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Quantification of Environmental Flow Requirement of the Khun Dan Prakan Chon Dam Using Hydrological-Hydraulic-Habitat Simulation Methods

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Abstract

With increased water demand, reservoir operation has become more complex with the need to quantify the exact amount of water needed for each demand sector. The environmental flow requirement, also known as instream flow is regarded as the first-prioritized objective of the multipurpose water resources projects in Thailand. The capability of reservoirs in Thailand to allocate water for environmental needs depends on available supply, strategies and operating policy. Therefore, this study aims to assess the environmental flow requirements of Khun Dan Prakan Chon Dam using three methods; 1) the hydrological method (Tennant, Tessmann, 7Q10, FDC, and VMF), 2) hydraulic method (R2CROSS and wetted perimeter) and 3) habitat simulation method, using the PHABSIM model for physical habitat simulation of aquatic organisms in the Nakhon Nayok River. The hydrological approach was performed under the historically-naturalized flow data of the NY.1B station and established hydrologic flow regime during low flow and high flow months. The environmental flow rates obtained from two hydraulic methods were based upon field observations at the NY.1B station significantly. However, the biological conditions and interactions of aquatic organisms in the river were not principally characterized in hydrologic and hydraulic approaches. In addition, the estimated results performed by habitat simulation model gave an additional meaning of ecological flow needs mainly for aquatic habitat conservation in the river. By integrating the conditions of hydrologic and hydraulic flow regimes as well as the habitat conservation objectives, environmental flow rates of 8-10 cm were recommended to determine the downstream release of Khun Dan Prakan Chon Dam; these recommendations were very close to those derived using the Tessmann, 7Q10 and PHABSIM methods-Tennant and flow duration curve methods.

Keywords: Environmental flow requirement; Instream flow requirement; Reservoir operation; Khun Dan Prakan Chon Dam; Nakhon Nayok River

Introduction

In the field of water resources engineering, water requirement can be classified into 2 categories; (1) offstream flow requirement and (2) instream flow requirement. The offstream flow requirement refers to water withdrawn from groundwater or surface water sources for public water supply, industry, irrigation, livestock, thermo-electric power generation and other uses [1]. The Instream Flow Requirement (IFR), also known as the "Environmental Flow Requirement (EFR)" refers to water used for such purposes as hydropower, navigation, water quality improvement, fish propagation and recreation [1]. Environmental flow requirement studies were first conducted in USA in the 1940s by the US Fish and Wildlife Service; formal legislation only appeared on the statutes in 1971. Following enforcement of the National Environmental Policy Act in 1969 and Water Resources Planning Act in 1965, the concept of environmental flow requirement began to be practiced in other countries including UK, Australia and New Zealand. However, the concept has yet to be widely adopted in Europe, South America and Asia. One of the problems encountered is that definition of environmental flows and protocols vary from country to country [2]. For example, "Instream flow" is used in USA to refer to a specific streamflow that is adequate to meet specific needs for the purpose of planning and management of a stream or river [3]. Meanwhile, the water required for environmental flows is also called "Instream flow Requirement" in South Africa, "Environmental Flow" in Zimbabwe, "River Flow Objectives" in Australia, and "Minimum Acceptable Flows" in Mozambique.

Few studies have been conducted on the environmental flow requirements for dam and reservoir operation in Thailand, focusing on preservation of ecosystems along the course of the river. However, the environmental flow requirement is today considered a high priority and a main objective of the multipurpose project to meet downstream needs. Quantifying environmental flow requirements in river basins in Thailand has mostly been based on the minimum low flow data during the most critical dry year; the flow duration curve is usually the preferred estimation method [4-5].

This study aims to estimate the environmental flow requirements downstream of Khun Dan Prakan Chon Dam (KDPC) in the Nakhon Nayok River, which is a part of the Upper Nakhon Nayok Basin Development Project in Hin Tang Sub-district, Mueang District, Nakhon Nayok Province. The Nakhon Nayok River originates in the Khao Yai National Park and flows to the southwest to join the Prachin Buri River and become the Bang Pakong River as shown in Figure 1. The KDPC was designed for multiple objectives, including both instream and offstream water uses including irrigation for the Tha Dan and Nakhon Nayok Irrigation Projects. The reservoir water also serves domestic consumption in Nakhon Nayok District and neighboring areas. It can help in mitigating flood and drought in refilled and drawdown periods and also reduce soil acidity and water quality problems in the area. With an increasing level of human activity and water demand on the downstream reach of KDPC, it is important to study and quantify the environmental flow requirement in the area.

Environmental flow estimation methods are generally classified into four categories; 1) hydrological; 2) hydraulic; 3) habitat simulation; and 4) holistic [6-7]. These methods are applied at river and basin scales, especially for flow restoration projects, and are also used for assessing the ecological status of main rivers at national and regional levels.

