*Research article*

# Clarification of Water Use under the Complicated Irrigation System and its Modeling in the Boribo-Bamnak River Basin, Cambodia

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**Abstract** Effective, equitable, and sustainable management of water resources in river basins requires clarification of the current river basin situation and potential water use and water balance challenges. This study performs a water balance calculation involving an analysis of the appropriate water distribution of the Boribo-Bamnak River basin in Cambodia. This river basin covers the Boribo and Bamnak basins, both of which are interlinked by the Bamnak headworks. Together, this constitutes an integrated irrigation and drainage system. The Soil and Water Assessment Tool (SWAT) model was used to simulate rainfall-runoff in the Boribo-Bamnak basin over a study period of nine years (2010-2018), whereupon a simulated daily streamflow was applied to the water balance computation in the river basin according to the water distribution ratio at Bamnak headworks. The SWAT model yielded NSE, PBIAS, and RSR values of 0.55, 9.70, respectively, and 0.67 for model calibration. It also obtained values of 0.51, 3.70, and 0.70 for model validation of the three quantitative statistics, NSE, PBIAS, and RSR. The results of the calculated water balance indicate that although the Bamnak and Boribo Rivers have abundant water in the wet season, they have faced water shortages in the dry season during every year of the study period except 2016. Irrigation safety during the dry season is always low (approximately 10%). Attaining a desirable safety level of 80% in all existing irrigation areas would require additional water resources of approximately $6.0 \times 10^6$ $m^3$ for the Boribo River basin and $10^7$ $m^3$ for the Bamnak River basin. In light of the above findings, this study provides recommendations for coordination strategies to improve water resource management and development plans in the river basin.

**Keywords** water balance, water distribution, SWAT model, water shortage, irrigation, safety

## INTRODUCTION

Irrigation is a mechanism for increasing agricultural production, thereby increasing the income of rural poor regions, and developing the economy. In this regard, it is a focus of the Royal Government of Cambodia as described in the Rectangular Strategy (CSIRO, 2013), a planning and development document. As a result, Cambodia has witnessed the planning and implementation of many water resources and irrigation development in recent years, many of which have focused on river basins (Masahiko, 2013). However, the rapidly increasing demand for water has intensified the competition for water resources, highlighted concerns about the equity of water allocation, the sustainability of water usage, social friction among water-user communities, and the long-term sustainability of water resources and environmental impact of irrigation (MOWRAM and JICA, 2014). Indeed, the Boribo-Bamnak River basin (MOWRAM, 2018) has been affected by a large increase in water use demand due to the expansion of irrigated areas, as well as competition for water allocation between upstream and downstream users.

Thus, it is crucial to address water use by assessing water supply and water demand for appropriate management and planning of water resources in the basin. Researchers have used many methods to assess and predict the intra- and interannual availability of water resources within a catchment. Among these methods, decision support tools, such as hydrologic models, can help researchers to develop better management strategies for local and regional water resources (Chea and Oeurng, 2017). Hydrological models have been developed to help calculate water discharge more accurately, easily, and quickly than when using traditional measurement methods. One such method is the SWAT (Soil and Water Assessment Tool) model, which is a basin-scale model integrated with ArcGIS to improve the accuracy of simulated streamflow from rainfall and the physical properties of a basin (Ang and Oeurng, 2018). Regrettably, conventional water supply-oriented simulation models are often insufficient for addressing contemporary water resource management problems (Yates et al., 2005). Therefore, this study uses the SWAT model to simulate streamflow in a catchment and then performs the computation to describe the water balance and amount of water available for allocation under current conditions.

## OBJECTIVE

This study aimed to (1) predict water balances involving different scenario evaluations of water distribution at Bamnak headworks in the Boribo-Bamnak River basin, and (2) clarify current water management problems by studying water distribution at Bamnak headworks.

