DEVELOPMENT OF AN INTEGRATED RESEARCH METHOD FOR EFFECTIVE WATER RESOURCE MANAGEMENT IN A COMPLEX WATERSHED SYSTEM: THE CASE OF MAHAWELI RIVER BASIN

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ABSTRACT

Water-related disasters are the most devastating natural disasters in the world. Loss of agriculture, lives, and properties in other hand water scarcity and conflicts among stakeholders are the most common, effective watershed management is one of the key solution for that, but watershed management is more complex and complicated due to its physical processes and human-made changes. The study address this problems, by developing a comprehensive scientific framework using complex hydrological, reservoir operation and diversion models which integrates simplified form of complex watershed based on topography and rainfall characteristics, incorporating evaporation process with bias-corrected satellite data and operation of water storage and diversion facilities to reproduce the present condition, and finally to develop an effective water resource management strategy in any basin. The proposed approach was applied to the complex Mahaweli watershed in Sri Lanka to address such issues.

Keywords: Complex Watershed Management, Dam Operation Rules, Flood, Drought, Diversion

INTRODUCTION

The watershed plays a crucial role in understanding hydrologic processes for the effective planning and management of water resources in a region. The watersheds are not simple or linear systems due to several reasons, e.g., spatial and temporal changes of precipitation, evaporation, infiltration, snow-melt process, water storage and diversion, vegetation type and its penology, land-use and soil characteristics, topography and river morphology. Particularly, human-made changes such as water storage and their usage for power generation, irrigation, diversion to other basins and drinking purposes make the hydrological processes even more complicated. In addition, the frequent confliction between the users and stakeholders to distribute the limited available water arises during the dry period.

In the case of Sri Lanka, the Mahaweli River basin is most vulnerable for such kind of problems. Therefore it is the selected study area. This basin is largest and also complex basin due to its physical and multipurpose capability, also it diverts water to cultivate more than 165,000ha of agricultural lands in the dry zone and supply the 25 -30% of the electricity demand in the country. Due to this complexity, it causes the confliction among the shareholders and severe flood and drought in downstream areas. Therefore, it is very important to have an effective water management system in this basin.

Researchers try to comprehend the complexity of watershed problems differently, such as a dynamic system approach (Shahbaz et al., 2007 & Ahmad et al., 2000). Some of the disadvantages of this approach are, that it is difficult to perform well in extreme events and long-term processers due to systems uncertainties and multipurpose behaviors. In other way, several physics-based simple hydrological models have been developed to address the hydrological processes at a catchment scale. However, due to the increasing degree of complexity, the applicability of these models is limited or used for a particular objective. Therefore the approach was used to understand the complex systems by using science-based system approach (Xin Li et al., 2018) with IWRM. However, the main problems of this physics-based watershed models are complicated, limited understanding of physical processes, limited

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facilities to introduce human-made activities. Rainfall-Runoff Inundation Model (Sayama. 2015) was selected to understand the hydrological processes in the basin, due to its flexibility and diffusion wave approximation of the stream, and incorporate the human-made changes to this model.
In this study, the approach was introduced to the Multipurpose Mahaweli Complex System to validate the present condition and then applied to identify the role of reservoirs in its maximum flood storage capacity to reduce the flood in the downstream area. The time period also identified to keep maximum flood storage, and changes of flood storage, according to rainfall distribution throughout the year. This storage management helped to store water for dry season and control the flood in the rainy season. The Combined Hydrological Model used to identify different issues, such as reduction of flood peak by using different dam operation scenarios and optimize the water diversion to reduce the drought in the dry zone.