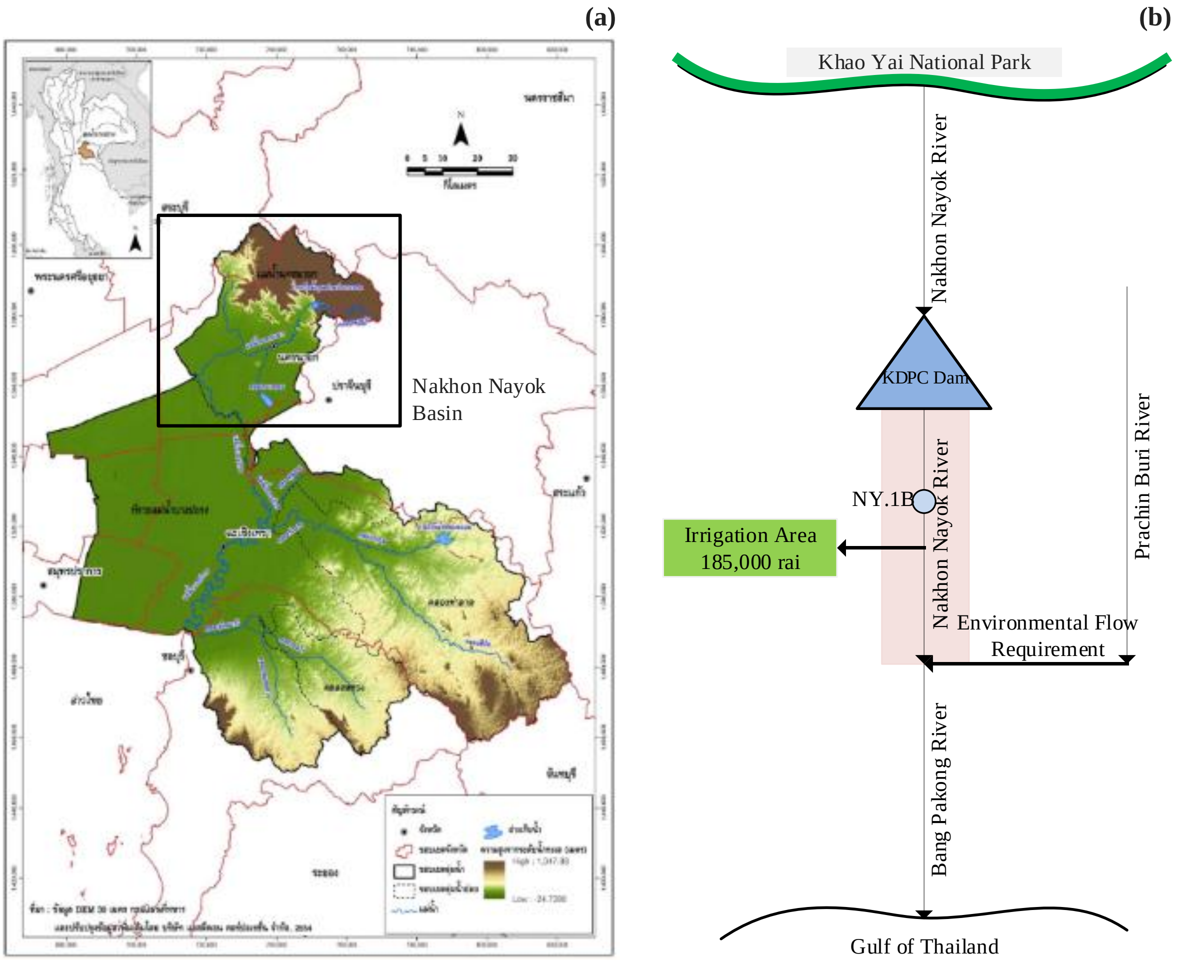

Figure 1 Geological map of (a) Nakhon Nayok Basin [4] and (b) schematic diagram of the Nakhon Nayok River.

The hydrological method is the simplest and most widely used approach for environmental flow assessment, and requires the long-term historical data set of unregulated or naturalized daily flows as an input. It is easily implemented at local or global scales depending on the level of complexity and availability of hydrological data, especially for water resource planning purposes. This method is widely used to cross-check suggested environmental flow regimes derived using other assessment methods as an increased safety measure. However, the method does not take into account seasonal or annual changes, stream morphology or direct ecological links. The hydrological method is therefore considered appropriate for non-controversial situations, but is not recommended for studies that require a higher level of detail. There are numerous hydrologically-based methods, including the Tennant method, Tessmann method, 7Q10 flow method, Flow Duration Curve (FDC) method and the Range of Variability Approach (RVA) method [8].

The hydraulic method establishes the relationship between the desired hydraulic features and discharge to calculate flow recommendations. This method is sometimes known as a transect method or wetted perimeter method because it deals with measuring and interpolating changes in hydraulic variables such as the wetted perimeter, average depth, and average velocity. The implicit assumption is that there is a threshold value of the selected hydraulic parameters to maintain the regulated flow regime and stream health [3]. Hydraulic method is used at a local scale when river cross-section measurements are available, and is especially suitable for rivers with well-defined single channels. However, this method is not well suited for braided rivers because inflection points cannot readily be found in such systems. As with the hydrological methods, hydraulic methods are recommended in situations with insufficient information on the river systems, e.g. where no historical flow records exist. This method is simple and should be used with caution to set a conservative protection limit [9]. The R2CROSS and wetted perimeter methods are the most widely used hydraulically-based methods, requiring data on driver hydraulic measurements, channel geometry of the specific site and field observation.

The habitat simulation method is also referred to as the ecological method. It requires information on the connection between discharge rate data and the physical aquatic habitat to estimate environmental flow requirement. However, a field survey is also required to select the key variables as descriptors of the ecological habitat and discharge rates. The habitat simulation method considers not only changes in physical habitat with streamflow but also the habitat preferences of a key species to determine the amount of habitat available over a range of streamflows.

The holistic method is a discussion-based approach which considers all aspects of flow and as far as possible retains the natural hydrological regime. It addresses all relevant components of the river ecosystem and also takes the associated societal needs into account. The holistic approach is sometimes referred to as the 'expert panel approach', where environmental flow standards are developed in a workshop setting where river-specific data is considered by a multi-disciplinary team of experts (typically including hydrology, geomorphology, water quality and various ecological specialisms). Holistic methods have the advantage of using an interdisciplinary approach to achieve an optimal compromise among competing water users for freshwater ecosystems [9].

Due to the limitations of data available in the study area, these three methods; 1) hydrological method, 2) hydraulic method and 3) habitat simulation method, were employed to quantify the environmental flow downstream of KDPC. The estimated results among these different methods were finally compared and selected to simulate a long-term operation of Khun Dan Prakarn Chon Reservoir. The simulated results performed with the estimated environmental flow requirement were compared with operational data to generate recommendations for future operation of the reservoir.