## METHODOLOGY

### Study Area

The Boribo-Bamnak River basin is located within two provinces of Cambodia, namely Kampong Chhnang, and Pursat, and has a total catchment of 1258 $km^2$ (Fig. 1). It covers the Boribo and Bamnak River basins, both of which are interlinked at Bamnak headworks (located on the Bamnak River, an upstream tributary of the Boribo River) and constitutes an integrated irrigation and drainage system (Fig. 2). The climate in the basin is influenced by tropical monsoon systems with distinct wet and dry seasons. The wet season, from May to November, receives approximately 90% of the total annual rainfall, ranging from 1200 mm to 1800 mm, and the dry season, from December to April, is characterized by the prevalence of hot and dry air with high potential transpiration demands. In the basin, agriculture is the predominant water-consuming sector and twelve main irrigation schemes have been developed; these have been classified into six schemes using water from the Bamnak River (Pursat Province) and the other six schemes using water from the Boribo River (Kampong Chhnang Province) as shown in Table 1.

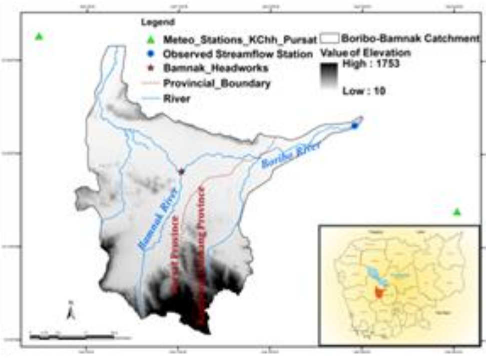


Fig. 1 Study area

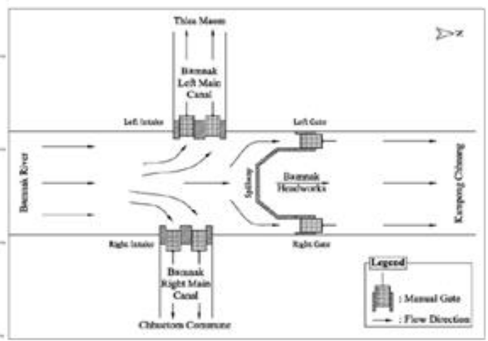


Fig. 2 Schematic Bamnak headworks

**Table 1 Identified irrigation schemes in the Boribo-Bamnak River basin**

| No | Scheme Name | Total Command Area (ha) | Total Farmland Area (ha) Using Water Irrigated from the Target Rivers | | |
|---|---|---|---|---|---|
| | | | ***EW*** | ***W*** | ***D*** |
| *I. Bamnak River (Pursat Province)* | | | | | |
| 1 | Bamnak | 6,000 | 600 | 2,400 | 1,122 |
| 2 | Chamkar Krouch | 350 | 100 | 100 | - |
| 3 | Kampong Lor | 130 | 30 | 100 | 70 |
| 4 | Thlea Maom | 3,500 | 500 | 2,000 | - |
| 5 | Tram Mneash | 1,200 | 120 | 1,080 | 30 |
| 6 | Trapeang Khley | 300 | 100 | 200 | - |
| | *Sub-total* | *11,480* | *1,450* | *5,880* | *1,222* |
| *II. Boribo River (Kampong Chhnang Province)* | | | | | |
| 1 | Achang (1) | 10,300 | - | 1,400 | 750 |
| 2 | Dambok Krahorm | 150 | - | - | 150 |
| 3 | Kamping Tatao | 700 | - | 300 | 700 |
| 4 | Lum Hach | 3,289 | - | 3,289 | - |
| 5 | O Rolus | 640 | - | 640 | - |
| 6 | O Chenhchraim | 170 | - | 170 | - |
| | *Sub-total* | *15,249* | - | *5,799* | *1,600* |
| | **Total** | **26,729** | **1,450** | **11,679** | **2,822** |

*(1) Including four sub-schemes: Banteay Thlok, Kum Reab, O Sanlang, and Svay Ka'er*
*EW: Early wet season rice, W: Wet season rice, D: Dry season rice*
*Sources: (1) MEIHO Engineering Inc. 2018. Final report, Survey on basic information in river basins (phase 3), JICA; (2) Field study in Cambodia, April 2022.*

## SWAT Modeling Approach

The SWAT model is a physically based, semi-distributed, agro-hydrological, continuous hydrological model developed to enable water resource managers to determine the most appropriate strategy or solution by considering the impact of different management practices on streamflow and non-point source pollution (Arnold et al., 1998).