THEORY AND METHODOLOGY

The complex system approach is mainly divided in to four parts such as; a) identifications of major components such as hydrological processes, topography, spatial and temporal variation of rainfall distributions and evapotranspiration, b) simplification of watershed, c) introducing Physical Processes and water storage and diversion facilities and, d) application of the combined complex hydrological model to understand the present condition and scenario development for effective basin management. The concept flow for this complex system approach is shown in Figure 1

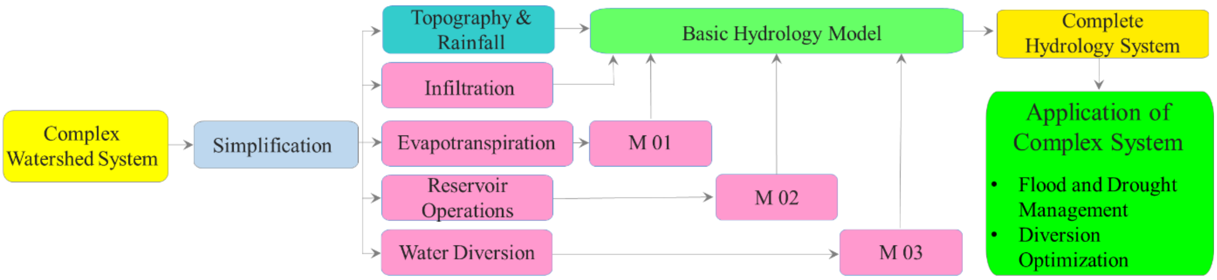

Figure 1. Simplification and complex system approach for complex hydrological model

As shown in Figure 1, it simplified the basin using the above mentioned four categories and prepared the simple rainfall-runoff model by considering rainfall, topography, and infiltration. Evapotranspiration was introduced by using satellite biased corrected data (M 01). For the reservoir operations, the monthly based flood storage concept was established based on seasonal rainfall characteristics, to reduce floods in lower parts of the basin, and to control the flood in rainy season, four stage reservoir operations which are pre-flood operation stage, flood operation stage, pre-emergency operation stage and emergency operation stage, was developed, to release the spill water fuzzy logic system (M 02) was introduced with linear operation. Monthly based water diversion method (M 03) also coupled to the system to address the drought condition in the dry zone. This approach is applied to the Mahaweli River basin accordingly.

Software used: Rainfall-Runoff and Inundation (RRI) Model software used for basin modeling and make some modification in the dam operation module and diversion module by using FORTRAN. It used the CROPWAT 8.0 software to find out the irrigation water requirement of paddy and other field crops.

Model Preparation: 30 Arc second grid data used as Digital Elevation Model (DEM), the watershed divided to three major parts according to hydrological processes, topography, spatial and temporal variation of rainfall distributions such as upper river basin (1), Aban River basin (2) and lower river basin (3) as shown in Figure 2. Inverse Distance Weighting (IDW) method was used to prepare the rainfall distribution of the system (Eq. 01), as evapotranspiration data, liner bias correction Eq. 02 used for correct the satellite data. (M 01 in Figure 01)

$$Z_i = \frac{\sum_{i=0}^{n} \frac{Z_j}{{d_{ij}}^P}}{\sum_{i=0}^{n} \frac{1}{{d_{ij}}^P}} \quad \text{-- } \mathbf{Eq.}\ (1)$$

Where Zi Interpolation value in an unknown cell, d_{ij} *distance between the known cell and unknown cell,* Z_j *Known cell Value, P power function for weighting of the distance for this it takes as 6.*

$$P_{corrected} = P_{Satellite} \times \frac{\mu\,(P_{Observed})}{\mu\,(P_{Satellite})} \quad \text{-- Eq. (2)}$$

Where $P_{Satellite}$, satellite-observed data, μ ($P_{Satellite}$) mean of the satellite data and, μ ($P_{Observed}$) mean of the observed data.

For calibration of the model, three station were used for calibration, which is Peradeniya, Mahiyanganaya and Mananpitiya shown in figure 2 and four parameter sets, to increase the performance of the basin, because of flood and drought condition in lower area should control by using upper area operations such as water diversion and reservoir operations. Then calibrated and validated the model without considering reservoir and diversion. The Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970) value is used for check the model efficiency.