Methods

1) Data sets used for quantification of the environmental flow requirements

The observed flow datasets before dam construction (during 1974-2004) and after dam construction (during 2005-2014) were gathered from the Royal Irrigation Department (RID) at the downstream gauging stations. Due to the non-natural condition of regulated flow after dam construction, a stationary test was employed to check the consistency and naturalized manner of these two datasets. The surveyed river cross section of the NY.1B station updated in 2014 and rating curve were also used. In addition, data on a study of species and numbers of aquatic animals in the Khun Dan Prakan Chon Reservoir and downstream conducted by the Inland Fisheries Resources Research and Development Bureau in 2009 [10] were also used to assist in understanding local aquatic habitats over their entire life stages. The types and sources of data gathered are summarized in Table 1.

Table 1 Research data gathered from related agencies in Thailand

Types of data	Station	Period	Agencies
Cross-section data	NY.1B [a]	2014	RID [b]
Rating curve	NY.1B [a]	2014	RID [b]
Daily runoff data	NY.1B [a]	1974 - 2014	RID [b]
Daily meteorological data	NY Basin	2009 - 2014	TMD [c]
Daily reservoir data	KDPC Dam	2007 - 2014	RID [b]
Aquatic animals data	NY River	2009	NYPFO [d]

Note: [a] NY.1B station (located in the Nakhon Nayok River, Ban Khao Nang Buat, Mueang District, Nakhon Nayok Province)
[b] Royal Irrigation Department (RID)
[c] Thai Meteorological Department (TMD)
[d] Nakhon Nayok Provincial Fisheries Office (NYPFO)

2) Selection of environmental flow requirement estimation methods

The hydrologically-based methods including Tennant, Tessmann, 7Q10 Flow, FDC, and VMF methods were selected for this study. Calculating environmental flow requirement by these methods were carried out based on historical flow records and hydrologic flow regimes as referred. The hydraulic-based method requires more direct survey data to determine the relationships between physical and hydraulic data at the specific site, including channel geometry, average velocity, mean depth, and observed discharge. Therefore, the R2CROSS and wetted perimeter methods were used in this study. This method quantifies environmental flow requirement by the R2CROSS macro which was initially developed by the Colorado Water Conservation Board (CWCB) and specifically applied in the state of Colorado in 1996. The instream flow requirement is defined as the quantity of water required to preserve the natural environment to a reasonable degree. Field data such as stream discharge and channel profile are input into the R2CROSS Microsoft Excel Spreadsheet which includes executing macros. The R2CROSS can produce a wide range of calculated information in numeric and graphic forms, depicting anticipated stream conditions at various flow rates, such as velocity, depth, and percent wetted perimeter. It is important to stress that the R2CROSS method signifies the proper site selection and standard field techniques for field data collection. It requires data from only a single stream transect in riffle stream habitat types, where flow is controlled by channel geometry rather than downstream flow control. The R2CROSS model uses Manning's equation to predict average depth, average velocity, percent wetted perimeter, and other instream hydraulic parameters at discharge both above and below the field-measured stream discharge [11]. After the R2CROSS is modelled, the environmental flow requirement is then accounted based upon three principal hydraulic criteria; 1) average depth, 2) average velocity, and 3) percent wetted perimeter to maintain the aquatic habitat. Due to many verification processes performed in the R2CROSS model, the hydraulic parameters generated from R2CROSS are also used to determine the P-Q relation for the wetted perimeter method. This method assumes that there is a direct relation between the wetted perimeter in a riffle and aquatic habitat in streams [12]. The catastrophe point on the P-Q curve is consequently located to determine the environmental flow requirement needed for aquatic habitat protection.

For the habitat simulation method, the PHABSIM model was used to simulate physical habitat under different flow regimes. PHABSIM was developed by US Geological Survey since 1984 for maintaining streamflow to protect aquatic organisms in streams. It can predict the physical microhabitat changes associated with flow alterations [13]. PHABSIM requires cross section, discharge, coordinate, and suitability curves as the input data. Once the data are entered and checked, the calibration and simulation processes of the hydraulics including water surface elevation and flow velocity are then carried out using any or a combination of the three available water surface elevation models; STGQ, MANSQ, WSP and velocity model; VELSIM. Finally, the user can select the appropriate habitat model and set the desired modelling options to generate the habitat-flow relationship. The habitat measured output is normally known as the Weighted Useable Area (WUA), expressed in units of microhabitat area per unitized distance along a stream. This WUA-Q curve obtained from PHABSIM is brought to finally quantify the environmental flow requirement.

Description of the environmental flow requirement methods and input data required were summarized in Table 2 and the sequences of operation performed by three estimation methods are presented in Figure 2.

In the absence of river cross-section data along the Nakhon Nayok River, formulating the R2CROSS model was done using the surveyed cross section only at the NY.1B station and other hydraulic parameters from a single river transect above and below the NY.1B station with a total length of 100 m. The river cross-section and channel index were assumed to be constant along this river length. The observed water level and velocity on 1 Aug 2014 were used for model calibration as shown in Figure 3(a).

At the final step, a reservoir operation model for KDPC was constructed by applying the water balance principle, and calibrated until it resembled the actual behavior of the reservoir operation system. Estimating parameters in the simulation and calibration processes was based upon the reservoir release needed to satisfy downstream water requirements for both offstream and instream flows. The long term data of observed outflow through irrigation outlet during 2007-2014 and the estimated environmental flow values were then used as inputs to simulate the long-term operation of the Khun Dan Prakan Chon Reservoir. Their operational performances in terms of reliability as well as the water quality index of the downstream river were then compared to the existing case to provide recommendations for future reservoir operation.