In this study, the SWAT model was used to simulate, using available data, daily streamflow in the catchment of Boribo-Bamnak. Running a comprehensive SWAT model requires spatial input data including a Digital Elevation Model (DEM), land use, soil type, and meteorological data. Each data input was obtained from different sources, such as a DEM with a resolution of 30 m downloaded from ASTER GDEM2. Soil-type data with a resolution of 250 m was retrieved from the FAO soil map, and land use data were obtained from the Ministry of Water Resources and Meteorology (MOWRAM) of Cambodia. Daily meteorological data from 2007 to 2018 were provided by the Provincial Department of Water Resources and Meteorology (PDWRAM) of the Kampong Chhnang and Pursat Provinces, respectively. The observed daily streamflow at Boribo River station was required by SWAT-CUP to be calibrated between 2010 and 2015 and validated from 2016 to 2018 using the SUFI-2 method.

## Irrigation Water Requirements

The irrigation water requirement (IWR) is the amount of water needed to fulfill crop water requirements after effective rainfall, thereby ensuring a disease-free crop in large fields under non-restricting soil and water conditions and adequate fertility (Solangi et al., 2022). In this study, the average five-day water requirements for proposed cropping patterns of each crop variety in the Boribo-Bamnak River basin were estimated using the following equation Eq. (1)

$$IWR = (ET_0 \times K_c + PR + LP - ER)/IE \tag{1}$$

where $IWR$ is the irrigation water requirement for a division unit, $ET_0$ is reference evapotranspiration, calculated using the FAO Penman-Monteith method (FAO, 1998), $K_c$ is the crop coefficient defined based on FAO guidelines (for the case of paddy) since there is no observed data in the basin, $PR$ is the percolation rate (3.0 mm per day in this study, referring to JICA (2012)), $LP$ is the land preparation requirement, estimated by assumption using two methods of direct sowing under dry soil and transplanting under wet soil, ER is effective rainfall, calculated following JICA (2012), and *IE* is irrigation efficiency, obtained from water losses during conveyance and application to the field and defined following JICA (2012).

## Water Balance Study

The water balance was computed using a simplified diagram of the present condition of water resource facilities and irrigation water uses in the river basin (Fig. 3). The fundamental formula for a water surplus or deficit at a major point where a large amount of water is taken from the river is expressed as follows Eq. (2)

$$Q_{sd} = Q + Q_{rf} - Q_q - Q_{rmf} \quad (2)$$

where $Q_{sd}$ is the surplus or deficit of water at the calculation point, $Q$ is the river runoff from the relevant catchment area, $Q_{rf}$ is the return flow from paddy fields to the river (17% of the irrigation demand was used in this study after JICA, 2012), $Q_q$ is a summation of irrigation water demand, and $Q_{rmf}$ is the river maintenance flow, which was supplied to the downstream part of the river in order to preserve the river as a part of the landscape (0.1 $m^3$/s/100 $km^2$ was applied, based on the JICA, 2012).

The water balance calculation was executed from upstream to downstream following the natural flow direction for a time unit of five days for nine years (2010–2018). To confirm the security of the irrigation water supply to the Boribo-Bamnak River basin, this calculation was performed as follows: (1) identification of the impacts of existing irrigation schemes in the basin, (2) assessment of impacts from the viewpoint of the safety levels of irrigation water supplies, and (3) assessment of the impacts of water distribution at Bamnak headworks.

An evaluation of the safety level of the irrigation water supply is made as follows (1) a water balance was performed at each scheme outlet in terms of deficit or surplus, i.e., the net available flow subtracting the irrigation water requirement (IWR), such that a deficit occurs when the net available flow is less than the IWR, (2) for each year, when the deficit was more than or equal to four continuous five-day units (20 days), this year is judged to be a deficit year, and (3) each irrigation scheme is successful if the safety level is less or equal to 1/5 (80% dependability). The formula to define the safety level at each irrigation scheme is expressed as Eq. (3)

$$Safety\ Level = (x + 1)/n \quad (3)$$

where *x* is the number of years with twenty-day successive deficits (irrigation failures) and *n* is the total number of simulated years. In this study, for nine years of successful irrigation, the 1/5 term can be stated as 2/9. Consequently, if the safety level is less than or equal to 2/9, the scheme is deemed successful, and we can determine that water resources are secured with 80% dependability.
To calculate the probability of the deficit/storage required for a safety level 1/5, we use Eq. (4)

$$y = c \times \ln(x) + b \quad (4)$$

where *y* is the probable deficit in x% non-exceedance, *c* and *b* are constants, ln is the natural logarithm, and x is the percentage of exceedance.

