【原著論文】

An integrated approach to evaluate potential impact of precipitation and land-use change on streamflow in Srepok River Basin

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Abstract: To manage water resources effectively at a local level, decision makers need to understand how climate change and human activity may impact local streamflow as a precious natural source of water use. However, the impact is often not well studied with locally obtained data such as monitored flow. This paper presents an integrated approach to study potential impact of precipitation and land-cover change on local streamflow over the next decades. The study area is the Srepok River basin, a tributary sub-basin of the Mekong River. A hydrological model was developed in the Hydrologic Modeling System (HEC-HMS) environment and calibrated using local precipitation and streamflow data. Several scenarios were developed considering climate change and socio-economic development in a GIS environment, and streamflow in 2025 and 2050 was estimated for each scenario. The paper ends with discussion on possible adaptations for a given area.

Keywords: river basins, water resources, precipitation, land-use, climate change

1. Introduction

In the 21st century, water is at the heart of serious environmental, political and economic issues around the globe. The impact of climate change and population growth on the quantity, variability, and spatial distribution of water resources is increasingly cited as a possible hindrance to economic and social development in many countries around the world.

Climate change and human development are considered major driving forces that will affect future water resources (Kundzewicz *et al.*, 2007; Rogers, 2008). Their contributions to the future state of global water resources have been intensively studied (Milly *et al.*, 2005; Oki and Kanae, 2006; Vorosmarty *et al.*, 2000). To study adaptation to water resource changes, however, attention to local scale is essential because the structure of the solution is different for each scale and set of local characteristics. Concrete adaptations based on practical analysis are often not well studied, particularly on local and regional scales (Pielke, 2005).

To make suitable adaptation plans for water resource use at a local level, decision makers need to understand the extent of the potential impact of both climate change and human activity on local water flow. It is important to compare these factors based on local data to respond to impending climate change and expanding human activity, particularly in fast-growing developing countries.

Geographic Information System (GIS) is a promising tool for integrated river-basin analysis and management. GIS allows rapid arrangement of a geospatial data infrastructure and comprehensive analyses of various other kinds of data at a local level (Downs and Priestnall, 1999; Jarvie *et al.*, 2002; Maidment, 2008). GIS allows us to delineate the watershed boundary from the topography and extract detailed watershed characteristics by overlaying data layers such as population, land-use and climate.

This paper presents an integrated approach to study the potential impact of ‘precipitation’ and ‘land-cover’ change on local streamflow over the next decades. The

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magnitude of the change is demonstrated with different, but likely scenarios. Arc Hydro, a geospatial and temporal data model specifically developed for water resources (Kawasaki *et al.*, 2007; Maidment, 2002; Patino-Gomez *et al.*, 2007; Whiteaker *et al.*, 2006), was used to develop a hydrologic model to simulate streamflow. The model was developed in the Hydrologic Modeling System (HEC-HMS) environment and calibrated using local precipitation and streamflow data. Several scenarios were developed considering climate change and socio-economic development in a GIS environment, and streamflow in 2025 and 2050 was estimated for each scenario.

2. Study Area

The Mekong River is the longest international river in Asia, rising in the Tibetan Plateau and emptying into the South China Sea. It travels 4,000km and flows through six countries: China, Myanmar, Thailand, Lao PDR, Cambodia, and Vietnam. As the World Wildlife Fund (2008) reported, over a thousand new species have been discovered in the Greater Mekong Basin in just the last decade; indeed, it is one of the richest remaining biodiversity areas in the world and many inhabitants rely on it for their livelihood.

Hydrology and water resources in the Mekong have been thoroughly studied to simulate unique phenomena of the Asian Monsoon Region (Takeuchi, 2008). General Circulation Models (GCMs) or self-produced distributed hydrological model were used to investigate hydrology and water balance at the entire basin level (Ishidaira *et*

al., 2008; Kiem *et al.*, 2008; Haddeland *et al.*, 2006). GIS has been used for analyzing local-scale flood risk and climate change impact on agriculture, but many research works mainly focus on Thailand (Weesakul, 2010; Rajin and Shibasaki, 2000) or the Mekong Delta in Vietnam (Wassmann *et al.*, 2004; Boochabun *et. al.*; 2007; Haruyama and Hoa, 2010), so there is a geographic imbalance in the knowledge distribution.

