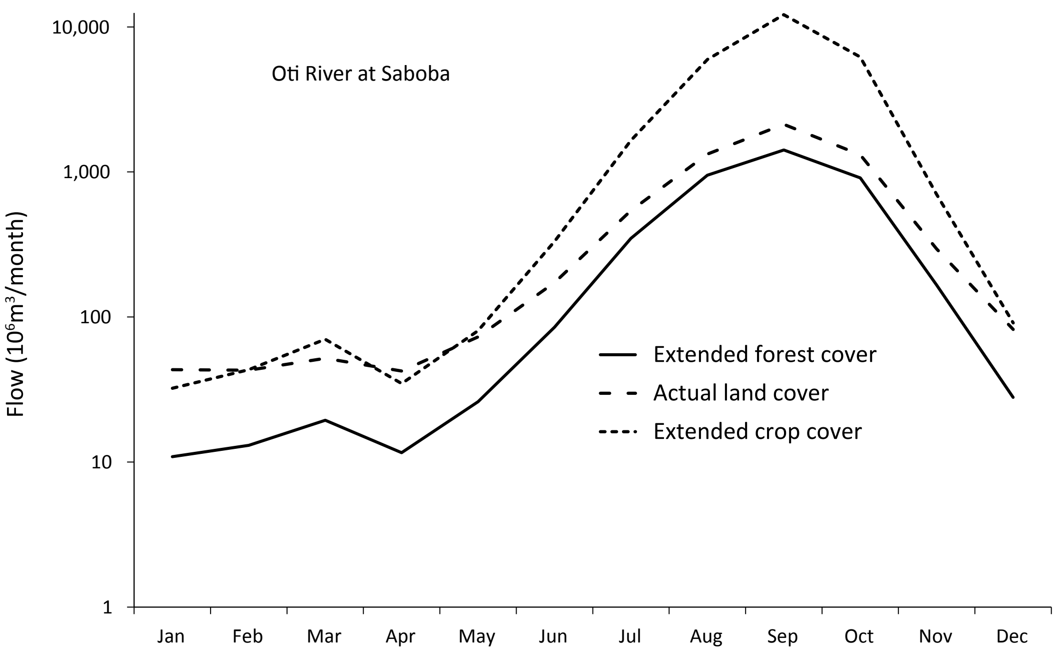
FIGURE 7. FDC of the Oti River at Saboba. (a) comparison of observed and predicted FDC under actual condition of land cover; and (b) predicted FDC under actual condition, and two scenarios either maximizing forest cover or crop cover.



It should be noted that investigation of the hydrological effect of such substitution of land cover (e.g., replacing forest by crops) could not be carried out in the Mekong, because only one land cover category (paddy) was found to significantly alter river flow in this basin.

Figure 8 displays the mean monthly hydrographs associated with each of the three FDCs depicted in Figure 7(b). An increase in the forest area from 19% to 48% of the sub-catchment area (at the expense of a reduction in the annual crop area from 38% to 8.9%) results in an overall flow reduction of 2,100 × 10^6 m^3/year, which is equivalent to 39 mm/year over the sub-catchment area (54,320 km^2). Flow losses in the dry season are relatively greater (75% reduction in January) than that in the wet season (29% reduction in August). This overall reduction in basin water yield could be attributed to higher evapotranspiration from deep-rooted forest trees, compared to that of annual crops.

FIGURE 8. Average hydrograph of the Oti River at Saboba for three land cover types: 'Original': actual conditions of land cover (38% and 19% of the sub-catchment covered by crop and forest, respectively). 'Forest' assumes an increase in forest cover (8.9% and 48% of the sub-catchment covered by crop and forest, respectively). 'Crop' assumes an increase in crop cover (55.4% and 1.4% of the sub-catchment covered by crop and forest, respectively).



Limitations of this Study

The variables listed in Tables 1 and 2 but not appearing in Tables 3 and 4, respectively (e.g., drainage directions, soil characteristics, longitude and wetland) were found not to have any explanatory power for any of the predicted flow metrics at the 5% significance level. However, these exclusions do not indicate that these variables have no hydrological impacts on downstream flow. For instance, the effects of soils and wetlands on catchment hydrology are complex, and depend on various context-specific situations (Ribolzi et al. 2011). Acreman and Holden (2013) show that the effects of wetlands on river regimes depend on their location within the catchment and on the geological nature of the substratum. In our analysis, the lack of explanatory power of these variables may be due to the selected metrics used to characterize soils and wetlands (surface area, guided by data availability), which do not necessarily capture the main properties controlling catchment-scale hydrological behavior. In addition, it should be noted that the surface area of wetlands never exceeds 1.23% of the surface area of the studied sub-catchments in the Lower Mekong River Basin and 0.6% (water bodies) in the Volta River Basin, which likely explains their apparent negligible role in the hydrological responses of the study sub-catchments.