Water distribution at Bamnak headworks is an important point of the water balance calculation in the Boribo-Bamnak River basin. In this study, water distribution at Bamnak Headworks was incorporated into the water balance calculation in two ways. (1) Water was allocated equally to Pursat and Kampong Chhnang (i.e., 50% each) during the wet season (May–October) and allocated 75% to Pursat Province, and 25% to Kampong Chhnang Province during the dry season (November to April); refer to the field study in Boribo-Bamnak River basin, March 2022. (2) Water was allocated equally to Pursat and Kampong Chhnang Provinces (i.e., 50% each) either in the wet season or dry season (refer to the regular rule of fair and sustainable water distribution).

Additionally, water management was considered through a study on actual water distribution using existing data for discharge at Bamnak headworks from 2018 to 2019.

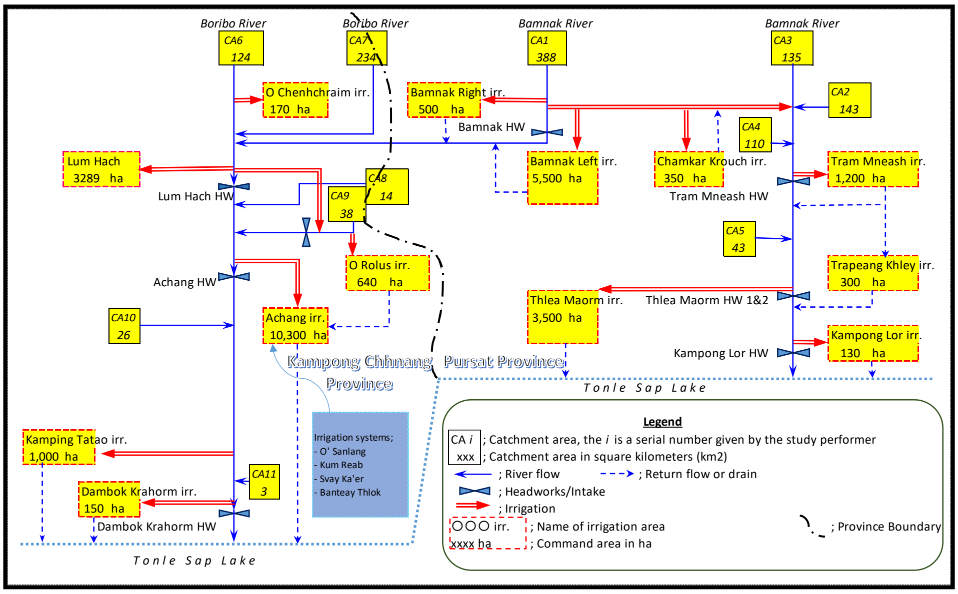


**Fig. 3 Diagram of present-day water use in the Boribo-Bamnak River basin**

## RESULTS AND DISCUSSION

### SWAT Calibration and Validation for Streamflow

Figure 4 represents the simulated streamflow for the daily time step (calibrated from 2010 to 2015 and validated from 2016 to 2018) compared with observed data. The model performance is shown to be satisfactory in terms of calibration and validation with NSE values of 0.55 and 0.51 according to the evaluation criteria of Moriasi et al. (2007). We noted, however, that the hydrological simulations did not perform well during the dry season (November-April) due to inaccuracies in the estimated discharge at the observation station. The estimated discharge was calculated *via* water level observation by applying H-Q curves produced by the River Basin Water Resources Utilization project of JICA in 2018. Because these water discharge measurements were conducted only during high-water level periods, they did not cover the entire range of water levels experienced during periods when the relationship between water level and discharge is known to be stable. This relationship was, therefore, not defined for low flow conditions.

