

Development of a land-use forecast tool for future water resources assessment: case study for the Mekong River 3S Sub-basins

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Abstract Land-use change is one of the major factors that alter local and regional hydrology. For areas experiencing fast expansion of urban and agriculture areas, land-use changes often adversely affect stream flow and water resources at the local and watershed scale. The Sekong, Sesan, and Srepok (3S) Sub-basins are a part of the Lower Mekong River Basin and include land in Cambodia, Lao People's Democratic Republic (Laos), and Viet Nam. The region is experiencing a dynamic land-use transition because of rapid changes in its economy, society, and environment. Major land-use changes include deforestation of native rain forest, expansion of agricultural and urban areas, and expansion of commercial plantation such as rubber trees. These land-use alterations have affected local and regional hydrologic processes, resulting in stream flow shortages during the dry season and flash flooding due to deforestation. In this research, deforestation in the 3S Sub-basins over the period 1993–1997 was analyzed using

multi-logistic regression. The regression analysis indicated that density of agricultural cells within a 5-km radius from each forest cell and slope strongly affected the deforestation process. A land-use forecast model to simulate deforestation and urbanization sites was developed in GIS based on local land-use change trends. The model was applied to 2003 land use to forecast 2033 land use and future water demand, which was further compared with present stream flow measurements during the dry season at various places in the region. The entire approach from the land-use forecast to its impact assessment on stream flow could help local stakeholders understand watershed-wide future water resources risks and develop future water resources plans. With the 3S Sub-basins being used as a case study area, this article presents a land-use forecast tool; simulated 2033 land-use and water demand; and the estimation of the impact of the forecasted future water demand on the local stream flow.

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Introduction

Economic and population growth place ever-greater demands on energy and water resources. Many countries in Asia already face major threats to their ability to provide their people with safe and secure drinking water (Rogers 2012). They need to develop policy to secure their future food and water resources to meet the demand under future economic and population growth and the uncertain climate-change scenario. One of the major components that would affect future water resources is change in land use. The impact that land-use changes can have on water resources

is large, but quantifying these impacts presents many challenges (Stonestrom et al. 2009). Land use is an important factor in hydrology because its changes can affect key atmospheric elements in the hydrologic cycle, including evapotranspiration, precipitation, and land-surface temperatures (Turner et al. 2007). Large-scale land-use changes can modify regional weather patterns and future climate (Foley et al. 2005; Schilling et al. 2008; Zheng et al. 2009). Land-use changes can also impact water quality by altering sediment budgets, increasing the salinity of soil water, groundwater, and surface water, and introducing chemical compounds, such as nitrogen and phosphorus, when land is used for a new purpose such as agriculture (Schlesinger et al. 2006).

There is growing interest in land-use change on environmental sustainability in academia (Bramoh and Osaki 2010). Different kinds of land-use prediction models have been developed, which include the Action-In-Context framework (Wu et al. 2010) and multilogistic regression analysis (Verburg et al. 1999; Muller and Munroe Muller and Munroe 2004). Many studies have been conducted to study or forecast the impact of land-use change in the modeling approach (Katsuyama et al. 2009) and in the data analysis approach (Croke 2005; Kim et al. 2007). A couple of studies have been conducted to integrate land-use prediction with water resources. Kawasaki et al. (2010) and Ty (2011) predicted future land uses and discussed their impact on future water resources in the Srepok River Basin, a part of the 3S Sub-basins. As to future water resources in the 3S Sub-basins, Cochrane et al. (2010) discussed simulated changes in water flows from potential dam development on the Sesan and Srepok Sub-basins and pointed out the potential increase in dry season flows and reduction in wet weather peak flows under a high development scenario. The Lower Mekong River had record low-flow conditions during the dry season in 2010, which raised great concern about the reservoir operation and water intake (MRC 2010). Climate change is another component affecting future river flow. In the Mekong River Basin, Kingston et al. (2011) assessed uncertainty of discharge using different GCM models and different temperature rise scenarios, and pointed out hydrological change would be highly dependent on projection of precipitation changes rather than temperature changes.

“Is future land-use and growing future water demand very damaging to local stream flow?” This is an important question for local decision makers and planners. Many existing models and studies already make predictions and discuss future water resources, but most of them are not designed for local decision makers and planners to use in assessing their own water resources risks. The need for a practical tool designed for local stakeholders is especially strong in developing countries where undergoing development would significantly impact local and watershed

scale water resources. Such a tool should be flexible to incorporate regional specific data/information. Based on this research motivation, this article presents a methodology to approach the question in a practical way by studying the 3S Sub-basin as the case study area. The specific research objectives are listed below:

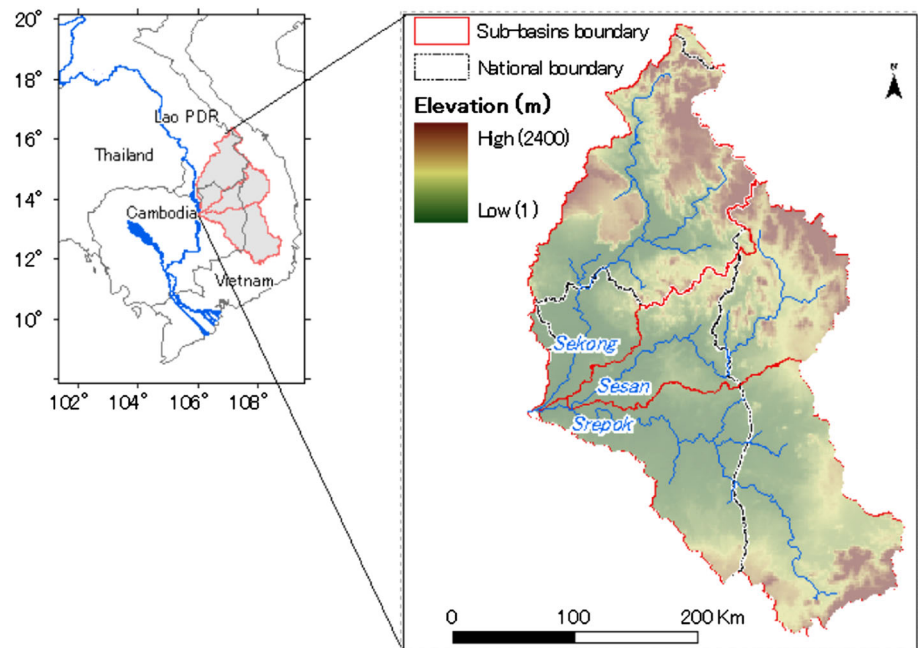
1. Develop a simple and flexible land-use forecast tool in GIS that forecasts deforestation and urbanization sites in the 3S Sub-basins;
2. Apply the forecast tool to the latest available land uses and forecast 2033 land use in the 3S Sub-basins;
3. Estimate existing and 2033 water demand and the impact of future water demand increase on local stream flow in the region.

Methodology

Site description and characterization

The 3S Sub-basins, named after the three basins it contains (Sekong, Sesan, and Srepok), is located in the Lower Mekong River Basin on the Indochinese Peninsula, including land in Cambodia, the Lao People’s Democratic Republic (Lao PDR), and Viet Nam (Fig. 1). The watershed area of the 3S Sub-basins is 78,650 km², making it the largest tributary system of the Mekong River Basin. The area is divided among the three countries, with 33 % of the area in Cambodia, 29 % in the Lao PDR, and 38 % in Viet Nam. It covers about 10 % of the area of the entire Mekong Basin and contributes 17 % of the total runoff (World Bank 2006). The Mekong River Commission (MRC) Basin Development Planning project (2009) identified the area as a region where considerable development potential exists; as a result, multilateral development banks have been investigating it. The World Bank (2006) has studied water resources assistance strategies for integrated development and management since the 1990s. The Asian Development Bank (ADB 2009) has been supporting arrangements to strengthen regional cross-border collaboration at the request of the national Mekong committees of the governments of Cambodia, Lao PDR, and Viet Nam since April 2006.

The total population in the 3S Sub-basins was about 2,900,000 in 2004, and the area has a relatively high population growth rate, higher than the national average in each country. The social and economic development and resulting environmental pressures are higher in the upstream regions compared to those located downstream. Precipitation varies across the 3S Sub-basins, ranging from about 1,500 mm in the downstream areas and middle reaches of the Srepok to more than 2,500 mm in upstream portions of the Sekong and Sesan basins.