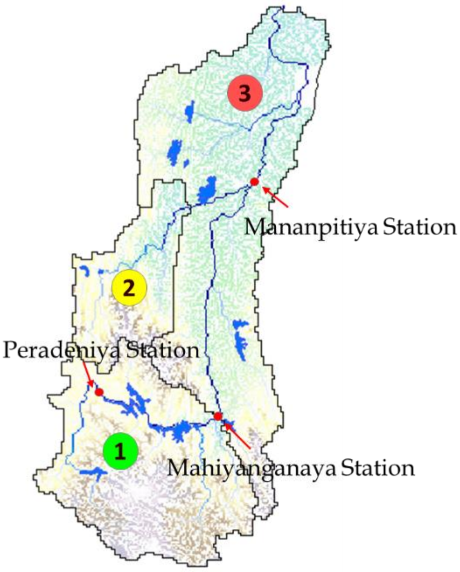

Figure 2. Mahaweli River Bain with Discharges

Introducing the Dam Operation and Diversion

Dam operation is essential in this basin, therefore the dam module was developed by considering the spatial and temporal variation of the rainfall to retain the flood peak in each reservoir, such as, in upper area of the basin gets more rainfall in July and August months due to South West Monsoon (SWM) (Figure 5) therefore Kothmale Reservoir was selected as SWM flood reservoir and maximum flood storage keep these two months, however the lower part gets high rainfall from October, November and December months during North East Monsoon (NEM) (Figure 4), therefore the other reservoirs were selected as NEM flood reservoirs in month of October, November, and December.

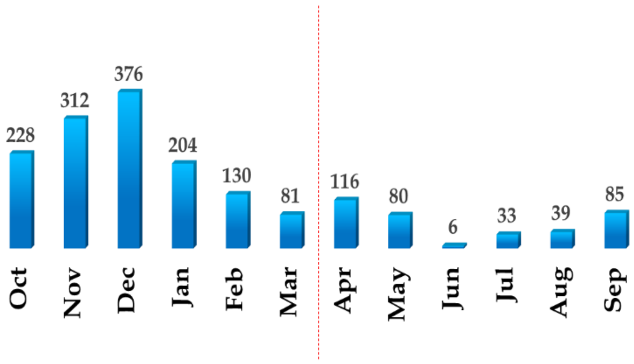

Figure 3. Average rainfall variation of basin

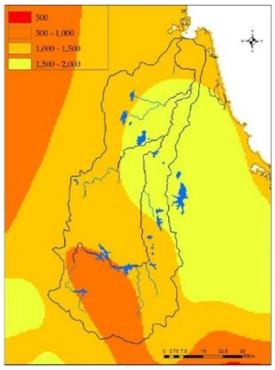

Figure 4. NEM

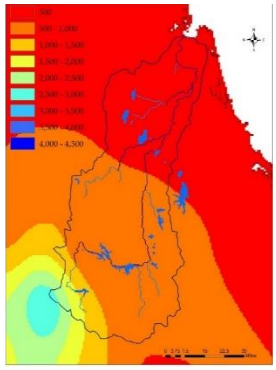

Figure 5. SWM

The temporal wise rainfall is gradually increasing after September (Figure 3), but decreasing after December, therefore the temporal wise change was used to gradually change the flood storage in reservoirs. In flood time period, the reservoir is operated according to the four-stage dam operation technics, such as Pre Flood Operation Stage, Flood Operation Stage, Pre Emergency Operation Stage, and Emergency Operation Stage. Pre Flood Operation Stage is used mainly to alert as a sign to start the operation of the reservoir, in Flood Operation Stage, it will spill water to avoid inundation in the downstream area, and in Pre Emergency Stage, minor flood will occur and Emergency Operation Stage it will release discharge which is equal to inflow. This optimization was introduced to the five major reservoirs, which made it possible to control floods, such as Kothmale, Victoria, Randenigala, Rantembe, and Bowathenna. The diversion module for water diversion was also introduced, according to water requirement in the dry zone, which need to consider the water requirement from outside basins. Mainly the water is diverted from Polgolla, Minipe and Mawil Aru barrages for the four major river basins, which is Kala Oya, Malwathu Oya, Yan Oya and Maduru Oya basin, altogether it cultivates more than 165,000 hectors in the dry zone. Therefore in reservoir operation stage it also considered this matter to retain the dry season requirement by limiting the flood storage in dry months. Dry zone diversion started from Polgolla barrage (D1 shown in Figure 6) and it diverts water to Bowathenna reservoir, then water divert to Anuradhapura Region for 56,029 ha and Polonnaruwa region for 44,610 ha, the second diversion start from Minipe (D2) and it diverts water to 54,945 ha and last diversion location which is Mawil Aru diversion (D3), diverts water to 10,000 ha. CROPWAT software is used to calculate irrigation water requirement in each location by considering cropping calendar, paddy variety, harvesting time, climatic conditions in different areas, water issuing method and canal efficiency. Finally, the drinking water requirement to calculate actual demand in all irrigated areas on monthly basis.