The multivariate relationships reported in Tables 3 and 4 were used to predict what the FDC would have been if the catchment areas covered by each land-use type were modified by setting the relevant area to different values in the regression models. This procedure enables an approximate assessment of the impact on flows of either an increase or a decrease in the area of a specific land use. When two different land-use types are selected as explanatory variables in the same regression model, the conversion of one land-use type to the other is easily determined (e.g., in the Volta Basin, where crop is replaced by forest or forest is replaced by crop [cf. Figure 8]). However, when the model includes only one land-use type as an explanatory variable (e.g., in the Mekong River Basin, where the rice area is decreased [cf. Figure 6]), this land-use change does not explicitly account for the nature of any replacement in land cover. Rather, the assumption made implicitly is that the area is effectively replaced by an 'average' land-use equivalent to a weighted average of all other land cover types included in the studied sample of sub-catchments (i.e., 65 sub-catchments for the Mekong). The impact could be considerably different depending on the actual replacement land use (e.g., if rice is replaced by another annual crop or forest).

The method is an improvement to that developed for the Zambezi River Basin, because it enables mean annual discharge to change as a consequence of land cover change. However, the approach remains limited by the assumption that there is no change in the frequency of specific flow events as a consequence of land-use change or the presence/absence of particular ecosystems. In reality, this is unlikely to be the case. However, without knowledge of how the frequency of specific flows change (which is likely to be location-specific), it is not possible to modify the percentiles. More research is required to quantify the effect of different land cover types on the frequency of flows.

A final constraint relates to the evaluation of land cover in each basin. Due to limitations in available data, we were only able to utilize land cover assessments at a single point in time. There was no possibility of determining land cover changes over time. Thus, the assumption was made that catchment conditions were stationary. This is, of course, not the case in reality, but without additional information on land use/land cover changes over time, it was necessary to make this assumption.

Implications for Water Resources Planning and Policy Making

Recent modelling efforts undertaken by river basin commissions to include land management in basin development plans have focused on irrigation and their impact on downstream flow (e.g., basin development plan of the Mekong River Basin: MRC [2011]). This study has demonstrated that rainfed lowland paddy fields (the majority of rice production in the Mekong River Basin is not irrigated) tend to significantly reduce downstream low flow in this basin. This is particularly important because the difference between water supply and demand in the dry season is narrowing, as a result of population growth and increasing dry-season water demand. Therefore, in the Mekong River Basin, hydrological modelling efforts for basin development planning should include paddy areas as an important component when modelling catchment-scale hydrological processes. This recommendation is of particular importance in Lao PDR where paddy is seen as a major crop in agricultural development plans. Similarly, further research is essential to understand the possible implications of converting significant areas of land to plantations, particularly of teak and rubber.

For the Volta River Basin, this study has highlighted the potential of increased high flows and likely additional flood risk, associated with the conversion of forest to crops. This result confirms that forest management is of tremendous importance in West Africa, not only for local communities, but also for downstream populations living in the vicinity of the major rivers. Given the relatively low runoff in the basin and high sensitivity to annual rainfall totals (in conjunction with rapidly increasing population), there is an urgent need for further research to identify the impacts of land-use change (deforestation, in particular) on low flows.

Conclusions and Recommendations

The primary goal of this study was to investigate how different types of ecosystems alter downstream river flows in two major river basins, which have very different hydro-ecological conditions: the Volta and the Mekong. Although the method developed inevitably has limitations, overall, it is more rigorous and more objective than that used previously in the Zambezi River Basin study. However, in part, because of data limitations, the results were seemingly less clear than those derived for the Zambezi.

Using multivariate power-law models to predict streamflow, we found that land cover/land use does indeed control downstream flows. The primary land cover types controlling downstream flows are paddy areas in the Mekong and crop/forest in the Volta. In contrast, wetlands and soil types were found not to have any significant effect on downstream flows in the sub-catchments investigated. This lack of statistical explanatory power was most likely a consequence of the selected metrics used to characterize these entities, guided by the data available. In addition, the surface area of wetlands never exceeds 1.23% of the gauged sub-catchment areas in the Mekong and 0.6% (water bodies) in the Volta, likely explaining their apparent negligible role in the hydrological responses of the study sub-catchments. We surmise that, in catchments with a greater proportion of wetlands, they would (as was the case in the Zambezi) have a significant impact on river flows.

In addition to flow prediction under various conditions of paddy, forest and crop cover, the multivariate power-law models derived in this study can be used for a range of applications, including prediction of the impact of change in rainfall amounts on mean, low and high basin water yields (especially in the Mekong, where annual rainfall is an explanatory variable in all flow percentile models), and regional impact assessment of local hydrological alterations through the comparison of water yields from nested basins.