Fig. 1 Research site

Deforestation and clearing land for permanent cultivation and the increased cultivation of annual crops have already led to a measurable increase in the frequency of flash floods in the upper catchments, and there are indications of declining low flows during the dry season (Qiu 2009; Ziegler et al. 2009). The Mekong Water Resources Assistance Strategy report (World Bank 2006) described the impact of land-use change to water resources as follows: “The stability of the hydrological systems and local climate, however, is threatened by degradation of critical watersheds, most significantly by deforestation in upper catchments, but also by increasing cultivation of annual crops and extraction of groundwater for irrigation on the plateaus.” Change in land use is one of the critical factors impacting water resources in the Mekong watershed, including the 3S watershed, and potential change in land use in the future is critical for water resources planning and management. The growing number of hydropower dams is another important factor to consider. As of February 2009, 9 hydropower plants were in operation, 8 were under construction, and 24 more were in design or planning stages (ADB 2009).

Land-use data

This study used 1993, 1997, and 2003 land-use data for the 3S Sub-basins. While all data were published by MRC, the 2003 land-use data used different categories from the 1993 and 1997 data. For example, land that would have been classified as mosaic in the earlier data was classified in a forest category in 2003. To make the best use of all three land-use data sets, the original land-use categories were

simplified from 23 down to 5 major categories: Forest, Agriculture, Grass/Shrub, Urban, and Inactive. Inactive refers to the areas where land-use change is not significant, such as water and wetlands. Table 1 lists the original land-use types from the 1993/1997 MRC and 2003 MRC data with the corresponding simplified land-use types used in this study. After simplifying the categories, the vector-based land-use data were converted into 500-m cell size grids for further analysis. These land-use grids are illustrated in Fig. 2. Some land-use types were difficult to categorize and require more explanation. “Wood- and shrubland, evergreen” and “cropping mosaic, cropping area <30 %,” for example, were assigned to the Forest category to make the 1993–1997 land use the most consistent with the 2003 land-use data. Forest quality categories (i.e., high cover density and medium–low cover density) were available for 1993 and 1997 data, but not for 2003 land use. As a result, although the quality of forest gives useful information about deforestation, they were both simply classified as forest in the study. No land-use change was allowed in protected natural areas (ICEM 2003a, b, c). The protected forest areas in the 3S Sub-basins were obtained from the 2003 ICEM Report.

Rain and stream flow data

Observed rain and stream flow data were collected to understand the existing hydrologic conditions in the 3S Sub-basins and to be used as a baseline for comparison with future water demand. Daily rainfall was available at 24 rain gages within and around the 3S Sub-basins, which cover the entire 3S Sub-basins fairly well. Stream flow data

Table 1 Re-categorized Mekong River Commission land-use classes

Simplified category	MRC original category, 1993 and 1997	MRC original category, 2003
Forest	Evergreen; high cover density; evergreen; medium–low cover density; Evergreen mosaic; mixed (evergreen and deciduous), high cover density; mixed (evergreen and deciduous) medium–low cover density; mixed mosaic; deciduous; deciduous mosaic; regrowth; wood- and shrubland; evergreen; bamboo; cropping mosaic, cropping area <30 %	Forest
Agriculture	Plantations; cropping mosaic; cropping area >30 %; agricultural land	Agriculture
Grass/shrub	Grassland; wood- and shrub land; dry	Rangeland
Urban	Urban or built-over area	Built-up area
Inactive	Barren land; water; other; wetland; and clouds	Barren land; marsh and swamp; water body

were obtained on a daily basis at six flow stations in the 3S Sub-basins. The list of these flow stations and their drainage areas are shown in Table 2 and mapped out in Fig. 3. Srepok has one upstream (Bandon) and one downstream (Lumphat) station. Both stations in the Sesan basin are located upstream, while the two Sekong stations are mid-basin.

Land-use change trend analysis

To assess land-use change trends, the 1993 and 1997 land-use area was broken down by each category and is summarized in Table 3. As a net, Grass/shrub and Forest were reduced by 470 and 303 km², respectively, while the agricultural area increased by 741 km². The net forest area reduced by 303 km², which is 966 km² change from forest to agriculture subtracted by 511 km² change from agriculture to forest. This latter change could be either regrowth of forest or error in land-use type assignment; if it did represent an error, the true reduction in forest area was even greater. Although, as discussed above, forest quality ratings were not included in the final analysis, it is important to note that both high- and low-density forest areas declined by 460 and 510 km², respectively, while mosaic forest area increased by 690 km². This indicates that the quality of the forest has been degrading.

Next, land-use change from forest to agriculture was studied at local scales. Figure 4 highlights areas where forest became agriculture between 1993 and 1997 in the Srepok River basin. Most deforestation occurred along the boundary between forested and non-forested lands, probably because of their better accessibility. Because we lacked a straightforward way to measure local accessibility, such as local road data, we assumed the density of agricultural cells within a certain radius of each forest cell would be a correlate that could be used as a proxy measure. This density was calculated using radii of 1.5, 2.5, 5, and 15 km for the 1993 forest cells. For any sample point where land use for 1993 was forest, it is given as attributes that flag

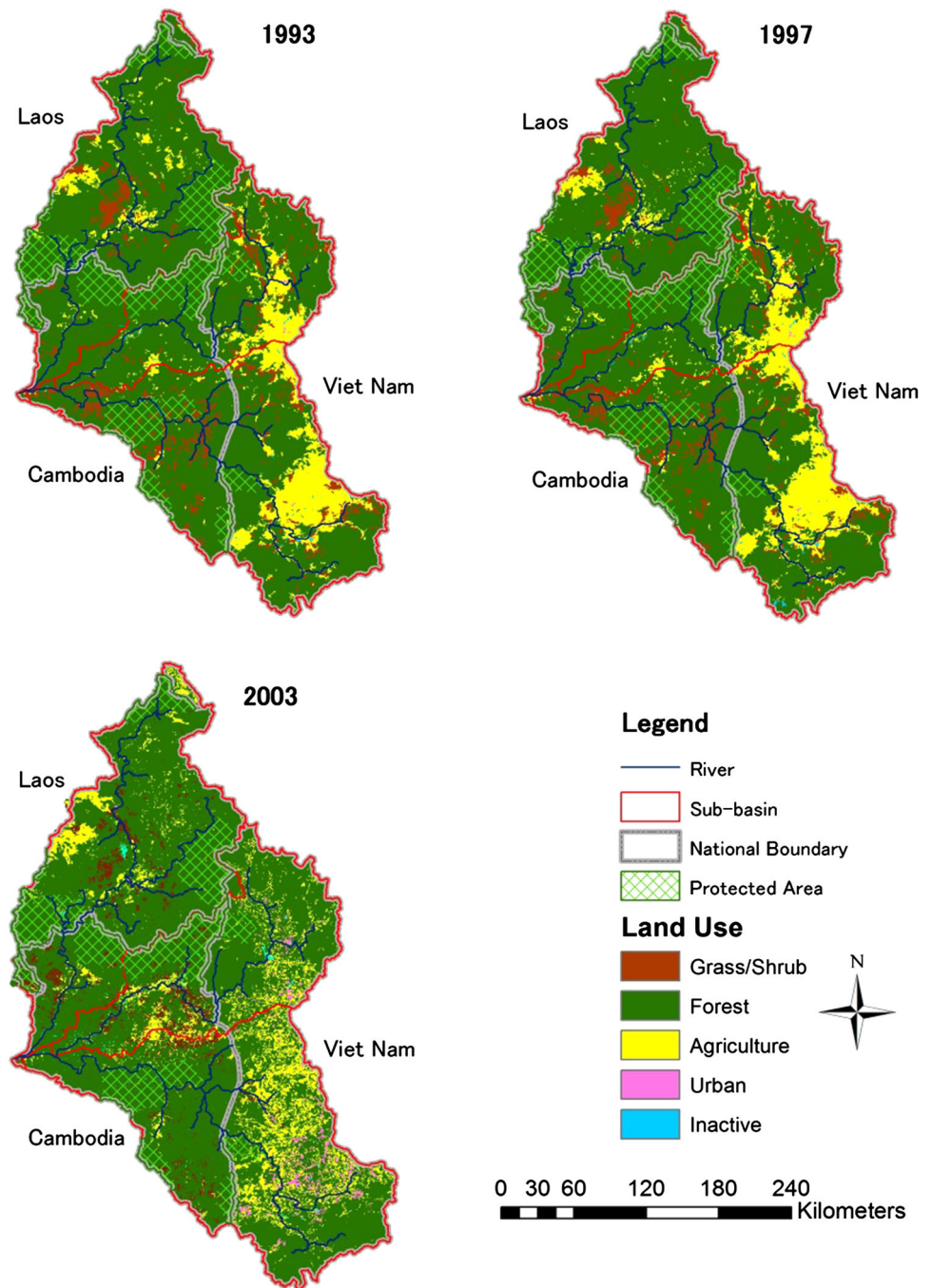
specifying whether the cell became agriculture in 1997 and the density of neighboring agricultural land. This table was then imported into the R statistical software (R Development Core Team 2008) for logistic regression. The regression results (Table 4) indicate that the density of nearby agricultural land is positively correlated with deforestation. Defining the neighborhood by a radius of 5 km shows the strongest regression among tested values [i.e., least Akaike's information criterion (AIC)]. The mean agriculture density within a 5-km radius of cells that were deforested into agriculture in 1993–1997 was 0.27, whereas that for the cells that remained forested was only 0.04. The mean values also supported the relationship.