Table 2 Description of environmental flow requirement methods selected in this study

Types	Data input	Selected method	Developed in
Hydrological method	Daily flow (>10 years)	Tennant	1976
		Tessmann	1980
		7Q10 Flow	1997
		FDC	1915
		VMF	1997
Hydraulic method	Flow velocity, average depth, stream discharge, wetted perimeter, river cross section data	R2CROSS	1979
		Wetted perimeter	1980
Habitat simulation method	Flow velocity, river cross section data, fish species	PHABSIM model	1982

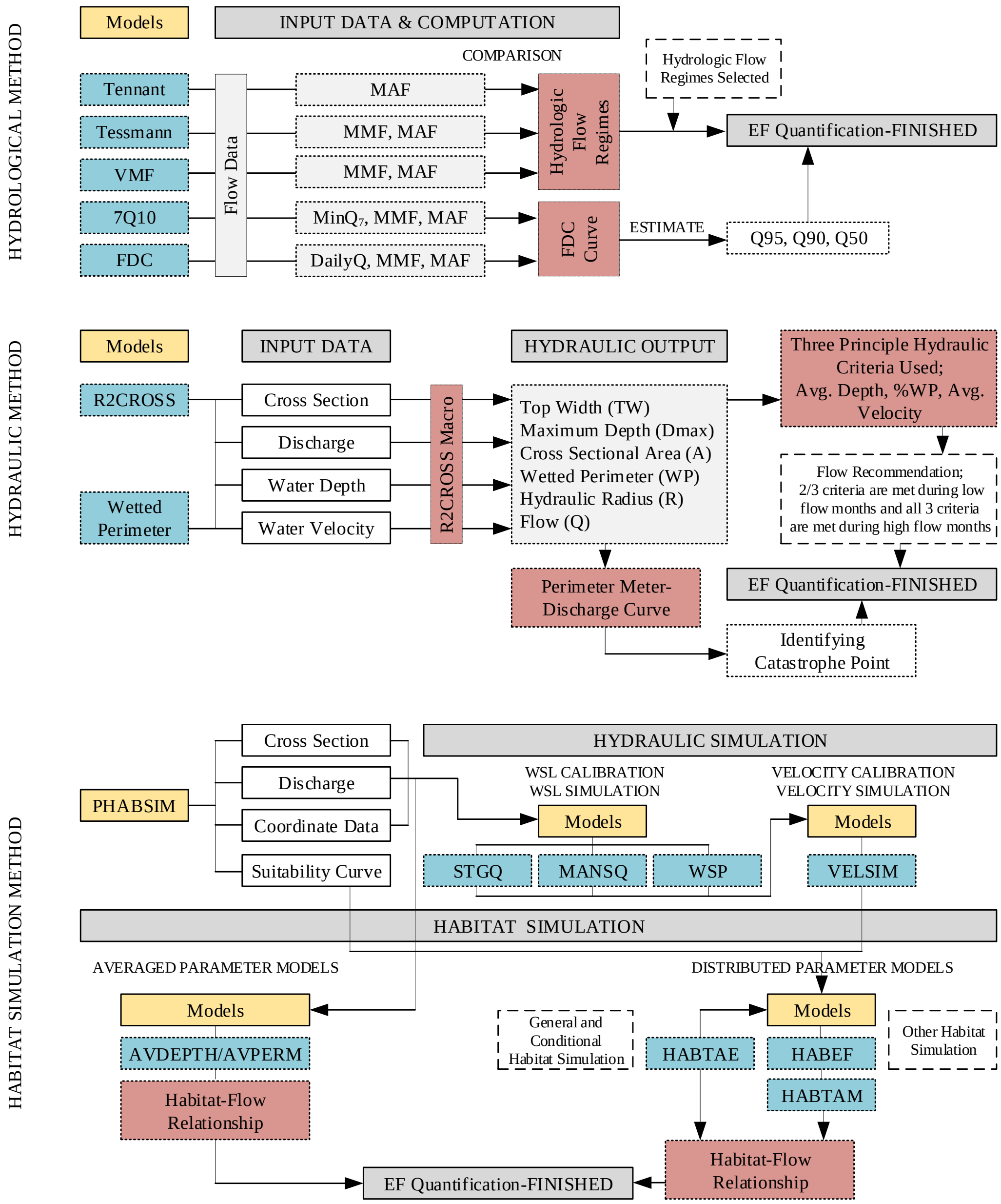

Figure 2 Sequences of operation performed by hydrologic-hydraulic-habitat simulation method.

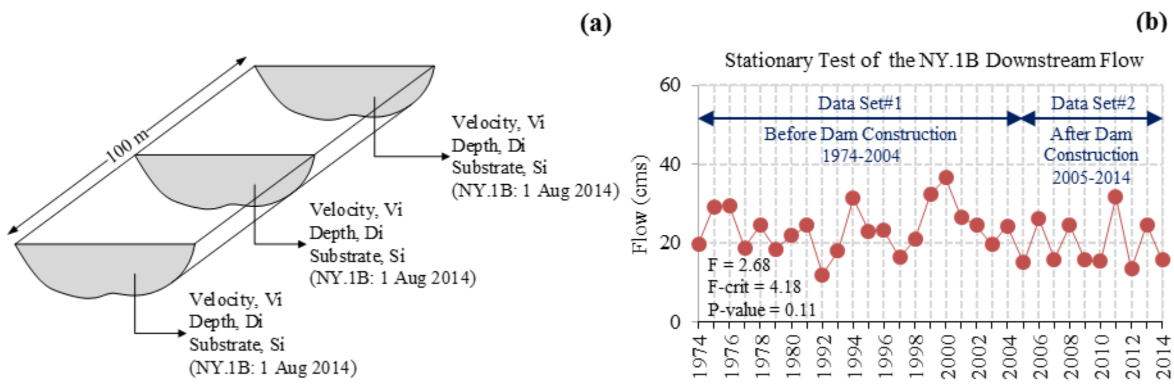

Figure 3 Pictures of (a) a single river transect above and below the NY.1B station and (b) the result of stationary test of the NY.1B streamflow data before and after dam construction.