By integrating the two modules which are dam & diversion, to RRI Model and use two-year data for simulations to check the validity of the model. The mentioned approaches are used to address the problems in the Mahaweli River basin.

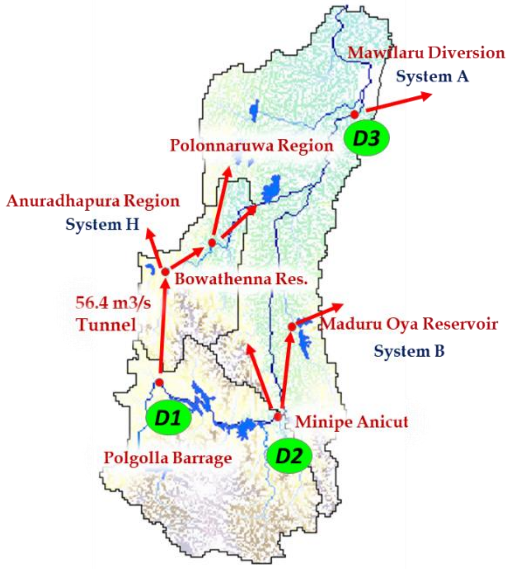

Figure 6. Water Diversion from Mahaweli River Basin

DATA

The Mahaweli River basin is covered with dense rain gauge stations and the rainfall data used for analysis from 1965 to 2015, and discharge data in several locations were also available along the stream for upstream area Peradeniya, and for lower part Weraganthota (Mahiyanganaya) and Mananpitiya. As for evapotranspiration data, MODIS satellite evapotranspiration data was used with bias correction in which the Palugasdamana station observed data was used for bias correction. Reservoir operation data was also collected for model validation.

RESULTS AND DISCUSSION

The simplified hydrological model was calibrated (NSE value 0.61) and validated (NSE value 0.76) without considering the dam and diversion, data used for calibration and validation before construction of reservoirs, for that considered the time period from 1960 to 1972. The modeling of complex Mahaweli river basin was completed by introducing, water diversion and dam operation in sequence according to Figure 1. The model was simulated using two years of data, and the simulated reservoir storage variation was compared with the actual storage variation of the reservoirs. It shows a good comparison between the actual and simulated one as shown in Figure 7 & 8. Then the developed and the completed complex hydrological model was used to understand the basin under three categories.

Dam operation rules to reduction flood in downstream areas

For dam operation rules, such as monthly based flood storage variation (the blue dashed line shown in figure 7 & 8) and the four-stage discharge release is compared with 2014 flood event which is the inundated took more than 14 days in Polonnaruwa and downstream of the basin. After introducing the dam operation rules for the selected five reservoirs, it showed that there’s a reduction of flood peak in Mananpitiya area from 2,800 Cumec to 1,450 Cumec. The selected five reservoirs help to store the flood peak without releasing high amount of discharge to the downstream. In figure 8, shows the storing of water, in the reservoir, in flood time. It was