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Annex

TABLE A1. Characteristics of the river gauging stations that were included in the analysis carried out in the Mekong River Basin.

Country	Station name	River name	Latitude	Longitude	Selected hydrological years
Cambodia	Ban Kamphun	Se San	13.55	106.05	1960-1963, 1965-1968, 1994-1996, 1999-2001
Cambodia	Ban Khmoun	Se Kong	13.74	106.19	1961-1968
Cambodia	Battambang	Stung Sangker	13.05	103.20	1999-2001
Cambodia	Kompong Putrea	Stung Sen	13.22	105.26	1965-1968
Cambodia	Kompong Thmar	Stung Chinit	12.50	105.13	1997-2001
Cambodia	Kompong Thom	Stung Sen	12.71	104.87	1961-1969, 1982-2001
Cambodia	Lumphat	Sre Pok	13.47	106.98	1965, 1967-1969
Cambodia	Treng	Stung Sangker	12.87	103.14	1963-1971
Lao PDR	Attapeu	Se Kong	14.81	106.84	1989-1990, 1993-1995, 1998-2004
Lao PDR	Ban Hin Heup	Nam Lik	18.63	102.36	1967-1974, 1993-1995
Lao PDR	Ban Keng Done	Se Bang Hieng	16.19	105.32	1965-1970, 1973-1977, 1979, 1992-2003
Lao PDR	Ban Kok Van	Nam Pa	19.96	102.30	1988-1991, 1996-2003
Lao PDR	Ban Mixay	Nam Khan	19.79	102.18	1960-1983, 1985-1991, 1995-2004
Lao PDR	Ban Muong Chan	Se Pon	16.66	106.29	1999-2002
Lao PDR	Ban Na Luang	Nam Ngum	18.91	102.78	1987-2008
Lao PDR	Ban Phalane	Se Xangxoy	16.66	105.57	1997-1999
Lao PDR	Ban Sibounhom	Nam Suong	19.97	102.27	1968-1971, 1987-1991, 1995-2003
Lao PDR	Ban Signo	Nam Theun	17.85	105.05	1989-2004
Lao PDR	Dong Hen	Se Champhone	16.70	105.29	1995-2003
Lao PDR	Highway Bridge	Se Thamouak	16.58	105.91	1995-2002
Lao PDR	Keng Kok	Se Champhone	16.45	105.21	1988, 1990, 1992, 1995-1996, 1998-2001
Lao PDR	Kham Keut	Nam Theun	18.24	104.66	1986, 1990
Lao PDR	Khong Sedone	Se Done	15.58	105.81	1989
Lao PDR	Mahaxai	Se Bang Fai	17.41	105.20	1989-2000, 2002-2004
Lao PDR	Muong Borikhan	Nam Sane	18.56	103.74	1985-1990, 1993-2004
Lao PDR	Muong Kasi	Nam Lik	19.24	102.26	1987-2003
Lao PDR	Muong Mai	Nam Nhiap	18.50	103.66	1987-1994, 1997-2004
Lao PDR	Muong Ngoy	Nam Ou	20.70	102.67	1989-1991, 1995-2001
Lao PDR	Muong Nong	Se La Nong	16.37	106.51	1995-2003
Lao PDR	Road Nb 13 Bridge	Se Bang Fai	17.08	104.98	1961, 1963-1971, 1973-1977, 1979-1984, 1994-2003
Lao PDR	Saravanne	Se Done	15.69	106.45	1988-1991, 1994-1996, 2000, 2002-2004

(Continued)

TABLE A1. Characteristics of the river gauging stations that were included in the analysis carried out in the Mekong River Basin. (Continued)