Results and discussion

1) The stationary test of downstream flow data

A stationary test was conducted to verify the consistency of downstream flow data before and after dam construction. The long term flow data from the NY.1B station were classified into two sets; 1) Dataset 1 for 1974-2004, which was considered as the natural flow prior to dam construction; and 2) Dataset 2 during 2005-2014, when the KDPC was completely constructed and regulated by reservoir operation. The results of the stationary test using ANOVA-single factor in Figure 3(b) showed the equivalent testing outcomes between two data sets at 0.05 significance level. Therefore, observed flow data of the NY.1B station during 1974-2014 were brought to quantify the instream flow needs downstream of KDPC.

2) Operational data of the Khun Dan Prakan Chon Reservoir

According to the existing operation of KDPC during normal flow period done by the RID, reservoir water has been controlled through two main structures which are separately located; 1) the irrigation outlet to satisfy downstream agricultural demand; and 2) the river outlet and bottom outlet to maintain the needs of environmental flow of the Nakhon Nayok River as shown in Figure 4(a). During the refilled period, excess water in the reservoir has been controlled by an auxiliary spillway with a maximum discharge of about 1,454 cm. It was explored that the reservoir inflow was 310.45 mcm a^{-1}, with 90.27 % of annual inflow occurring in the rainy season from May to October. The operational records for 2007-2014 as shown in Figure 4(b) illustrate the seasonal patterns of water storage in the reservoir, which reached almost full capacity in the rainy season, dropping during the dry season to near the minimum pool level. The total annual outflow of KDPC was 351.21 mcm which was very close to the incoming inflow. It could be seen that 42.33 % of this outflow amount was supplied for agricultural water demand, 48.44 % for downstream flow need, with 9.23 % lost through spilled water and seepage. The released water to maintain downstream river flow was specified based on the experience of reservoir operators without established criteria which varied between 0.85-11.21 cm on average and 5.84 cm in high flow months and 5.27 cm in low flow months (Figure 4(c)).

3) Environmental flow requirement estimated by 3 different methods

3.1) Hydrological method

The estimation of environmental flow requirement downstream of the KDPC using five hydrological methods gave a result of 0.17-12.80 cm. It was found that streamflow rates at Q90 and Q95 performed by 7Q10 and FDC methods became lowest and were much lower than the reservoir outflow. Therefore, these flow rates were not considered as recommended flows in this study. Among these hydrologically-based methods selected, Tessmann and 7Q10 method offered closer estimates than the FDC and VMF methods. The values of environmental flow requirement by the Tennant method was expressed as the percentage of Mean Annual Flow (MAF), while the Tessmann and VMF methods were presented as the percentage of Mean Monthly Flow (MMF) in the different hydrologic flow regimes. The result obtained via the FDC method at Q50 was 12.8 cm, the highest value compared to the other methods. The VMF method resulted in a flow value of 6.14 cm which was equal to the one obtained by Tennant method for low flow conditions. The comparison of the estimated environmental flow requirements by hydrological methods with the water allocation scheme of KDPC during 2007-2014 showed that the reservoir outflow to maintain downstream river flow was slightly lower than those environmental flow estimated by the hydrological methods as presented in Table 3.