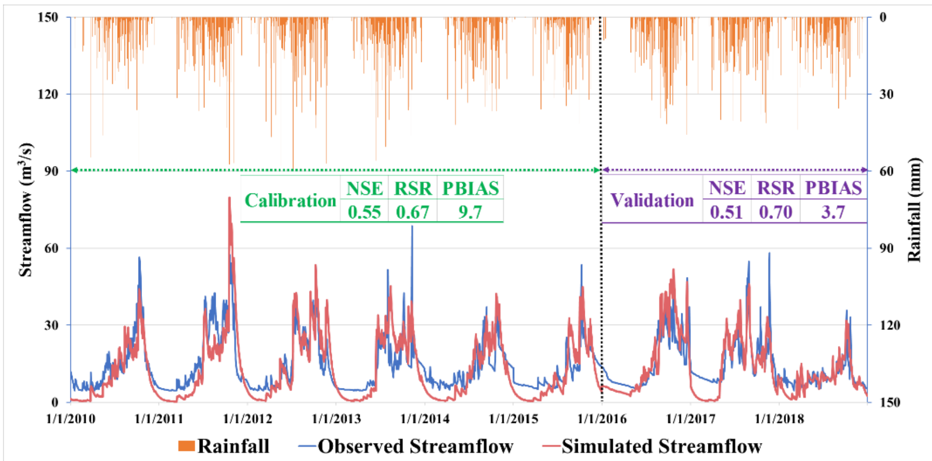


**Fig. 4 Daily streamflow during the calibration and validation periods**

Referring to the information about water management in the Boribo-Bamnak River basin obtained through a field study conducted in March 2022, we found that the water level in the river was very low in the upstream region, drying up in the downstream region during the dry season. This variation is known to be challenging for the farmers in the river basin and has been reported by numerous farming households located in the upstream and downstream parts of the river basin (27 households in Pursat Province and 6 households in Kampong Chhnang Province). Simulated streamflow from the SWAT model was used for the water balance study.

### Water Balance Study

The water balances of the Bamnak River in Pursat Province and the Boribo River in Kampong Chhnang Province were calculated taking into consideration the ratios of water distribution at Bamnak headworks. Fig. 5 shows the results of the first case of water distribution at Bamnak headworks (wet season: Pursat = Kampong Chhnang = 50%; dry season: Pursat = 75%, Kampong Chhnang = 25%). Fig. 6 illustrates the results of the second case (wet season and dry season: Pursat = Kampong Chhnang = 50%). Water resources are sufficient during the wet season; however, water shortages frequently occur in the dry season. Indeed, a water deficit occurred annually during the dry season every year between 2010 to 2018, except for 2016. Thus, the irrigation safety is approximately 10% either in Pursat and Kampong Chhnang Province under these two ratio cases. This indicates that the Bamnak and Boribo Rivers lack sufficient water to guarantee 80% irrigation safety for existing areas of irrigation. By calculating the probability of the deficit/storage required for a safety level of 1/5, the water deficit is estimated in both cases as approximately 6 million cubic meters in Kampong Chhnang Province and 10 million cubic meters in Pursat Province.

The Bamnak and Boribo Rivers have abundant water during the wet season. The irrigation of wet season paddy was examined without dry season rice taken into the calculation; as a result, the irrigation safety during the wet season paddy was 80% in both provinces by virtue of the natural river flow alone. Under these conditions, water distribution at Bamnak headworks is not considered to be an issue during the wet season (May to October).