Country	Station name	River name	Latitude	Longitude	Selected hydrological years
Lao PDR	Souvannakhili	Se Done	15.40	105.83	1986-1990
Lao PDR	Tchepon bridge	Se Bang Hieng	16.68	106.21	1999-2003
Lao PDR	Tha Ngon	Nam Ngum	18.13	102.62	1962-1970
Lao PDR	Vang Vieng	Nam Song	18.92	102.44	1988-1994, 2002-2004
Thailand	Ban Chot	Nam Chi	16.10	102.58	1976-1986, 1988-1992, 1994-2002
Thailand	Ban Fang Phe	Lam Dom Yai	14.69	105.15	1969-1998
Thailand	Ban Huai Khayuong	Huai Khayuong	15.01	104.64	1980-2002
Thailand	Ban Huai Yano Mai	Nam Mae Chan	20.11	99.79	1976-2002
Thailand	Ban Kae	Nam Pong	16.86	102.18	1980-1996
Thailand	Ban Na Kham Noi	Huai Bang Sai	16.72	104.63	1985-2002
Thailand	Ban Na Thom	Nam Yang	16.05	104.03	1980-1998
Thailand	Ban Nong Kiang	Huai Rai	16.13	101.66	1976-1977, 1979-2002
Thailand	Ban Pa Yang	Nam Mae Kham	20.23	99.80	1981-1997, 1999-2002
Thailand	Ban Pak Huai	Nam Heung	17.71	101.41	1967-1993, 1996-2002, 2006
Thailand	Ban Tad Ton	Huai Pa Thao	15.94	102.03	1977-1986, 1988-1989, 1991-2002
Thailand	Ban Tha Kok Daeng	Nam Songkhram	17.86	103.78	1965-1974, 1992-2000
Thailand	Ban Tha Mai Liam	Nam Mae Fang	20.02	99.35	1970-2002
Thailand	Ban Tha Sai	Nam Mae Lao	19.86	99.84	1972-1998
Thailand	Ban Tha Ton	Nam Mae Kok	20.06	99.36	1970-1993, 1996-2004
Thailand	Ban Wang Sai	Nam Loei	17.05	101.52	1976-1979, 1981-2002
Thailand	Chiang Rai	Nam Mae Kok	19.92	99.85	1977-1992
Thailand	Dam site	Nam Mae Suai	19.70	99.52	1976-1993, 1996-1997
Thailand	Dam site	Nam Mae Pun Luang	19.43	99.46	1976-2002
Thailand	Dam site	Nam San	17.43	101.27	1966-2002
Thailand	Dan Sai	Nam Man	17.28	101.15	1968-2002
Thailand	Rasi Salai	Nam Mun	15.33	104.16	1979-1993, 1996-2000
Thailand	Thoeng	Nam Mae Ing	19.68	100.19	1969-2002
Thailand	Ubon Ratchathani	Nam Mun	15.22	104.86	1951-1965
Thailand	Wang Saphung	Nam Loei	17.30	101.78	1967-1988, 1991-2002, 2006
Thailand	Yasothon	Nam Chi	15.78	104.14	1952-1965
Vietnam	Cau 14	Ea Krong	12.61	107.93	1984-2003
Vietnam	Duc Xuyen	Krong Kno	12.33	107.86	1985-2006
Vietnam	Kontun	Dak Bla	14.34	108.00	1984-1988, 1990-2005
Vietnam	Trung Nghai	Krong Po Co	14.37	107.87	1992, 1995-1997

TABLE A2. Characteristics of the river gauging stations that were included in the analysis carried out in the Volta River Basin.

Country	Station name	River name	Latitude	Longitude	Selected hydrological years
Benin	Porga	Pendjari	11.05	0.97	1954-1955, 1959, 1973
Burkina Faso	Dakaye	Red Volta	11.78	-1.6	1977, 1979-1980, 1982
Burkina Faso	Diebougou	Bougouriba	10.93	-3.17	1978-1979
Burkina Faso	Samandeni	Black Volta	11.46	-4.46	1977-1978, 1981-1982
Burkina Faso	Samboali	Singou	11.28	-1.02	1978, 1981
Burkina Faso	Yilou	Nakanbe	13	-1.55	1977-1980
Ghana	Bamboi	Black Volta	8.15	-2.03	1951, 1955, 1957, 1960, 1964, 1968-1971, 1973, 1975, 2003
Ghana	Bui	Black Volta	8.28	-2.23	1971-1976, 1981, 1983-2007
Ghana	Chache	Black Volta	9.17	-2.72	1998, 2002
Ghana	Kpasenkpe	White Volta	10.43	-1.05	2005
Ghana	Nakong	Sissili	10.8	-1.5	1972, 1974, 2003
Ghana	Nangodi	Red Volta	10.87	-0.62	1972
Ghana	Nasia	Black Volta	10.15	-0.8	1969-1972, 1990, 1992-1995, 2000, 2002, 2004-2005
Ghana	Nawuni	White Volta	9.7	-1.08	1954-1979, 1984, 1986-1989, 1991, 1993-2000, 2002-2003, 2005-2007
Ghana	Pwalagu	White Volta	10.58	-0.85	1952, 1963, 1966, 1968, 1971-1972, 2003, 2005
Ghana	Sabari	Oti	9.28	0.23	1976-1977, 1982, 1984, 1997, 2004-2005
Ghana	Saboba	Oti	9.6	0.31	1954, 1956, 1961, 1963-1966, 1971, 1976, 1985-1987, 1989, 1991-1993, 1995-1998, 2004-2007
Ghana	Wiasi	Sissili	10.33	-1.35	1966, 1976, 1990, 1992
Ghana	Yarugu	White Volta	10.98	-0.4	1962-1969, 1971-1972, 1975, 2005
Ghana	Yagaba	Kulpawn	10.23	-1.28	1965, 1971, 1992, 2005

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