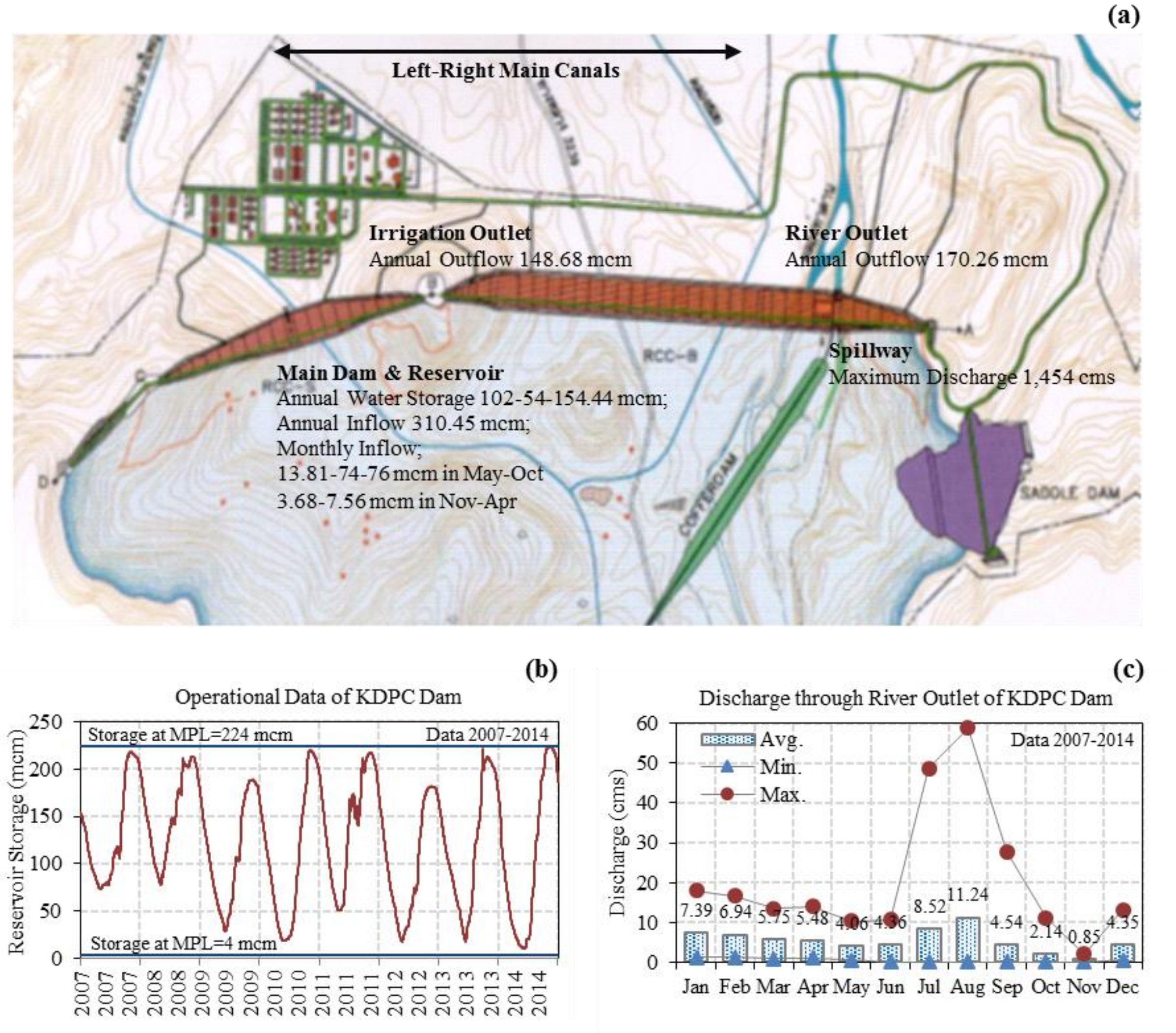

Figure 4 Pictures of (a) structural diagram of the KDPC, (b) time series of daily water storage of the KDPC, and (c) monthly discharge through river outlet during 2007-2014.

Table 3 Comparison of environmental flow requirement of the KDPC obtained from the different hydrologically-based methods

Hydrological methods	Tennant	Tessmann	7Q10	FDC	VMF
Environmental flow requirement (cm)	Low flow: 6.14 [a] High flow: 10.24 [b]	8.19 [c]	9.40 [d1] [0.38] [d2] [0.17] [d3]	12.80 [e1] [0.75] [e2] [0.34] [e3]	6.14 [f]

Note: [a] 30 % MAF, [b] 50 % MAF, [c] 40 % MAF, [d1] Q50, [d2] Q90, [d3] Q95, [e1] Q50, [e2] Q90, [e3] Q95, and [f] 30 % MMF

3.2) Hydraulic method

In this study, the instream hydraulic parameters of the NY.1B station in Figure 5(a) were extracted from the R2CROSS model, including the relationships between percent wetted perimeter-discharge, water velocity-discharge, average water depth-discharge, and stage-discharge. These parameters were used to quantify instream flow recommendation associated with hydraulic criteria of the R2CROSS and wetted perimeter methods. The two hydraulic-based methods resulted in a recommended environmental flow requirement of 5.41 and 5.21 cm, respectively.

The identification of estimated instream flow by the R2CROSS method was carried out based upon three main hydraulic criteria: average depth, average velocity, and percent wetted perimeter. It was found that a flow of 180.77 cm was required to achieve all three criteria; this flow level was recommended during high flow period. However, the flow required to meet two of the three criteria recommended during the low flow period was only 5.41 cm, which was adopted as the recommended environmental flow requirement in this study.

For the wetted perimeter method, the relationship between percent wetted perimeter and discharge for the NY.1B station provided by the R2CROSS model were brought to construct the P-Q curve as shown in Figure 5(b). The catastrophe point was then located to identify the environmental flow requirement. At that point, the wetted perimeter was 28.3 m at the equivalent discharge of 5.21 cm which was very close to the figures obtained by the R2CROSS method and its operational record specifically in the dry season, as summarized in Table 4.

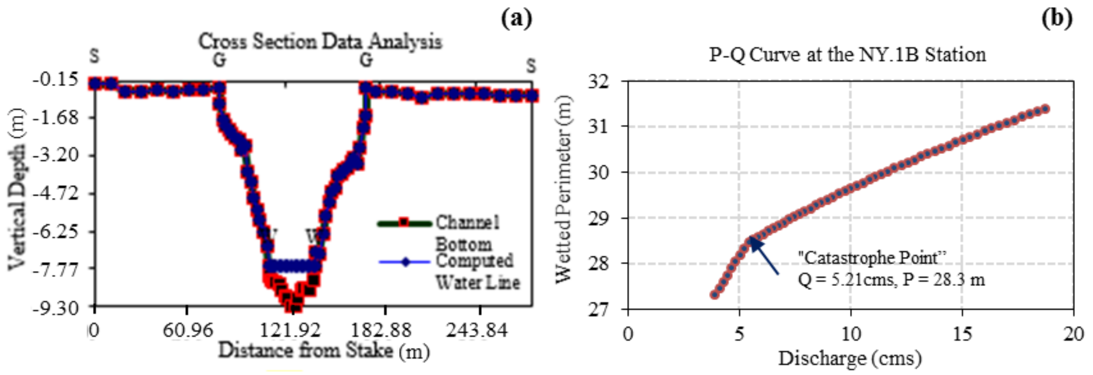

Figure 5 Graphs of (a) cross section data of the NY.1B station and water level data in August 2014 and (b) P-Q curve at the NY.1B station showing the relationship between wetted-perimeter and discharge.

Table 4 Environmental flow requirement of the KDPC estimated by hydraulic method

R2CROSS method					
Required avg. depth (m)	Flow to meet avg. depth (cm)	Required WP (%)	Flow to meet WP (cm)	Required avg. velocity (m/s)	Flow to meet velocity (cm)
0.18	1.35	60%	180.77	0.30	5.41*
Wetted perimeter method					
Catastrophe point : Q = 5.21 cm, P = 28.3 m					