Other variables, including elevation, slope, and population density, were incorporated into multivariate logistic regression models to gain more insight into the other factors impacting deforestation rates. Distance to rivers, known as an important driving factor for land-use change (Ty 2011), was not considered in this analysis because river data available for this research did not have enough upstream branches to take accessibility to water into account. The regression model with the most explanatory power included only the agricultural density measure discussed above and slope. The multilogistic regression result is shown in Table 5. Equation (1) shows the multiple regression analysis results using 5-km agriculture density and slope as explanatory variables. Agricultural density has a strong positive correlation, while slope has a negative correlation with the probability of deforestation.

$$P(\text{def}) = 7.07A_{r=5\text{km}} - 0.026S - 4.67 \quad (\text{AIC} = 3, 256) \quad (1)$$

where $P(\text{def})$ is the probability of deforestation (dimensionless); $A_{r=5\text{km}}$ the agricultural density within 5 km radius (dimensionless); S is the topographic slope (%).

The land-use change trend from 1997 to 2003 is briefly discussed. The urban area in Viet Nam expanded significantly between 1997 and 2003, while the urban area remained quite small in both Cambodia and Laos. The

Fig. 2 3S Sub-basin land use in 1993, 1997, and 2003**Table 2** List of flow monitoring stations

Station name	River	Country	Data period	Drainage area (km ²)
M. May (Attopeu)	Sekong	Laos	1998–2006	9,714
Veun Khene	Sekong	Laos	2001–2006	16,434
Kontum	Sesan	Viet Nam	1993–2006	2,848
Trung Nghia	Sesan	Viet Nam	1993, 1995–1998	3,208
Ban Don	Srepok	Viet Nam	1995–2006	10,687
Lumphat	Srepok	Cambodia	2000–2006	30,459

Fig. 3 Rain gages and flow stations in the 3S Sub-Basin

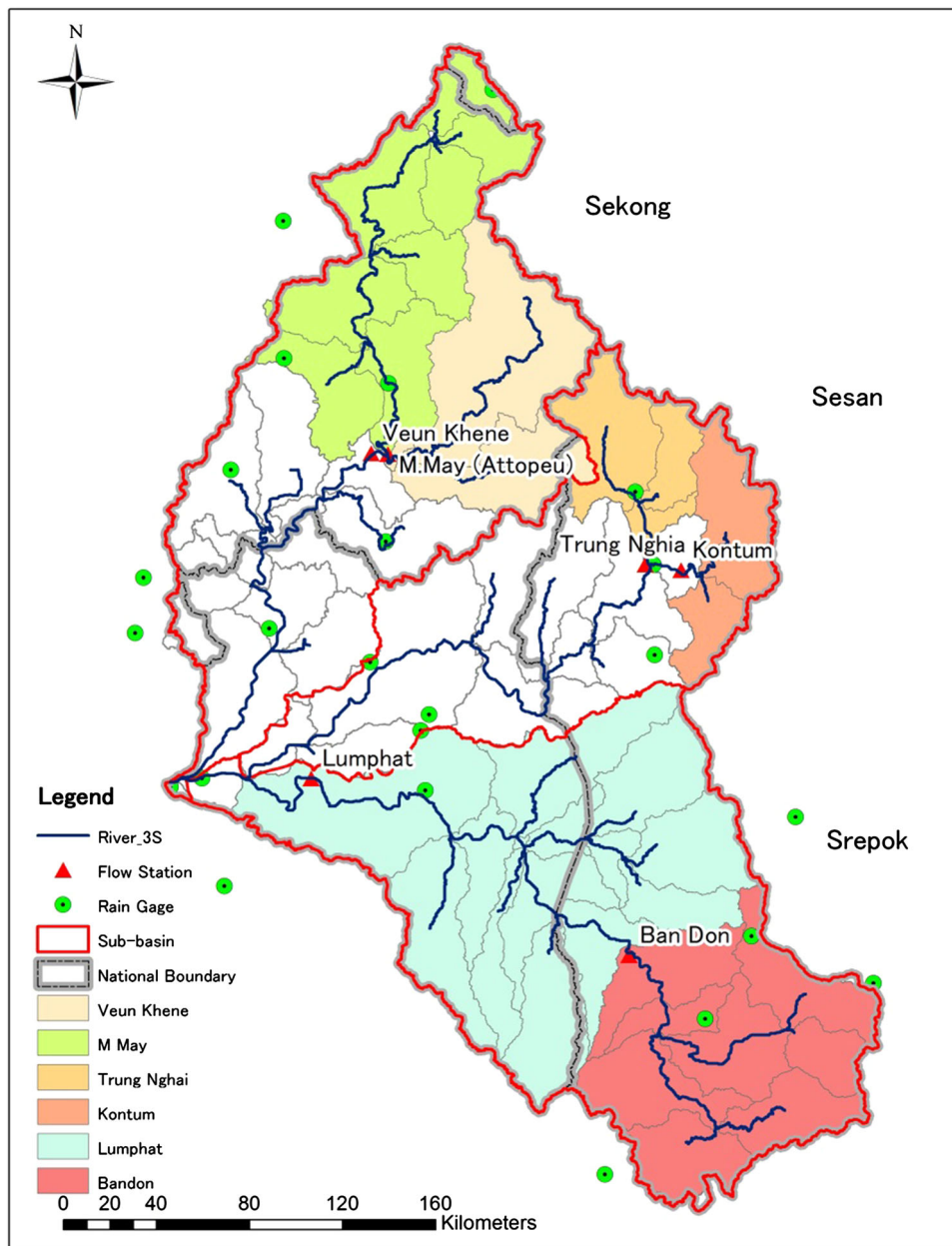


Table 3 Area breakdown of the land-use change from 1993 to 1997

Years	1993 (km ²)							Change 93–97 (km ²)
	Land use	Grass/shrub	Forest	Agriculture	Urban	Inactive	Total	
1997 (km ²)	Grass/shrub	4,462	70	13	0	0	4,545	−470
	Forest	242	63,293	511	0	0	64,046	−303
	Agriculture	305	966	8,152	0	1	9,425	741
	Urban	0	0	0	40	0	40	0
	Inactive	6	20	7	0	345	378	32
	Total	5,015	64,349	8,683	40	346	78,432	0

Fig. 4 Area where forest became agriculture between 1993 and 1997 in Srepok basin