The Srepok River basin, a sub-basin in the Lower Mekong which straddles the two national borders of Cambodia and Vietnam, was selected as a study area (Fig. 1). Scientific investigation on future available water is required in this sub-basin to study water resource adaptation because rapid population growth, agricultural development, and several dam projects planned upstream in Vietnam may threaten the valuable ecosystem and the economic survival of downstream residents in Cambodia (Mekong River Commission, 2007). The Cambodian side remains largely covered in thick forests, whereas the Vietnamese side features a small, concentrated urban population of 390,660 as of 2004 in Buon Ma Thuot, which has a total area of less than 10km² (CarlBro Intelligent Solutions, 2005). There is also significant agricultural development, a hydropower dam (Dray Linh Old), and reservoir systems that control flow and collect hydrological data. The climate in the area is very humid (78-83% annual humidity) and features a distinct wet and dry season. The wet season lasts from May to October (with peak floods often in September or October) and accounts for over 75-95% of the region's annual precipitation.

Fig. 1 Research site and the hydro-meteorological stations

3. Method

3.1 Overview

The overall structure of this research involves the integration of two software programs - a hydrological simulation tool, Hydrologic Modeling System (HEC-HMS) (US Army Corps of Engineers, 2009) and a GIS environment (ArcGIS) through the use of two ArcGIS-based system applications: Arc Hydro Tools (Maidment, 2002) and the Geospatial Hydrologic Modeling Extension.

sion (HEC-GeoHMS). This enabled us to effectively process local geospatial and climate data into one integrated model of the hydrological processes. This provides a holistic and coherent database, supporting a series of processes including data generation, management, analysis and simulation, problem-solving, and demonstration, that are required commonly in water resources and river-watershed management. Another advantage of combining these tools is that one can reflect effects of changes in climate and land-cover over time on a local scale, which is very helpful for scenario analysis.

Then, streamflow in 2025 and 2050 was estimated by considering the potential impact of climate change and socio-economic development on water supply and demand from domestic and agricultural uses. Scenarios of ‘Precipitation change only’, ‘Land-cover change only’ and ‘Both precipitation and land-cover change’ were considered in the model to evaluate future flow conditions.

3. 2 Hydrologic Model Development

ArcGIS was used to develop a dataset to build a hydrologic model. Terrain processing tools in the Arc Hydro tools application were used to delineate sub-watersheds from a 50m DEM (Digital Elevation Model) of the Srepok River basin. Time-series precipitation data was mapped from seven precipitation observation sites (Ban Don, Duc Xuyen, Cau 14, Krong Buk, Buon Ho, Dak Mil, Krong Bong) in Vietnam using Thiessen’s Polygon method (Longley *et al.*, 2005), and allocated to individual sub-basins based on their aerial proportions. No rain data was readily available for the Cambodian side; all sub-basins in Cambodia are assumed to have uniform precipitation estimated from data from the Vietnamese side.

The land surface characteristics used in this study were based on the U.S. Soil Conservation Service (SCS) curve number (CN) system (McCuen, 1982; Soil Conservation Service, 1986), which determines a runoff coefficient from a simple land-use and soil drainage type table. With available land-cover and soil type maps for the region and a modified CN lookup table to match key land-use

types of interest in this study, curve numbers and curve number based lag times were estimated for each individual sub-basin. These calculations were all executed in the ArcGIS environment using the HEC Geo-HMS Tools application.

Land-cover data compiled by the Mekong River Commission (MRC) in 1997 consisted of 21 categories which were integrated into six categories shown at Table 1. For example, "Thick cover forest" consists of high cover density of evergreen or mixed forest (evergreen and deciduous). "Thin cover forest" consists of medium - low cover density of evergreen or mixed forest (evergreen and deciduous), or regrowth forest. "Agriculture" consists of agricultural land, plantations, or cropping mosaic based on the MRC's classification. SCS curve numbers were generated from a modified curve number lookup table (Table 1) and averaged over the entirety of the sub-basin.