3.3) Habitat simulation method

Formulating the simulation model of aquatic habitat in the Nakhon Nayok River was carried out based upon the observed hydraulic data in a single river transect above and below the NY.1B station with the total length of 100 m. This study selected the PHABSIM model as a tool to assess the environmental flow by taking the biological conditions and interactions of aquatic organisms in the river as well as hydraulic data into consideration. For the first part of the modelling process, the surveyed cross section data and coordinate data for the NY.1B station were input into the hydraulic model of PHABSIM. The observed water level and velocity were then used for model calibration. Three selected observed flow values at the NY.1B station covering the low flow to high flow periods; 0.20, 8.15, and 36.06 cm were used as calibration flow and five selected simulation flow values; 0.10, 0.46, 56.55, 85.00, and 147.70 cm were input in hydraulic simulation model to calibrate the water surface elevation and flow velocity. It could be investigated from the model result that calculated water level from both two data sets apparently showed a minor difference of -0.01 to 0.10 m compared to the observed water level except during high flow period. Identifying high values of simulation flow of 85.00 and 147.70 cm to simulate water surface elevation gave unsatisfactory results. Due to the limit of the distribution of observed velocity data across the river cross section in a straight reach, this study could only identify a constant value of flow velocity in the velocity simulation model. Therefore, the simulation results showed a distinct pattern among observed and simulated velocity which their profiles were generated corresponding to the theoretical principle of open channel flow. However, there was not much difference in the average value of simulated and observed velocity at various calibration and simulation flow levels. For the second part of modelling process, all the aquatic species including *Bagridae, Mastacembelidae, Cichlidae, Belonidae, Channidae, Nandidae, Cyprinidae, Eleotridae, Chandidae,* and *Palaemonidae* [14] found in the Nakhon Nayok River were classified into four groups according to their numbers and habitat types in order to identify the habitat suitability curve in the habitat simulation model. The results performed by hydraulic model were then combined with habitat simulation model to generate the relationship between the Weighted Usable Area (WUA) and its corresponding discharge, or so-called habitat-flow relationship. The results received from the HABEF model were expressed in Figure 6 and were consequently used to quantify the environmental flow requirement.

The idea to quantify the optimal flow suitable for all stages of aquatic life habitat was carried out by considering the corresponding discharge at 80 % and 100 % of the peak values of habitat quality index [15]. According to the established relationship between the integrated WUA and discharge obtained from PHABSIM, a flow rate of 8.16 cm corresponded to the highest value of the integrated WUA and was considered as the recommended flow for habitat conservation objectives for the Nakhon Nayok River.

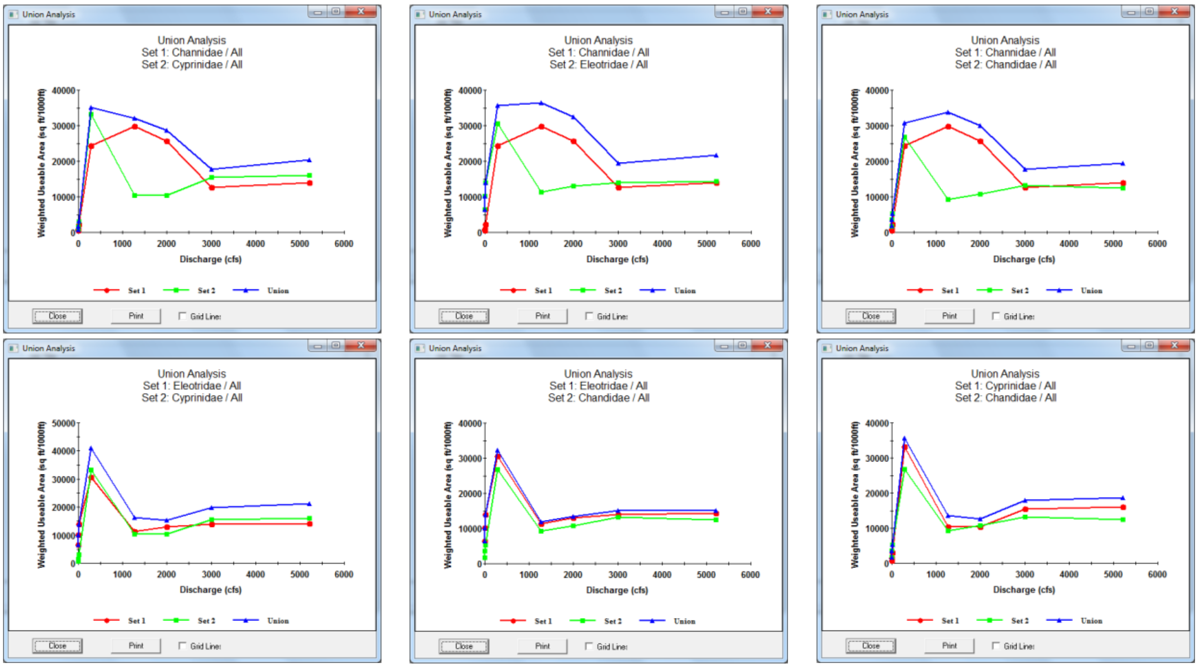

Figure 6 The combination sets of Weighted Usable Area-discharge relation generated from four fish species groups of the Nakhon Nayok River.

4) Comparison of estimated environmental flow and operational performances

Among these three estimation methods used, the estimated instream flow results performed by hydrologic method as well as habitat simulation method were higher than the actual environmental flow release of KDPC, as presented in Figure 7(a). The values of instream flow rate varied between 6.14-12.80 cm representing the entire periods of low flow and high flow months. The estimated results performed by two hydraulic methods seemed to be very close to actual operation in dry and wet seasons (5.84 and 5.27 cm, respectively). This study also compared the results of existing reservoir operation with river water quality index at the Nakhon Nayok monitoring station during 2014-2015 which reflected a quantitative and qualitative picture of the existing performance of water resource management very well. The analysis of operational record of reservoir during 2007-2014 expressed that the average water release through river outlet was 5.56 cm and the minimum and maximum flow releases were 0.85 and 11.24 cm, respectively which were frequently occurred in November and August. Meanwhile, water quality data measured every 30 min at the Nakhon Nayok monitoring station (pH, DO, temperature, EC, and TDS) were classified following the established water quality standards for aquatic organisms [16]. This signified that the reservoir operating scheme of KDPC has been worked without any problem of water quality downstream of the Nakhon Nayok River. Therefore, the environmental flow rates of 8-10 cm were recommended to determine the downstream release of KDPC for the habitat conservation objectives which were very close to the estimates performed by Tessmann, 7Q10 and PHABSIM methods-Tennant and FDC methods, respectively.