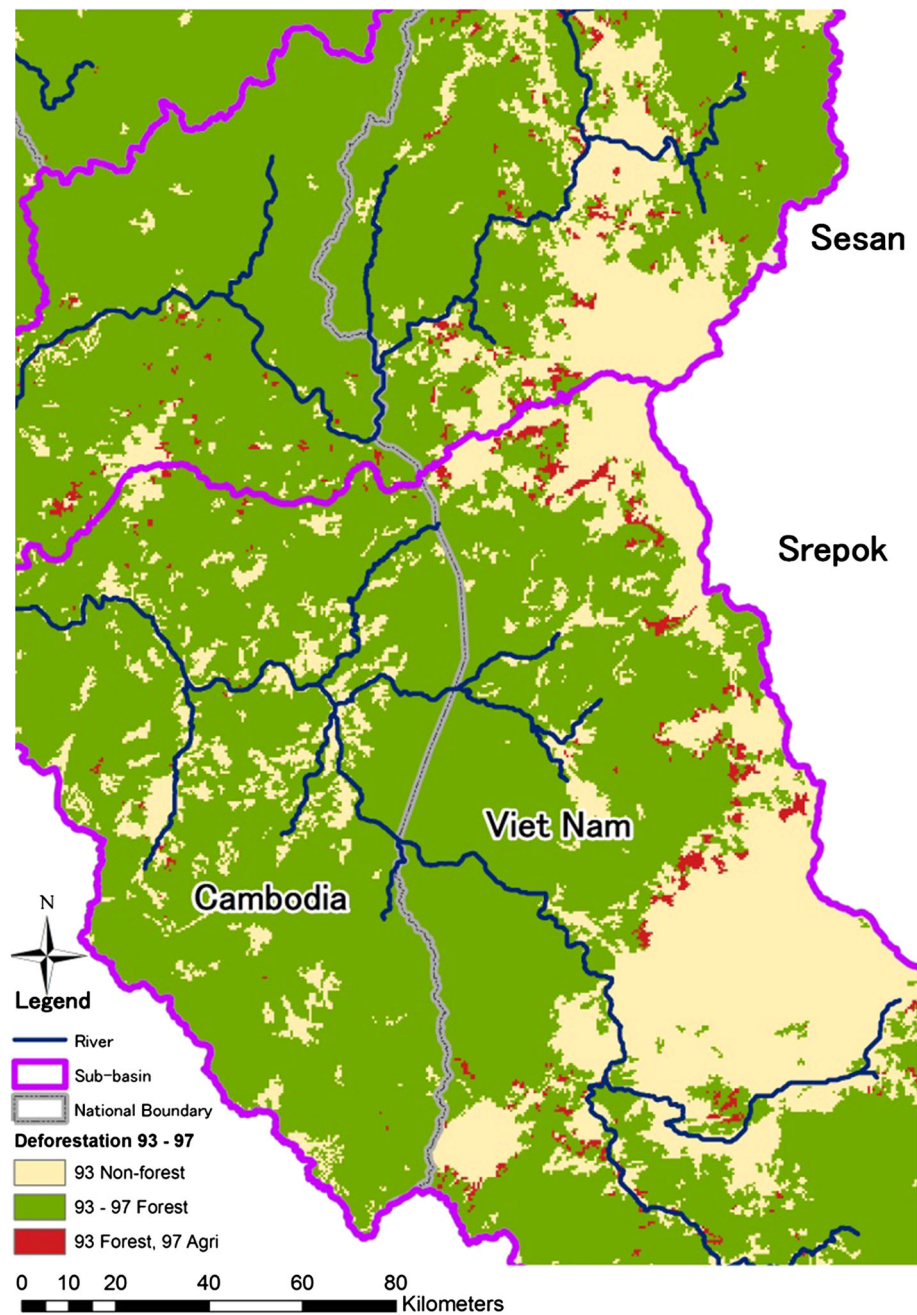


Table 4 Statistics summary

Radius (km)	Slope	Intercept	AIC
1.5	6.62	-4.75	3,521
2.5	6.95	-4.89	3,402
5	7.21	-5.02	3,330
15	7.25	-5.10	3,444
25	7.67	-5.18	3,551

AIC Akaike's information criterion

agricultural area in Viet Nam expanded in the Srepok basin from upstream to downstream up to the border with Cambodia. The density of the agricultural area in Viet Nam was reduced, but this is probably an artifact from the difference in data granularity rather than an actual reduction of agricultural area. In Laos, the agricultural area expanded upstream of the Sekong basin near the border with Thailand. In Cambodia, deforestation and agricultural area expansion were significant in the mid-Sesan basin. A

Table 5 Multi-logistic regression results

Variable	X_2		
	Slope (%)	DEM (m)	Population per 500×500 m cell
5 km agri density	7.07	7.25	7.57
X_2	-0.026	$1.5E-04$	$-8.8E-05$
Intersect	-4.70	-4.97	-5.03
AIC	3,256	3,295	3,292

AIC Akaike's information criterion

variety of studies in the forestry sector indicate that trends in forest change accelerated during 1997–2002 and further increased between 2002 and 2005 (SCW 2006).

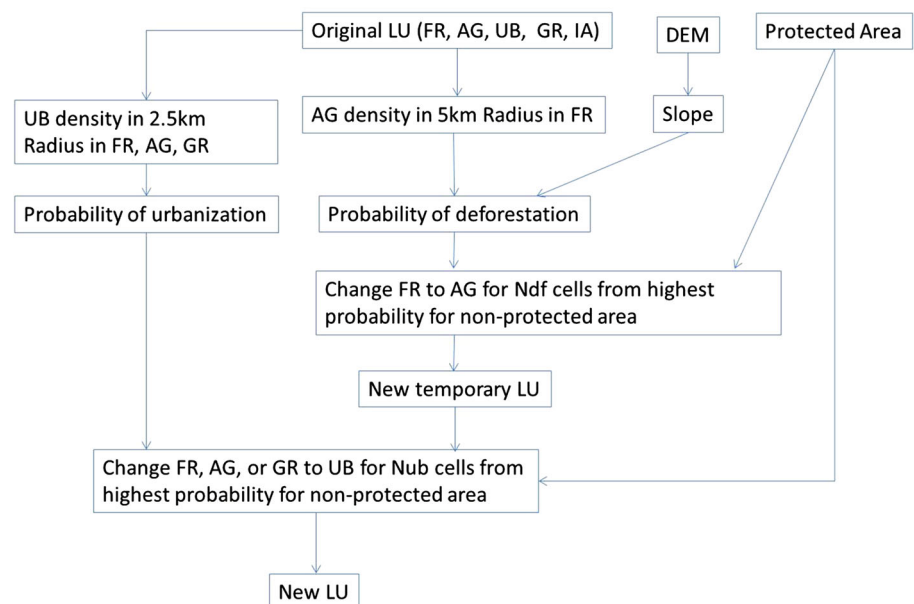
Land-use change forecast

Based on the land-use change trend analysis, a GIS-based tool was developed to forecast deforestation and urbanization sites in the 3S Sub-basins. Most land-use change prediction models using multilogistic regression employ distance to major roads as a driving factor of accessibility (Muller and Munroe 2004); however, in the 3S Sub-basins local road data were not available for the entire drainage area. Instead, the density of agriculture land use and slope were used to prioritize future deforestation and urbanization sites. The long-term deforestation rate is another important variable for land-use prediction. It could be highly dependent on the local economy and policies, which are not considered in this research. Instead, the deforestation rate was set as a user input variable in the tool to control the number cells that change from forest to agricultural land.

Urbanization is the other major land-use transition process in the 3S Sub-basins. Based on the MRC land-use data, the urban area increased significantly between 1997 and 2003. A similar logistic regression approach using the density of urban cells for each non-urban cell as a driving factor was tested, but it was not successful because almost no change was observed in urban areas between 1993 and 1997, and many new urban sites emerged between 1997 and 2003. It was assumed that most expansion of urban areas would occur from the outer boundary of existing urban areas and the likelihood of urbanization is linear to the 2.5-km radius urban density for non-urban cells. New urban cells were determined based on the likelihood and a pre-fixed urbanization rate in the similar way of forecasting deforestation sites. Urbanization trends should be analyzed with other driving variables such as population density when the latest land-use data become available.

Deforestation and urbanization site prediction concepts and parameters were incorporated in Python script, as illustrated in Fig. 5. It is a grid-base processing starting from existing land use as an input and ends with predicted land use after going through deforestation and urbanization sites forecast. The script calculates the probability of deforestation and urbanization, and sorts them so that a pre-fixed number of cells can be selected from the highest probability and transferred to a new land use. The total number of cells subject to land-use change is externally calculated and provided in the script based on deforestation and urbanization rates. The protected site is provided in the tool as an input so that during the sorting process, any cell from protected sites won't be selected for land-use transition even if some cells have higher probability of land-use change. Putting these individual processes into a single

Fig. 5 Land-use forecast process. *FR* forest, *AG* agriculture, *UB* urban, *GR* grass or shrub, *IA* inactive, *Ndf* number of deforestation, *Nub* number of urbanization



script helps reduce processing errors and provides a simple means to test different scenarios. The land-use forecast model can also be used as a planning tool. A user can set a goal such as the target deforestation rate for each watershed and let the model pick and visualize where deforestation would take place. The input data set or parameters can be changed to reflect more site-specific information.