The Muskingum Routing method was selected to model stream routing. Assumptions include a Muskingum X value of 0.1 (indicating a small, natural stream), a sub-reach value of 2, and a streamflow speed of 3.2km/hr was used to calculate Muskingum K value (length of time to travel a stream reach).

Table 1 Curve number table for Antecedent Moisture Conditions II (regular conditions)

	Soil Type			
	A	B	C	D
Thick cover forest	30	55	70	77
Thin cover forest	43	65	76	82
Mosaic	43	65	76	82
Glass land	30	58	71	78
Agriculture	67	77	83	87
Urban	89	92	94	95

* Soil Type ranges from A (absorbent) to D (not absorbent). This table is base on MaCuen (1982) and Soil Conservation Service (1986).

3. 3 External Calculation Process in Precipitation Abstraction

In this study, it was critical to represent hydrological

process with a SCS curve number so that future land-cover change could be represented by curve number change. However, the SCS method for abstraction (interception, depression storage, and infiltration) is more suitable for event simulation than continuous simulation because initial abstraction should be fully updated at the beginning of each storm event, which is not easy in the SCS module in HEC-HMS. In order to conduct continuous simulation in the HEC-HMS environment, excess precipitation was externally calculated with the SCS abstraction method and directly brought into the model.

In the SCS method, abstraction, F_a , is represented as:

$$F_a = \frac{S(P - I_a)}{P - I_a + S}$$

where S is potential maximum retention, P is precipitation, and I_a is initial abstraction. The potential maximum retention, S , for normal antecedent moisture conditions is empirically defined as follows with given curve number, CN :

$$S = \frac{1000}{CN} - 10$$

The retention S can be further adjusted based on 5-day antecedent precipitation (Chow *et al.*, 1988). Initial abstraction, I_a , was also defined as $0.2S$ as suggested.

In this study, 17 precipitation events in 2001, which have depth greater than 30mm in all the 7 precipitation stations in the basin, were selected using daily precipitation data. Each storm event was split into two when there is a period with rainfall less than 3mm within 72 hours. For each precipitation event, CN , S , and I_a , were calculated based on the 5-day antecedent precipitation. Figure 2 shows actual daily hyetograph and calculated excess precipitation for the 11th precipitation event in 2001, the largest precipitation event during the year. The graph shows the excess precipitation for CN of 70 and 80. Excess precipitation is greater for $CN=80$ than $CN=70$ especially during initial and peak period of the storm. This is because initial abstraction, I_a , and potential maximum retention, S , are both smaller for larger CN value (i.e.,

urbanized case). In this example, calculated amount of excess precipitation with $CN=70$ is 307mm and $CN=80$ is 380mm among the total 487mm precipitation.

For a given CN value, excess precipitation was calculated for each event with the external process, and then combined as a continuous time-series data to conduct a continuous simulation in HEC-HMS.

3. 4 Model Calibration

This pre-processed data was then integrated into the HEC-HMS environment. Calibration was conducted using observed daily streamflow at Ban Don in 2001. Simulation results were compared to the observed streamflow at the Ban Don station in 2001 (Fig. 3). In the calibration process, the lag time and Muskingum K values were mainly used as calibration parameters whereas the estimated CN based on land-use data were kept as estimated. In the study sub-basin, an existing hydropower dam called Dray Linh Old has been in operation in Dak Lak Province, approximately 30km upstream of the Ban Don streamflow observation point (Fig. 1). The dam has an active storage of 1.5Mm^3 and a water depth difference between design head and minimum head of 4m. To generate electricity, a discharge of $90\text{m}^3/\text{s}$ is designed to be diverted to the turbine structure (SWECO Groner, 2006). The dam with the active storage can be emptied in less than 5hrs with the design discharge without inflow. With a $500\text{m}^3/\text{s}$ of wet weather flow, the dam can be filled from the minimum depth for about an hour. The dam may moderate a flood peak slightly only until the dam fills, however the influence is minimal because of the small storage volume of the dam. Therefore, this hydropower dam was not considered as storage in the simulation.