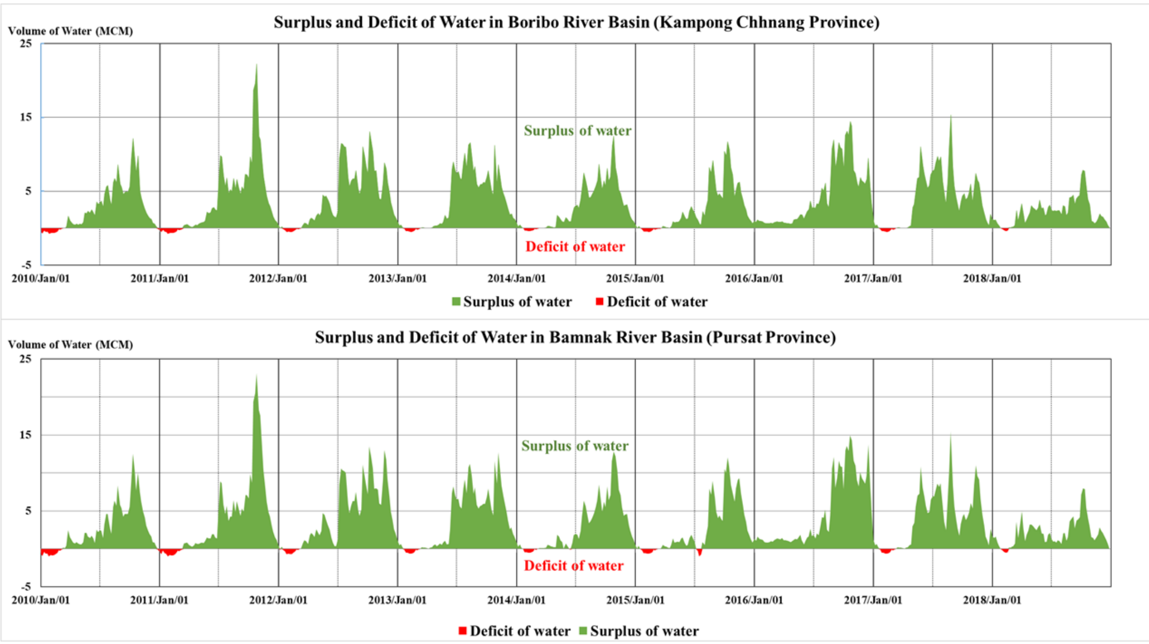


**Fig. 5 Hydrograph showing surplus and deficit water between 2010 and 2018**

*Water allocated at Bamnak headworks: Pursat = Kampong Chhnang = 50% during the wet season; and Pursat = 75%, Kampong Chhnang = 25% during the dry season.*