Model verification was conducted using the 2003 Sekong Watershed land-use data since 1993–1997 land-use change was used to establish the deforestation forecast process and parameterization. As described in the previous section, the 2003 land-use data type is inconsistent with 1993 and 1997 data, especially on the Viet Nam side, and the Sekong Watershed has very little area from Viet Nam. Figure 6 shows the forecasted 2003 Srepok land use from the 1997

land use and published 2003 MRC land use. The forecasted map captures the agricultural growth trend relatively well in larger agricultural areas than in emerging smaller agricultural areas scattered in large forest areas because of the nature of the forecast driving force (i.e., agricultural density). Figure 6 also shows the land-use forecast result for each subcatchment, which was delineated based on DEM for water demand assessment. The agricultural area expansion was largely under-predicted for the subcatchment located at the upstream end of the Sekong Watershed. The northeast part of the subcatchment is in Viet Nam, and that level of rapid land-use change may have some other driving forces, such as planning and policy, which are not covered in this land-use forecast tool. Other than the subcatchment, the agricultural expansion forecast is relatively

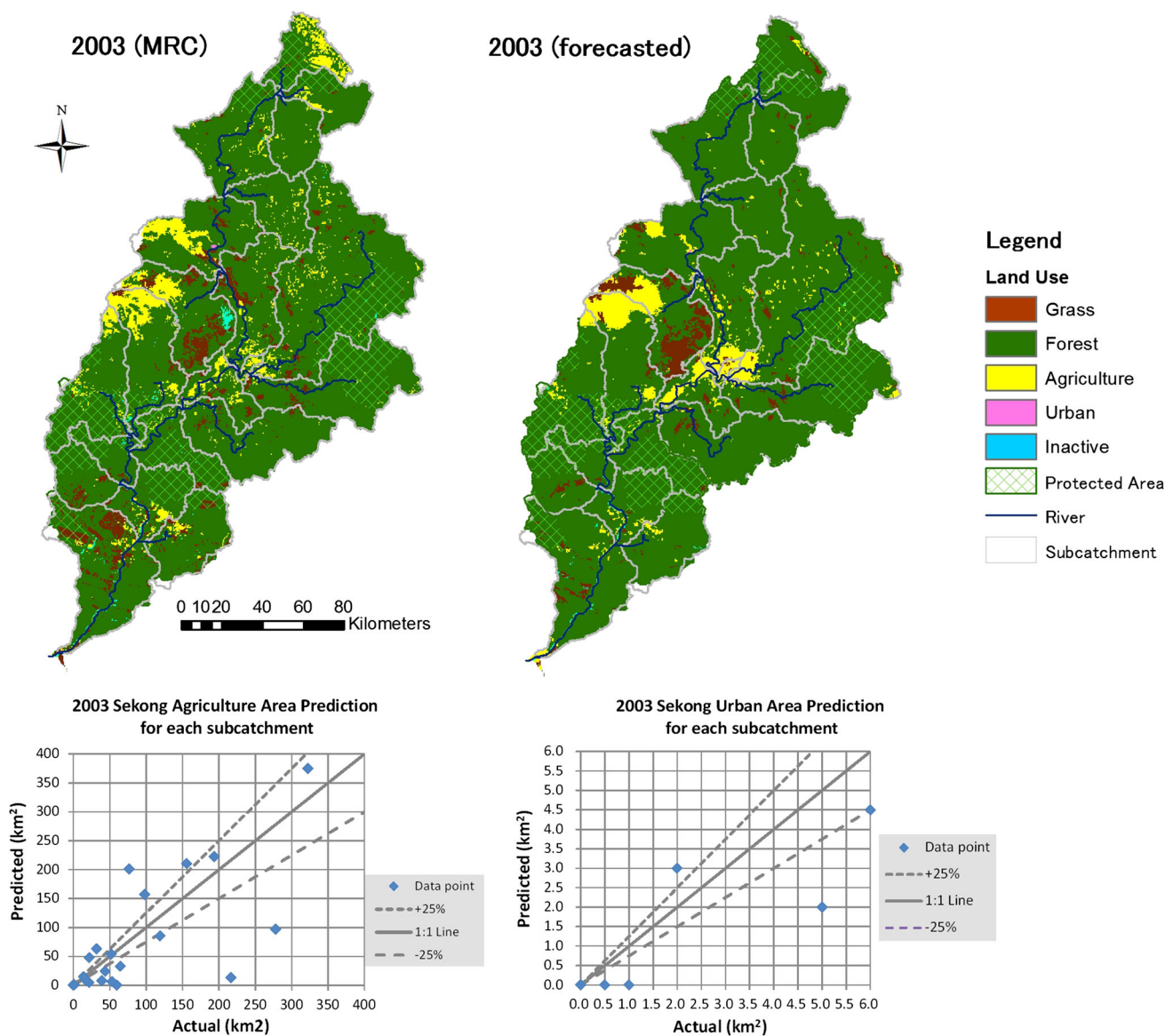


Fig. 6 Land-use forecast tool verification for Sekong Watershed 2003 land use

good, considering that water demand and availability analysis are not conducted at the cell level, but the sub-catchment level. There were very few urban areas in Sekong during that period, and this is why the number of data points in the graph is less than that for agriculture.

Impact assessment of land-use change on stream flow

To assess the degree of hydrologic alternation due to human activities, indicators of hydrologic alternation (IHA) and a range of variability approaches (RVAs) have been suggested (Richter et al. 1996). The use of these indices requires intensive data availability and calibration, which may not be possible for areas with limited data and resources. In this study, a simpler approach was taken: a future water demand increase due to agricultural and urban area expansion was estimated seasonally, and then it was compared with existing flow conditions. For spatial assessment, the entire 3S Sub-basin was subdivided into 64 smaller subcatchments, and water demand estimation was conducted for each subcatchment.

Agricultural water demand varies by growing crops and by season. As rainfall during the dry season is significantly low in the 3S Sub-basins, irrigation is needed to conduct dry season cropping, and it requires more diverted water than wet season agriculture. The amount of water needed for irrigation is significant. In most Asian countries, irrigation for agriculture accounts for over 80 % of the fresh water withdrawals (Xiao et al. 2006). In the 3S Sub-basins, the current total available dry irrigation area is about 0.8 % in Cambodia, 2.2 % in the Lao PDR, and 7.8 % in Viet Nam, (3Ss Basins 2011). The irrigated area ratio for each country was used to calculate dry-season agricultural water demand.

Water demand information was available mostly only for the Viet Nameese side of the Srepok River Basin. Unit area water usages for agriculture and urban areas were estimated from the information from Srepok and applied to the entire 3S Sub-basins. For agricultural water demand, as crop type information was not available for this study, general cropping water demand per unit area was used. For wet months (April–September), 0.27 million cubic meters per square kilometer per year (MCM/km²/year) and for dry months (October–March), 0.54 MCM/km²/year were used based on our previous study (Kawasaki et al. 2010). Estimated total irrigated agricultural water usage from the Srepok Watershed in 2004 was about 0.34 MCM/km²/year (i.e., 1,618 m³ for 4,789 km²/year agricultural area), which was used as a cross check of the unit area agricultural water demand used in this study. Urban water demand consists of industrial and domestic demand. Estimated annual urban water demand in the Viet Nam side of the upper Srepok River basin in 2004 was 51.8 MCM in total, of which

30.5 MCM was for industry (i.e., water for industrial areas: 10 MCM; processing industry: 4 MCM; mining industry: 4.5 MCM; material industry: 12 MCM) and 21.3 MCM for domestic use (Carl Bro 2005). For the urban area on the Viet Nam side of the upper Srepok River basin of 771 km², the unit area urban water demand was calculated as 0.067 MCM/km²/year.

The existing agricultural and urban water demands would not be constant until 2033. Agricultural water demand would increase significantly if irrigation is widely implemented, and urban water demand would increase if either population density or per capita water consumption increases. Two scenarios were prepared for water demand forecast to account for the variability in water demand per area. The first scenario, Sc.1, assumes the estimated existing unit area water demand would remain the same until 2033 to reflect a conservative estimate. The second scenario, Sc.2, as an aggressive scenario, assumes that by 2033 the irrigation system will be widely implemented, 30 % of the agricultural area will conduct cropping for each country during the dry season, and the unit area water demand for urban areas will be doubled from the 2003 level, corresponding to the expected population growth and per capita water use increase. In Table 6, inputs for the land-use and water demand forecast model are summarized.

Rainfall in the 3S Sub-basins varies by season significantly. Total rain is only 100–500 mm during the dry season (November–April), whereas it is typically 1,800–2,200 mm during the wet season from May to October. The very little rain in the dry season can cause shortages in the stream flow if agricultural and urban water usages are significant. To understand seasonal stream flow with respect to rainfall, the seasonal runoff coefficient, the ratio of river flow to the rainfall precipitated in the watershed, was calculated at the flow stations listed in Table 2. Rainfall was assigned for each meter's drainage

Table 6 Inputs for land-use and water demand forecast model

Input	Sc. 1	Sc. 2
Deforestation rate	3 %/5 year	3 %/5 year
Urbanization rate	20 %/5 year	20 %/5 year
Dry season agricultural water demand (MCM/year/km ²)	0.27	0.27
Wet season agricultural water demand (MCM/year/km ²)	0.54	0.54
Irrigated area (% per agricultural area)	Cambodia: 0.8 %, Laos: 2.2 %, Viet Nam: 7.8 %	30 %
Urban water demand (MCM/year/km ²)	0.067	0.134

area using the square inverse distance weighted average. The seasonal runoff coefficient was then calculated as the ratio of total flow to the total rain in each season.