In addition, there are 484 small reservoirs and 76 diversion dams on the Vietnamese side of the border with an approximate volume of 280Mm^3 as of 2006 (Ty *et al.*, 2009). This volume is approximately 15% for the total precipitation volume in the area. Their capacity and local water use pattern in paddy field can impact on basin-wide hydrological process including CN value representation

Fig. 2 Storm hyetograph for August 5th, 2001 and calculated excess precipitation for $CN=70$ and 80

Fig. 3 Observed and simulated streamflow at Ban Don observation station in 2001

Fig. 4 Existing land-cover in 2000, and predicted land-cover in 2025 and 2050

of paddy field. However in this research, due to the lack of spatial and volumetric information of each small dam and reservoir, model development and calibration process in agricultural water use had to be simplified. Instead of adjusting CN values for agricultural area or explicitly include reservoirs in the model, we used depression storages and runoff routing coefficients to reproduce overall hydrologic process in the Srepok River basin. This storage data is being collected and will be utilized in future studies.

3. 5 Creating Future Land-Cover Scenarios

Land-cover data was used to determine two key factors in the future streamflow estimation: runoff and water demand. Future land-cover scenarios were developed to evaluate the impact of future land development. Though many land-use models have been developed using GIS (Almeida *et al.*, 2008; Nagasaki *et al.*, 2006; Steinitz *et al.*, 2005; Xia and Xiaoping, 2008), a simple approach was taken for scenario analysis of this study due to the limited data access. To reflect urban and agricultural development in 2025 and 2050, existing population density

data was used to model future land-use policy decisions. A local annual population growth rate of 1.95% (CarlBro Intelligent Solutions, 2005) for the upper side of the Srepok River basin was uniformly applied across population density grids from 2000 (CIESIN, 2008) to generate population density grids for 2025 and 2050, though the actual relationship between population growth and land use conversion is complex and changing depending on the transition stage of the region (Acharya and Nangia, 2004).

To develop land-cover and population density relationship in the sub-basin, population density grids for 2000 were cross-related with the land-cover polygon of 1997. From the cross comparison, the population density ranges in Table 2 were proposed for each land-cover in this study area. Approximately 73% of the agricultural area and 75% of the urban area in the observed land-cover polygon for 1997 fall into their respective proposed population density ranges, which supports the validity of these proposed ranges. The proposed ranges were then applied to the new population density grids for 2025 and 2050 to predict future land-cover with the assumption that land-cover change is highly dependent on population growth. Existing undeveloped land (i.e. forest) could become more developed as population increases, but not vice versa. Like so, land-cover polygons for 2025 and 2050 were generated (Fig. 4). As shown in the figure, the Vietnam side of the basin is much more developed for agricultural use than the Cambodian side. The parameters of the runoff process of each sub-basin (CN , lag times, and Muskingum K) were recalculated based on these two new land-cover scenarios for their respective future simulations.

Land-cover change, specifically urban and agricultural development, significantly affects human water demand. Annual water demand in the Vietnam side of upper Srepok River basin in 2004 was 1,618Mm³ for agriculture and 51.8Mm³ for urban area, where 30.5Mm³ for industry and 21.3Mm³ for domestic uses (CarlBro Intelligent Solutions, 2005). These total water demand values and

Table 2 Population density ranges for each land-cover in the study area

Land-cover category	Population density range (persons/km ²)
Thick cover forest	0-7
Thin cover forest	8-15
Mosaic	16-23
Open land	24-31
Grassland	32-47
Agriculture	48-799
Urban	over 800

Table 3 Agricultural and urban water demand per unit area in the Vietnamese side of upper Srepok River basin

	Water demand (Mm ³)	Area (km ²)	Water demand per area (Mm ³ /km ²)
Agriculture	1,618.0	5,996.6	0.27
Urban	51.8	6.7	7.73

Table 4 Projected increase of total water demand from 2000 at Ban Don and basin outlet in 2025 and 2050

		Dry season (m ³ /s)	Wet season (m ³ /s)
Ban Don	2025	81.5	40.8
	2050	297.1	148.5
Outlet	2025	94.1	47.0
	2050	328.8	164.4

Fig. 5 Total area of agricultural and urban area (Y1 axis) and total annual water demand in 2025 and 2050 (Y2 axis) in the entire Srepok River basin.