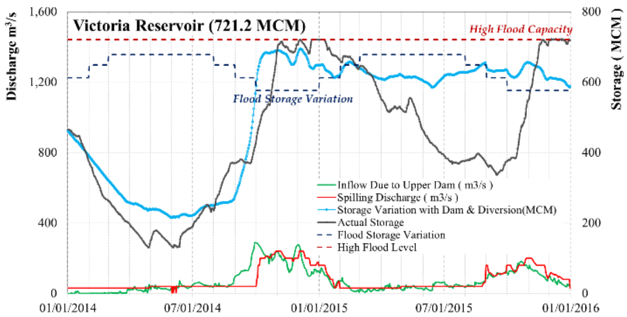

Figure 7. Storage variation Victoria Reservoir

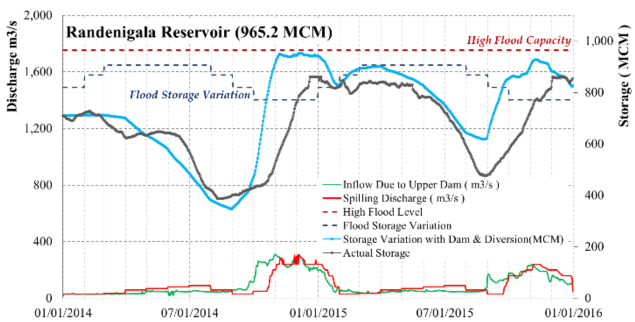

Figure 8. Storage variation Randenigala Reservoir

identified that actual reservoir operators didn't use full capacity for reduction of the flood, by this approach it was used as flood storage in flood time period and release less flood water to the downstream. Figure 9 shows the flood peak reduction due to dam operation rules in this approach. The comparison between the actual inundation in the downstream part and simulated inundation show the reduction of floodwater level by 1.5m height in Mananpitiya area. Figure 10 shows that, reduction of inundation extent, and comparison between actual and simulated using this approach. This was proved that the complex system approach with introduced human-made scenarios model performed well to reduce disasters like flood, drought and store water to dry season.

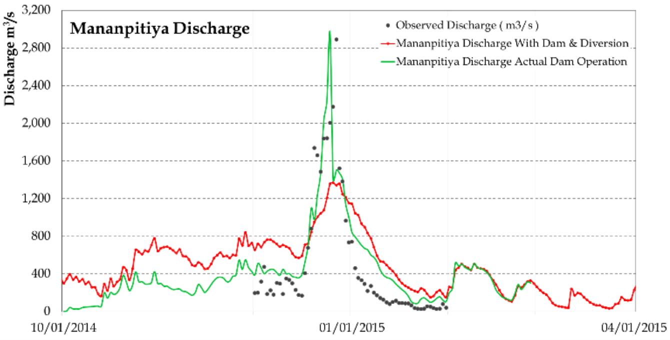

Figure 9. Discharge Variation in Mananpitiya due to Complex Model

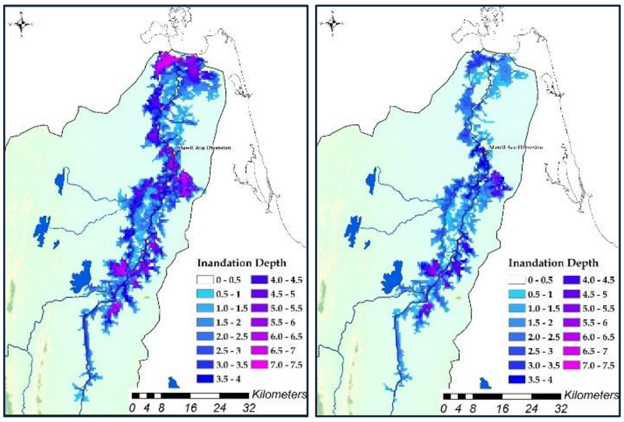

Figure 10. Inundation change due to Dam Operation, Actual Inundation left, Simulated right

Water Diversion Optimization to increase the Cultivation extent in Dry Zone

Two different simulation scenarios was selected to understand the increment of cultivation extent in dry zone area, which is proper water management with existing tunnel (Figure 11 blue line shows the diversion to dry zone due to this scenario 01) and increment of tunnel capacity (Figure 12 shows the diversion due to increment of tunnel capacity), for these two conditions, show that increment of the cultivation extent in dry zone by considerable amount, for scenario 01 it shows the 10% increment of land in 2014 Yala and 6% increment in 2015 Yala, using the scenario 02 it shows the 21% increment in 2014 Yala and 17% increment in 2015 Yala. It was further clarified, that the increase of farmer benefits in income wise, in Table 1 shows the income increment in US$ millions. It shows that the study is very important to decide the cultivation extent in the dry zone and help to Mahaweli Water Panel in their decision making during the meeting. In advance use of these two scenarios, it is essential to have forecast of the reservoir storage, therefore before the start of the Yala season, it is essential to consider the forecasted storage in Kothmale reservoir and decide accordingly. This study recommends studying the rainfall forecast in upper catchment area and storage prediction to further verify the above findings.