Figure 7 shows the flow volume normalized by each drainage area with respect to total seasonal rainfall. All points with rainfall less than 500 mm are from the dry season and the rest are for the wet season. The slope of the regression curve was calculated as the mean seasonal runoff coefficient and is presented in Fig. 8. Findings from the seasonal runoff coefficient analysis are summarized below:

1. Dry season runoff coefficients are greater than 1.0 at the Bandon, Kontum, and Trunk Nghai stations, all of which are located in Viet Nam where many local ponds and dams were built and maintained for agricultural water use. The data imply that they can

provide a significant amount of storage as a total, and they store as much water as possible by the end of the wet season and release them for irrigation during the dry period. Stream flow at Lumphat was only slightly higher than the flow at Bandon. This implies that water withdrawal has been already significant along the Srepok River downstream of the Bandon stations.

2. In Sekong, dry and wet season runoff coefficients are close, which implies the river flow is less controlled by dams and reservoirs.
3. Annual runoff coefficients were the least at Srepok and highest at the Sekong River. This can be attributed to their land uses. Srepok has a larger agricultural area and less forest, while Sekong has a larger forest area and less agricultural area.

Fig. 7 Total seasonal flow with respect to corresponding watershed-wide seasonal rainfall

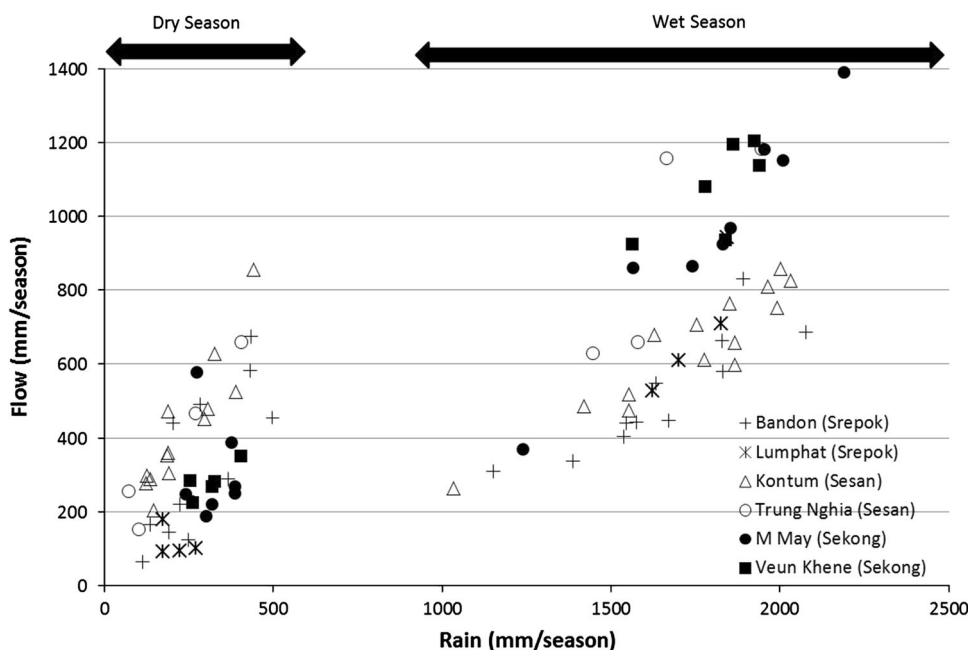
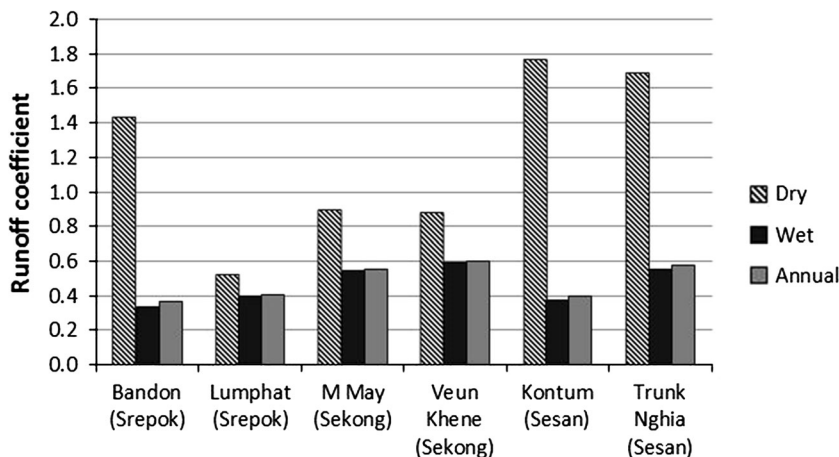


Fig. 8 Calculated average seasonal and annual runoff coefficient for each flow station



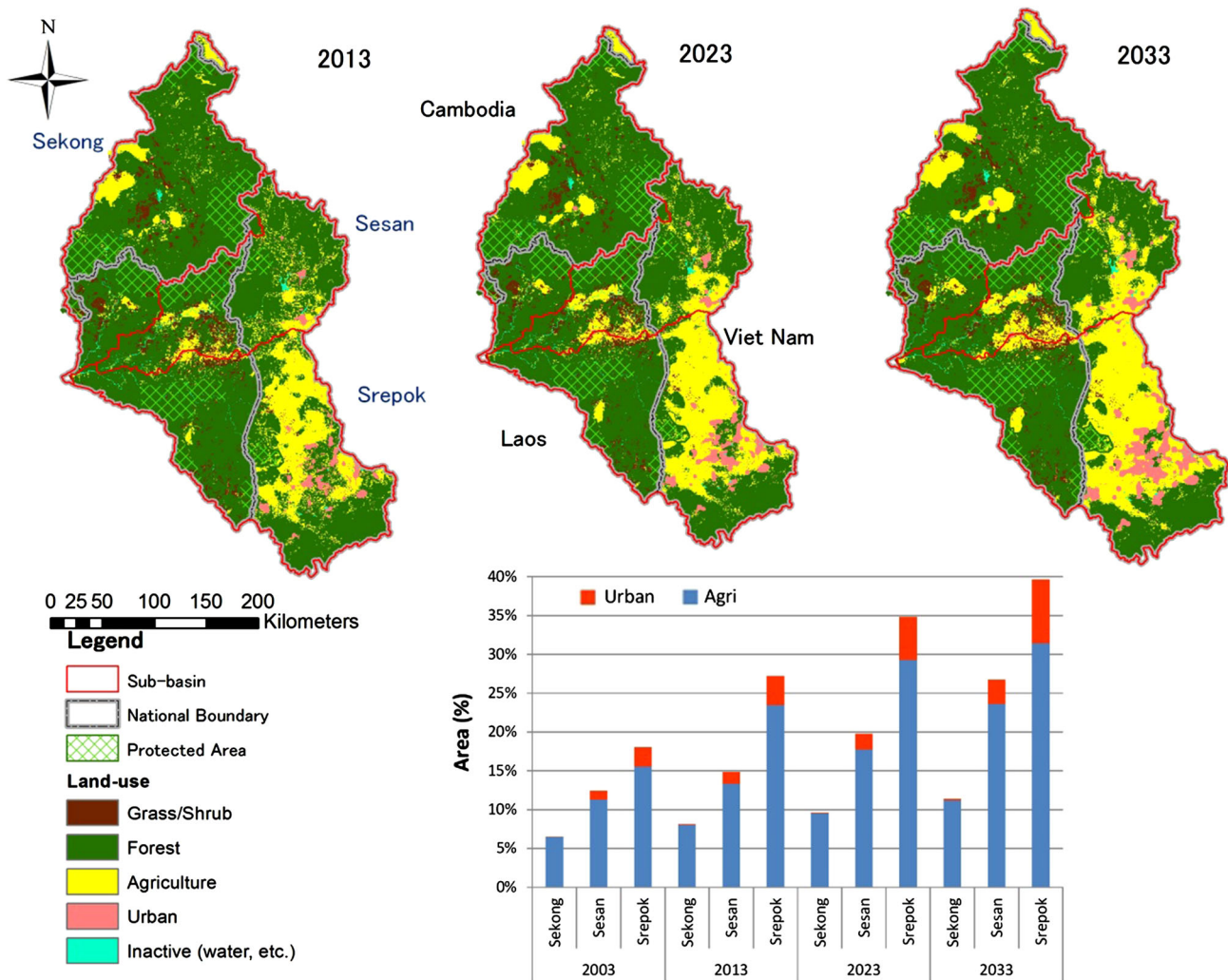


Fig. 9 Forecasted 2013, 2023, and 2033 land-use map and agricultural and urban area summary for the 3S Sub-basins

- To have a holistic picture of river flow in the 3S Sub-basin, flow should be measured at least at the downstream end of the Sekong and Sesan River. Existing and any new flow monitoring stations should be in operation for a long period to watch the long-term river flow trend.