the areas of agriculture and urban in land-cover polygons in 1997 were used to calculate water demand per area for agricultural and urban land types (Table 3). These factors were then multiplied by their respective agricultural and urban areas in each sub-basin to create a new water demand per sub-basin based on future land-cover scenarios. This process is based on the assumption that future water demand per area would remain constant, though water consumption is generally increasing as economy grows. Our total water demand estimation seems valid by

comparison with the basic water requirement for human needs calculated by Ty *et al.* (2009); our estimated total water demand of 3,075.8Mm³ in 2025 in the Vietnamese side of the upper Srepok is less than the 3,699Mm³ in 2020 calculated by Ty *et al.* In this study, the projected increase of total annual water demand in 2050 from 2025 is more than twice of the increased demand in 2025 from 1997 because urban areas are assumed to increase on a greater scale than agricultural areas with lower water demand per area (Fig. 5). Seasonality was also ac-

Fig. 6 Predicted annual discharge change for each scenario at (a) Ban Don and (b) the outlet in 2025 and 2050 compared to the level in 2000

Fig. 7 Contribution of precipitation, CN value, and water demand to the annual discharge change at (a) Ban Don and (b) the outlet in 2025 and 2050 for Sc3

counted for when calculating annual water demand: Two thirds of water demanded was used for the dry season for greater agricultural usage and one third was used for the wet season (Table 4). This split was based on the seasonal water demand in the upper Srepok River basin; in 2006, 591.0Mm³ was used during the wet season and 1,094.6Mm³ was used during the dry season in the area (Ty, 2008).

3. 6 Creating Future Precipitation Scenarios

For precipitation prediction, some hydrological studies use General Circulation Models (GCMs) available from the IPCC coupled with downscaling techniques (Beyene *et al.*, 2010; Kiem *et al.*, 2008). GCMs are generally more reliable for temperature predictions than for precipitation, wind, humidity or air pressure predictions. Though new methods such as ensemble-based ap-

proaches are developed for evaluating uncertainties and its interpretation has been improved in the IPCC AR4, quantitative projections of precipitation change at the river-basin scale remain uncertain (Kundzewicz *et al.*, 2007). Also, Christofides *et al.* (2008) demonstrated that these large scale models were unsuitable for predicting regional precipitation change. Therefore, in this local scale study, a simplified approach was taken to develop a future precipitation scenario. Most estimates of global precipitation change using GCMs on the IPCC report vary between no change and 2.5% increase in 25 years, and no change and 5% increase in 50 years (Meehl *et al.*, 2007). As an example of climate scenarios using Japan Meteorological Agency atmospheric general circulation model (JMA AGCM) used at IPCC report, Kiem *et al.* (2008) estimated that annual mean precipitation will increase 6.3% during 2080-2099 comparing to 1979-1998 in the entire Mekong River basin, and the Srepok River basin is expected to have 10.0% increase in annual precipitation during 2080-2099. Based on these research results in the study area, 2.5 % and 5.0% precipitation increase for 2025 and 2050 were assumed as a maximum case of annual precipitation increase and the increase was applied uniformly to the daily 2001 precipitation.

We did not consider any spatial variability of the precipitation change. ‘No change’ in precipitation was also considered as a baseline case of precipitation change. Temperature change was not considered in the scenario development process since temperature is already indirectly combined into the estimation of precipitation and water demand.

Fig. 8 Predicted time-series streamflow (Y1 axis) and difference from 2000 (Y2 axis) at Ban Don in 2025 and 2050 for Sc 1 and Sc2.

4. Results

Streamflow was reviewed at the Ban Don flow station in Vietnam and at the outlet of the Srepok in Cambodia (Fig. 1). Future streamflow was calculated under the three scenarios in Table 5.