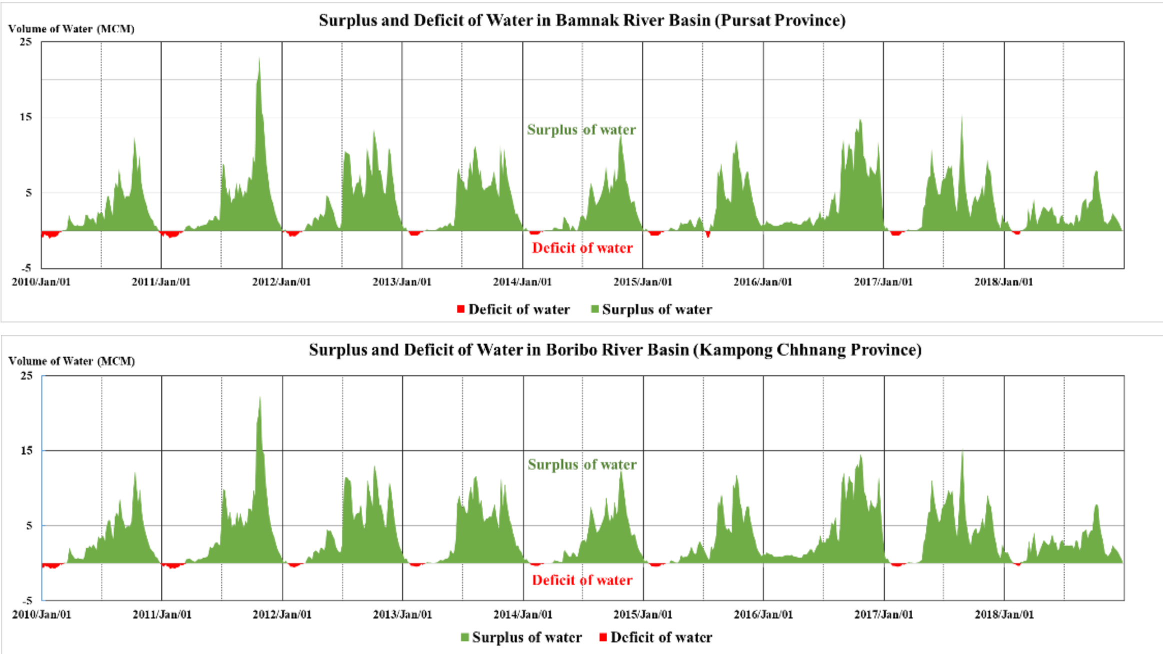


**Fig. 6 Hydrograph showing water surplus and deficit between 2010 and 2018**

*Water allocated at Bamnak headworks: Pursat = Kampong Chhnang = 50% during the wet and dry seasons*

According to our calculations, although 100% of the water was distributed to Pursat during the dry season, it was insufficient to maintain the irrigation water required for existing dry-season rice in this province (1,222 ha). Moreover, river maintenance flow in both provinces could be secured in case equitable water distribution at Bamnak was made and dry season rice in both provinces was not taken into calculation.

## Water Distribution at Bamnak Headworks

The actual water distribution at Bamnak headworks was estimated based on available data for 2018 and 2019. Which were obtained from Pursat PDWRAM (recorded water level) and the JICA River Basin Water Resources Utilization project (H-Q curve). The water distribution at Bamnak headworks was found to be similar to the distribution ratio of the first case study in the water balance calculation (Fig. 7). On average, the ratios of water distribution were made as 40% and 30% to Kampong Chhnang Province, respectively, and 60% and 70% to Pursat Province, respectively, in the wet and dry seasons.

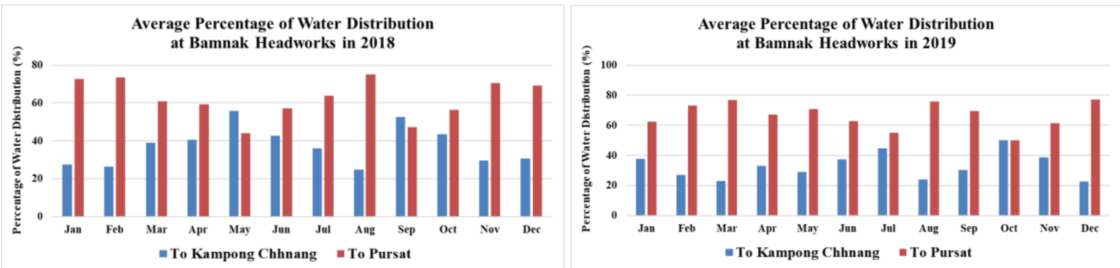


**Fig. 7 Water distribution at Bamnak headworks in 2018 and 2019**

To assist water management in the basin, the Bamnak headworks were constructed in 2010 by MOWRAM with the base idea of allocating 50% of the water available to Pursat Province and 50% to Kampong Chhnang Province. In practice, this concept has been difficult to realize because the total width of four intake gates to Pursat Province is 8.8 m (=2.2 × 2 × 2) when the total width of two spillway gates to Kampong Chhnang Province is 3.0 m (=1.5 × 2) (Fig. 2). Therefore, fair, and sustainable water distribution at Bamnak headworks must be made based on a consensus between province stakeholders.

## CONCLUSION

This study has shown that the SWAT model is an appropriately sensitive model for predicting daily streamflow in the Boribo-Bamnak River basin. It provides insights into the importance of better analysis relationships, which depends mostly on the quality of available data and the necessity for additional hydrological observation.

The results of water balance studies in the Boribo-Bamnak River basin clearly indicate that the availability of water in the river is not sufficient to supply all water demands for existing irrigation schemes in Pursat and Kampong Chhnang Provinces. Water shortages occurred in the dry season almost every year during the study period (2010-2018). Therefore, to ensure sustainable water use in the river basin, a study of the possibility of constructing reservoir dams in the upstream region of both the Bamnak and Boribo Rivers should be considered.

In terms of water management at the Bamnak headworks, this study suggests that Pursat PDWRAM should make efforts to communicate with Kampong Chhnang PDWRAM and related local authorities, for example, the Farmer Water User Communities, in order to appropriately implement water flow operations that ensure sustainable water use while avoiding conflicts among water users.

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