Table 1. Income Increment in Millions

	2014 Yala	2015 Yala
Scenario 01	$ 20.0	$ 14.9
Scenario 02	$ 43.3	$ 34.9

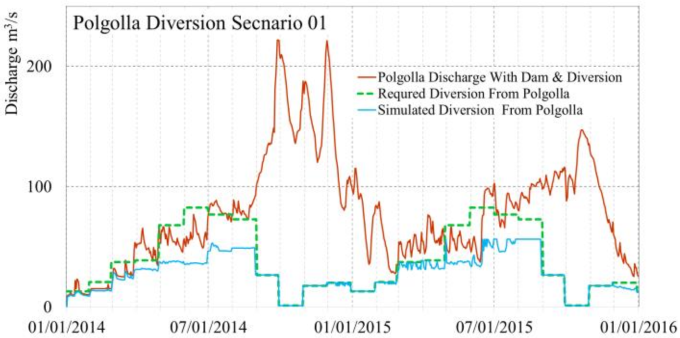

Figure 11. Proper water management with existing tunnel capacity (Scenario 1)

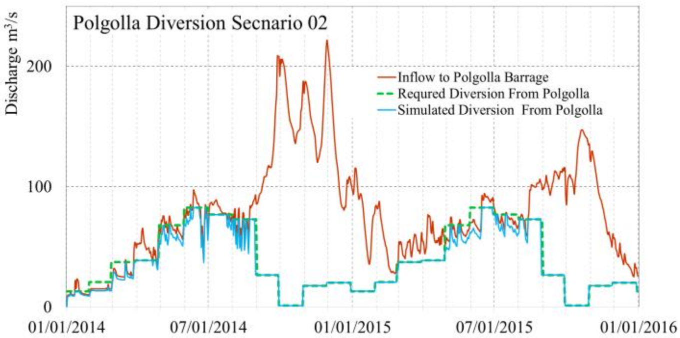

Figure 12. Increment of tunnel capacity (Scenario 2)

Understanding of Reservoir Priority for water management works.

From this study, we understood the importance of the storage in Kothmale reservoir which helps to decide the cultivation extent in dry zone area by comparing Kothmale storage with respect to the cultivation extent in the dry zone. It indicates that the first priority should be given to irrigation water supply and if there is an excess they can use it to generate hydropower.

CONCLUTION & RECOMMENDATION

In this study, an approach for complex watershed management was developed. The new approach consists of; a) identifications of major components such as hydrological processes, topography, spatial and temporal variation of rainfall distributions and evapotranspiration, b) simplification of watershed, c) introducing physical processes and water storage and diversion facilities and, d) application of the combined complex hydrological model to understand the present condition and scenario development for effective basin management. The proposed method was applied to the Mahaweli River basin system to study the characteristics of the basin and to develop a hydrological modeling system including dams and diversion facilities to enhance the present status. The developed system was used to develop an integrated water resources management plan to increase the efficiency of the system and reduce the disaster damages and confliction among the shareholders.

The results from the system showed that, there is a considerable amount of flood reduction in downstream area, two scenarios shows the importance of upper Kothmale reservoir to water diversion and cultivation extent increment to dry zone, and recommended that, coordination water management is very important factor, to optimize water diversion and flood operation in reservoirs, that belong to different organizations. This study proposes the new committee between all shareholders e.g., Hydropower, Irrigation and drinking sectors, to manage and discuss the problems according to the approach of the study, because of the purpose of existing water panel meeting is the distribution of irrigation water among shareholders. And also, it is recommended to study the forecast of rainfall seasonally in upper Catchment area by using Global Climate Models, considering Indian Ocean Dipole Conditions effect, because of it caused the strong El Niño and Na Niño conditions in the region.

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