Simulations were conducted with the calibrated model based on conditions that reflect each scenario. Simulation results suggest that under the Sc2 conditions, predicted

Table 5 Three scenarios developed for evaluating future streamflow

Sc1	Precipitation change scenario – 2.5% and 5% uniform precipitation increase in 2025 and 2050, respectively, with no change in land-cover and water demand from the 2000 levels.
Sc2	Land-cover change scenario – This scenario reflects predicted 2025 and 2050 land-cover and water demand, while no change was applied in precipitation: daily precipitation in 2001 was used for this scenario simulation. This scenario assumes the lowest end of the expected precipitation change over the next 50 years and helps us differentiate the impact of land-cover change from the precipitation change on flow rate.
Sc3	The combination of Sc1 and Sc2 – This scenario reflects both the defined land-cover and precipitation changes.

annual discharge decreases by 18% in 2025 and by 52% in 2050 compared to the 2000 level at Ban Don; at the basin outlet, predicted annual discharge decreases by 10% in 2025 and by 30% in 2050 (Fig. 6). However, under Sc1 conditions, annual discharge increases with the assumed precipitation increase by 2% and 3% in Ban Don and by 3% and 6% in the basin outlet in 2025 and 2050, respectively. The combined scenario Sc3 result was very similar to that of Sc2 because the water demand increase would overwhelm the precipitation increase.

Predicted annual discharge decrease at Ban Don would be more severe than that at the basin outlet because most development is expected upstream of Ban Don, such as Buon Ma Thout, Krong Pak, and Krong Ana in Vietnam, which have population densities in 2004 of 852 persons/km², 349 persons/km², and 306 persons/km², respectively.

Figure 7 illustrates the contribution of precipitation, *CN* value, and water demand change to the predicted annual discharge change at Ban Don and basin outlet in 2025 and 2050 under Sc3. Water demand is the only factor that reduces streamflow since urbanization, which increases *CN* value, is considered to increase peak flow due to quicker runoff. At Ban Don, predicted water demand contributes to decrease streamflow by 22% and 59% in 2025 and 2050 from the level of 2000, and at the basin

outlet, predicted water demand decreases streamflow by 13% and 37% in 2025 and 2050. Land-cover change increases annual discharge by 3-4% and 7% in 2025 and 2050 at Ban Don and the basin outlet.

Time-series results at Ban Don under two scenarios in 2025 and 2050 are shown in Fig. 8. Simulated streamflow patterns for 2025 and 2050 are similar to that for 2001 because the distribution of future precipitation is assumed to be the same as the 2001 precipitation pattern. During the summer rainy season, streamflow would increase due to quicker and larger runoff created by the slightly increased precipitation. However, flow rate would decrease for most of the year and the decrease would be severe for the dry months from November to March. In the simulation, minimum streamflow was set to zero if the water use exceeded the available water supply. Water demand exceeded streamflow for 5 months in the dry season in 2050 under Sc3.

5. Discussion and Conclusions

This study demonstrates the magnitude of potential impact of changes in both precipitation, human activity and their combination on local streamflow, and its effect on the extent of seasonal variation. These results indicate that water demand increase, due to population growth and land development, has a greater impact on streamflow change than precipitation in the next 50 years. This suggests that adaptation planning should be considered to maintain steady water supply especially in the dry season. Adaptation requires policy adjustments in land development, although this may be difficult since economic incentives are important in the region and there is great momentum to expand agricultural land in the area. Additional water infrastructure, such as large dams, for both hydropower and water storage, and smaller reservoirs should be considered in the region to avoid the predicted dry season water shortages.

Some limitations in this research are addressed. The same distribution of daily 2001 precipitation was used to create future daily precipitation. This is not a realis-

tic scenario although the simplification helps us better understand flow changes for each scenario. In order to capture the effect of local climate variability, longer time span of data need to be analyzed. Spatial and temporal data were very limited in Cambodia. Several assumptions had to be made such as population increase and human water demand based on the Vietnam data.

Though several assumptions and simplifications were applied, this study proposes a simple methodology to integrate available data and findings and conventional methodologies through a common GIS computing environment. The methodology to evaluate impacts of precipitation, land-cover and corresponding CN value and water demand on streamflow rate in next 50 years is simple and practical. Regarding the prediction of streamflow decrease, it is important to understand quantitatively whether it is due to runoff reduction modelled by changes in curve number, or human water demand increase. The predicted results can be used as a basis for setting priorities for local policy considerations, research for climate adaptation, and urban and regional planning, in the Srepok River basin and beyond.

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