The calculated dry seasonal runoff coefficients were applied to each meter's drainage area uniformly to calculate the mean dry seasonal flow in a typical dry year, which was defined as 200 mm of rainfall in 6 months. In Sesan and Srepok, dry seasonal flow had to be assumed downstream of the meter locations because no data were available at their downstream ends. For the non-metered streams, 40 % was assumed as the dry seasonal runoff coefficient to be conservatively low and close to the dry runoff ratio observed at Lumphat, the meter at the downstream end of the Srepok Basin. The calculated dry season flow for each subcatchment was accumulated toward downstream, and the accumulated flow was assigned to each river link.

Results

The developed land-use forecast tool was applied to the existing 2003 MRC land use to forecast future 3S land uses for 2013, 2023, and 2033. Based on current land-use change trends in the 3S Sub-basins (ADB 2009; SCW 2006; WB 2006; Tanji 2005), the pre-fixed rates of deforestation and urbanization were set as 3 and 20 % per 5 years, respectively, through 2033. The land use of the protected area (ICEM 2003a, b, c) was kept unchanged from 2003 throughout the simulation. Figure 9 presents the forecasted land-use maps and area summary for agricultural and urban areas for each watershed. Based on the forecast, both agricultural and urban areas would continue to grow on the Viet Nameese side of the Srepok and Sesan basins. In addition, there would be significant growth in the middle of the Sesan basin and northwest side of the Sekong basin in Laos. The area in Sekong is a large industrial plantation area based on the 2003 MRC land-use data, the

growth of which may be also dependent the on local economy and policy.

Existing 2003 water demand was calculated based on the 2003 land use and the specified agricultural and urban unit area water demands; future 2033 water demand was forecasted using the predicted 2033 land use for each

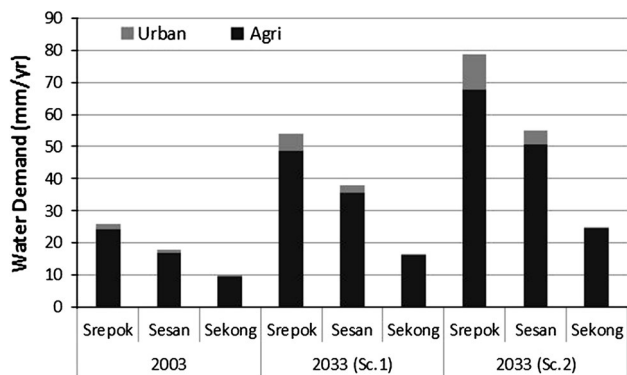


Fig. 10 Existing and future agricultural and urban water demand for each scenario

scenario, and the total for each sub-basin is shown in Fig. 10. In Fig. 11, the forecasted water demand was presented in two ways. First, water demand was calculated for each subcatchment, and it was presented as equivalent water depth to clarify regional differences; next the calculated annual water demand was assigned to each corresponding link as flow rate and accumulated toward downstream to evaluate the impact of increased water demand on stream flow. Existing water demand is prominent on the Viet Nam side of the Srepok basin. The 2033 water demands in both scenarios show water demand would increase the most in the Srepok then Sesan basin. At the downstream end of the 3S Sub-basins, total estimated annual water demands were 44, 87, and 128 CMS for 2003, 2033 Scenario 1, and 2033 Scenario 2.

The estimated average dry seasonal flow in the 3S Sub-basins under the existing conditions is shown in the left map in Fig. 12. Finally, to assess the potential impact of water demand increase on stream flow, water demand increase from 2003 to 2033 was compared with the estimated existing dry seasonal flow. Figure 12 shows the ratio

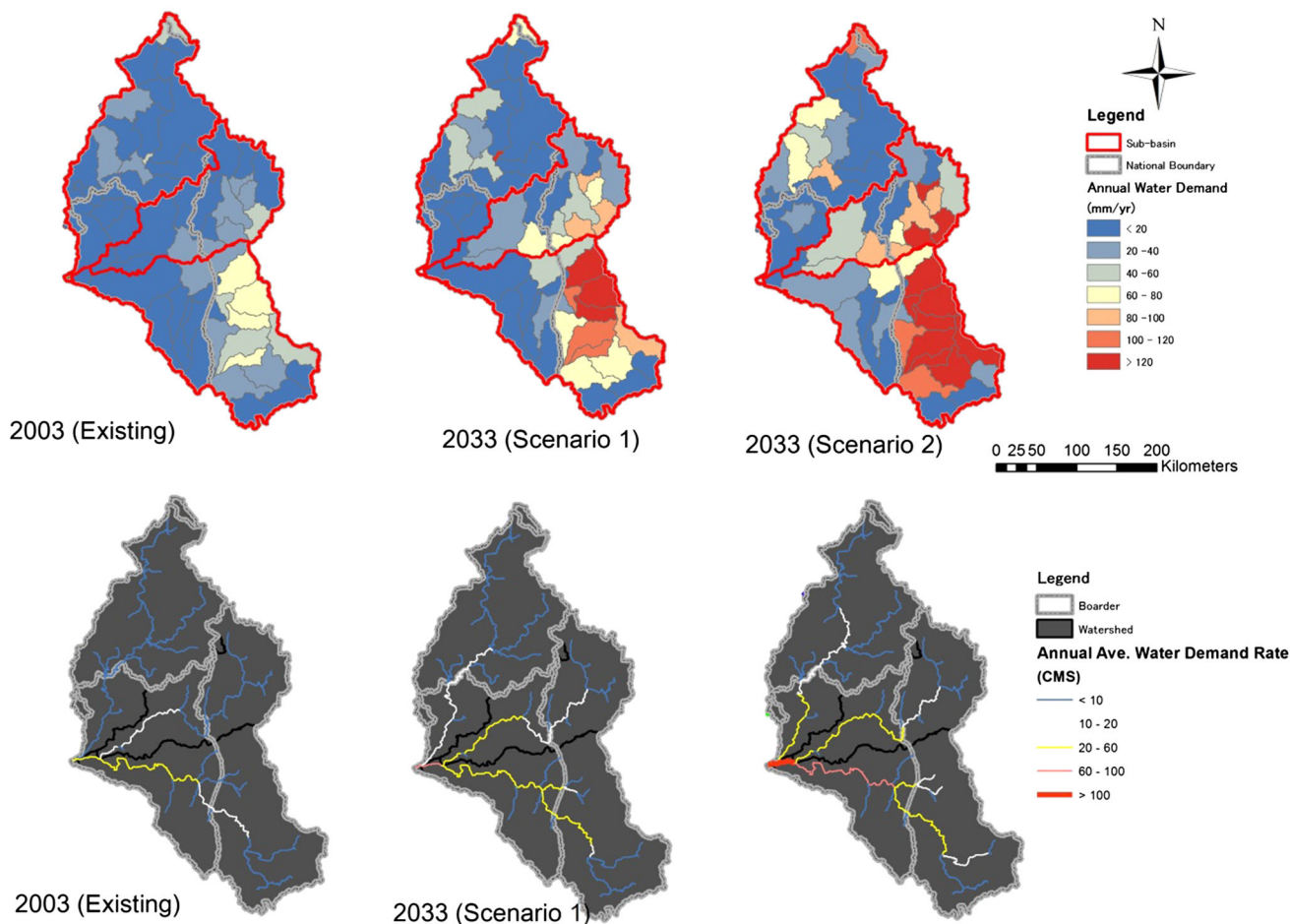


Fig. 11 Estimated 2003 and 2033 water demands for each subcatchment (*top*) and accumulated water demand for each river reach (*bottom*)