Finally, the recommended environmental flow rates of 8 and 10 cm and the observed water discharge for irrigation were combined and used as the downstream water demand to simulate long term operation of the Khun Dan Prakan Chon Reservoir and to compare the operational results as shown in Figure 7(b). The operational performances of reservoir corresponding to the downstream release flow conditions were compared in terms of the monthly water storage, ending water storage, and reliability index. It was found that the percentage of water storage at ending simulation time step were 82.66 % and 82.54 % performed by 8 and 10 cm, respectively; these values were very close to the actual operation value of 82.87 %. Moreover, the reliability index representing an attempt to avoid controlling reservoir water in flood control reserve storage zone above upper rule curve by two environmental flow schemes reached a high of 76.04 %. The distribution of monthly water storage was also in the range of the lower rule curve and upper rule curve, which are considered as a guideline for reservoir operation. The quality of river water at the Nakhon Nayok monitoring station during 2014-2015 was reported in Figure 7(c).

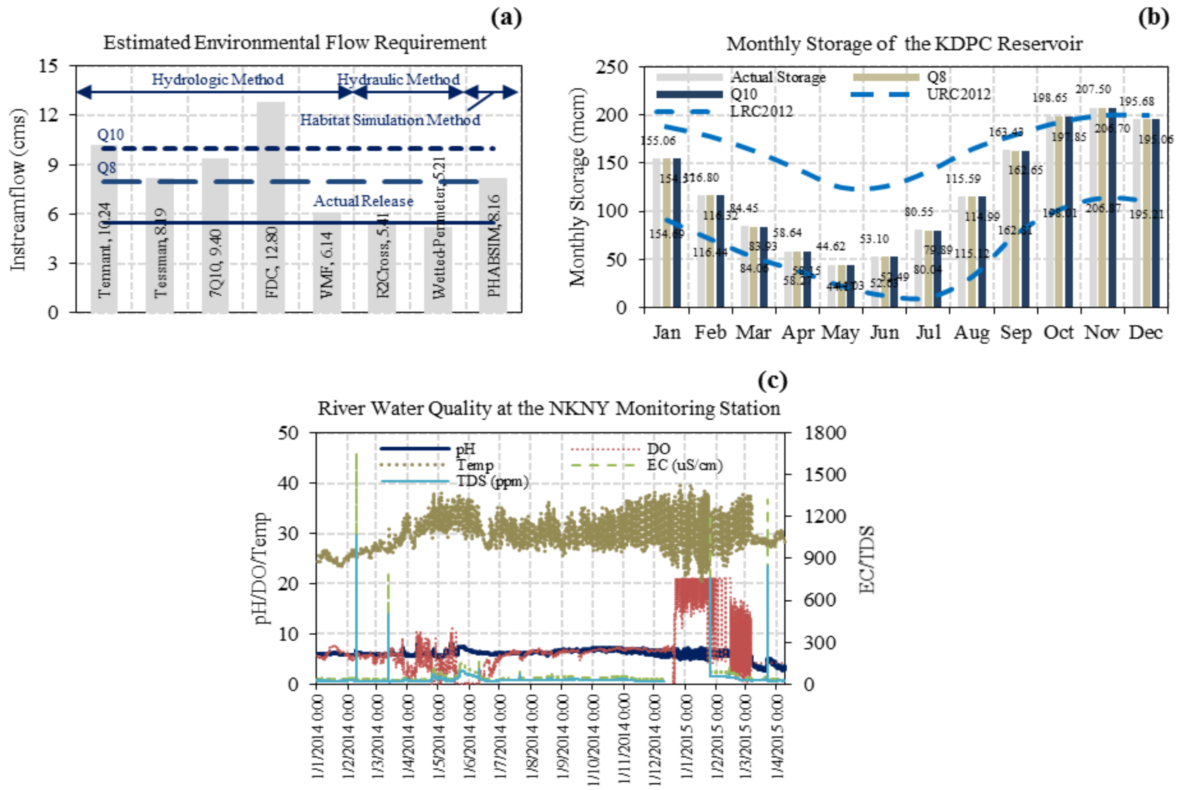

Figure 7 Plots of (a) the estimated environmental flow requirement by 3 different methods, (b) monthly storage of the Khun Dan Prakan Chon Reservoir as a result of existing operation and (c) river water quality at the Nakhon Nayok monitoring station in 2014-2015.

Conclusions

Nowadays, the environmental flow requirement is prioritized as a primary objective of multi-purpose water resources projects in Thailand. The environmental flow requirement is generally used by reservoir operators as a basis to determine reservoir operating policy to meet real-world downstream needs. This study applied three estimation methods; hydrological method, hydraulic method, and habitat simulation model to quantify environmental flow rates in the Nakhon Nayok River downstream of the KDPC for day-to-day operation. The hydrological approach was performed under the historically-naturalized flow data and established hydrologic flow regime; however, this method did not consider the biological conditions and interactions of aquatic organisms in the river. The hydraulic method required hydrologic flow and surveyed hydraulic data as well as channel geometry to generate the instream hydraulic parameters at the gauge station, and the resulting environmental flow rate obtained from this method was based primarily on field observations. In addition, the estimated results performed by habitat simulation model gave an additional meaning of ecological flow needs mainly for aquatic habitat conservation in the river. However, the environmental flow rates recommended in this study were considered by integrating all the obtained results associated with hydrologic and hydraulic flow regimes and habitat quantity into consideration. Moreover, the quantification of environmental flow rates was carried out based upon the hydraulic parameters on the downstream reach of the Nakhon Nayok River only which the obtained flows might not be adequate to preserve the national environment in the Bang Pakong River. Therefore, the further studies specifically in the Lower Bang Pakong Basin are recommended to be conducted for the environmentally beneficial operation practices by adding more river cross sections downstream, raw field data and associated hydraulic parameters, and taking seawater intrusion into account.

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