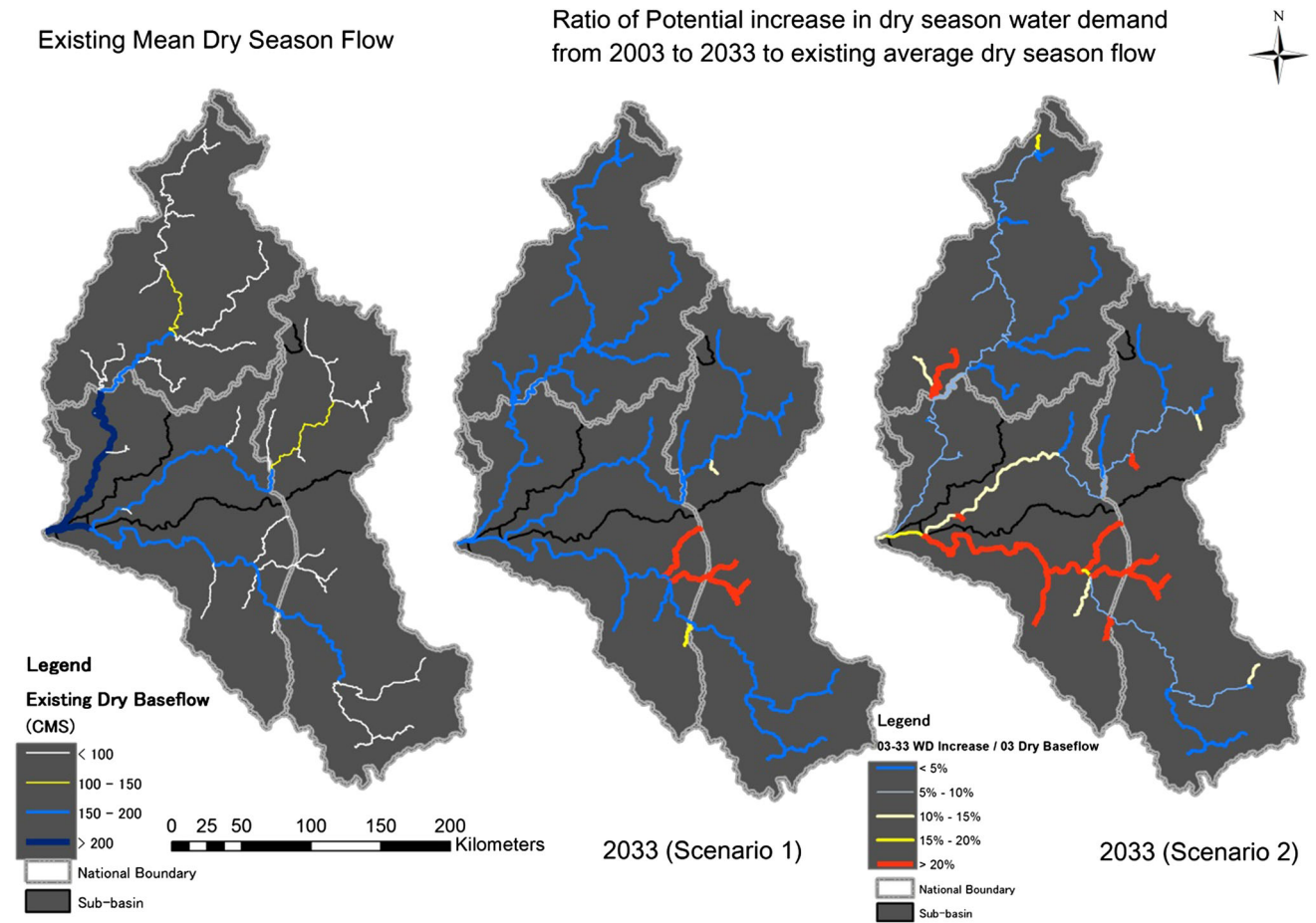
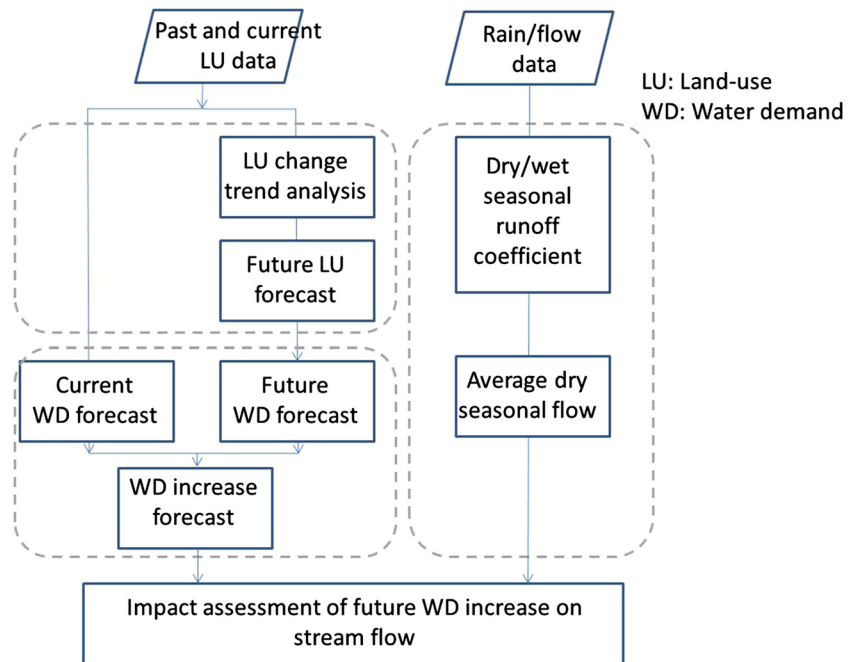


Fig. 12 Average dry seasonal flow in the 3S (*left*) and forecasted water demand increment from 2003 to 2033 with respect to existing dry seasonal flow

Fig. 13 Diagram of the overall methodology



of water demand increase to the estimated dry seasonal flow at each river link for both scenarios. The result shows that the largest water demand increase would impact the Srepok River basin the most, and it could be more than 20 % of the existing dry seasonal flow for the Cambodian side of the main Srepok River in Scenario 2.

Future water demand increase and its impact on seasonal flow could be better forecasted in the entire 3S watershed if (1) observed flow data are available at the downstream end of the Sesan and Sekong River, and (2) existing crop information is available. It should be also noted that return flow was not considered in the water demand estimation and its comparison with the dry weather flow.

Conclusions and discussion

“Is future land-use and growing future water demand very damaging to local stream flow in areas undergoing rapid agricultural and urban expansion?” This is the question that this research tries to approach in a practical way. An integrated methodology was proposed and applied to the 3S Sub-basins. Figure 13 illustrates the overall methodology in a diagram. The methodology consists of three components: land-use forecast, water demand estimate, and assessment of its impact on stream flow during the dry season. The land-use forecast model aims to simulate future deforestation and urbanization sites, and the model uses the density of growing land uses (i.e., agriculture and urban) as the primary driving factor to select deforestation and urbanization sites. The model was applied to 2003 MRC land use to forecast 2033 future land use under prefixed rates of deforestation (3 % per 5 years) and urbanization (20 % per 5 years).

Water demand assessment uses unit area water demand for agricultural and urban areas. For agricultural areas, dry seasonal water demand was assigned only for irrigated areas. Future water demands were then estimated based on predicted 2033 land use. Two scenarios were created for irrigated area growth because irrigation during the dry season can have a significant impact on local water resources. The existing stream flow condition was evaluated using the seasonal runoff coefficient. Results show the seasonal runoff coefficient varied significantly whether flow was regulated or controlled by local reservoirs and dams. It was also found that flow at the downstream end of the Srepok River was already low even under the existing conditions. The calculated dry seasonal runoff coefficient was applied for each flow station’s upstream areas to calculate average dry seasonal flow, and it accumulated toward downstream as the average dry seasonal stream flow. It was compared with the forecasted future water demands at each link of the 3S Sub-basins. Considering the

potential increase of water demand and the existing lower flow condition, the downstream side of the Srepok would be most impacted by the future land-use change.

Land-use and hydrological data were critical in the analysis. Although data were relatively well available to conduct the entire analysis in the 3S Sub-basins, some were limited in quality and quantity. Land-use types were inconsistent in 1993/1997 and 2003 land-use data, which made it difficult to conduct longer term land-use change trend analysis. Data that would help better forecast future water demand include flow monitoring data at the downstream ends of the Sekong and Sesan River basins and crop type information for existing agricultural area. If crop type information is available, crop-specific water demand can be used instead of the uniform unit-area rate for the water demand forecast.

There are limitations in the proposed methodology. With the land-use forecast model, deforestation and urbanization only expanded from land-use edges because the model used density of growing land use as a driving factor. Dams and reservoir data were not explicitly used in the research. The impact of dams and reservoirs on local stream flow was evaluated as a seasonal runoff coefficient, and its impact was implicitly figured into the model to forecast the impact of water demand on stream flow. Climate change, although an important factor for future precipitation and stream flow, was not considered in the methodology.

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