

# EVALUATION OF RESERVOIR AND IRRIGATION EFFECT ON RUNOFF SIMULATIONS IN THE MEKONG RIVER BASIN

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Reasons for the errors in runoff simulations for large-scale watersheds are discussed. BTOPMC (Block wise use of TOPMODEL with Muskingum-Cunge flow routing method) was used to simulate hydrological processes in the Mekong river basin. The Model was calibrated for the year 1987 and verifications were carried out for the years 1993 and 1994. The digital stream network was created after removing depression points in the original Digital Elevation Model (DEM). Discussion of the reasons for the differences between simulated and observed runoff values is done using daily hydrographs at five stations in the lower Mekong river basin. Not only the physical characteristics of watershed such as topography, vegetation, geology and soil but also the human activities such as paddy cultivation and reservoir operations control the hydrological processes in a watershed. BTOPMC, coupling with human activities and reservoir water operations can be used to simulate runoff in large-scale watersheds.

**Key Words:** *Block wise TOPMODEL, Muskingum-Cunge method, Hydrologic model, Mekong river basin, Land use, Reservoir operation*

## 1. Introduction

Distributed hydrologic models can be used to simulate major hydrological processes in river watersheds. Watershed physical characteristics such as morphology, geology, soil and land use alone with precipitation control the hydrological processes in a watershed. Modeling of hydrological processes is not an easy task even in the physically based distributed models due to this complex governing process and loss of information in downscaling. Therefore, precise estimation of water resource potential is very difficult especially for large watersheds.

Spatially distributed water balance components plays an important role in decision making for water utilization in large-scale basins, and moreover in detailed studies for long lasting ecological stability. Human activities such as changes in land use and water usage as well as water storage by reservoirs significantly effect the hydrological processes in a watershed (Nawarathna et. al, 2001). Once the distributed models are capable of modeling above mentioned activities, those can be used to predict the effect on hydrological processes due to land use changes and dam constructions.

Although Takeuchi et. al., (2000) simulate the runoff in the lower Mekong river for 1987, verifications was not carried out. In this paper, an attempt has been made to discuss the reasons for the differences between simulated and observed runoff in large-scale watersheds using runoff simulation results of BTOPMC model applied to the Mekong river basin.

## 2. Study Area

The Mekong river, twelfth longest river in the world originates from Tibet and has a total length of 4200 km and covers an area of 795 500 km<sup>2</sup>. It is the life-blood of Southeast Asia. Fed by melting snow on the Tibetan Himalayas and monsoon rains, the river nourishes millions of lives from Southern China, Burma, Laos, Thailand, and Cambodia to the delta in Vietnam. It covers all of the Lao PDR and Cambodia, a large part of Thailand, the delta and central highland in Vietnam, the eastern part of Myanmar and a small area of China. Annual discharge from the watershed into the South China Sea is about 475 000 MCM. More than 50 million

people depend upon the Mekong River and its tributaries for food, water, transport, and many other aspects of their daily lives. The study area is shown in Fig. 1.

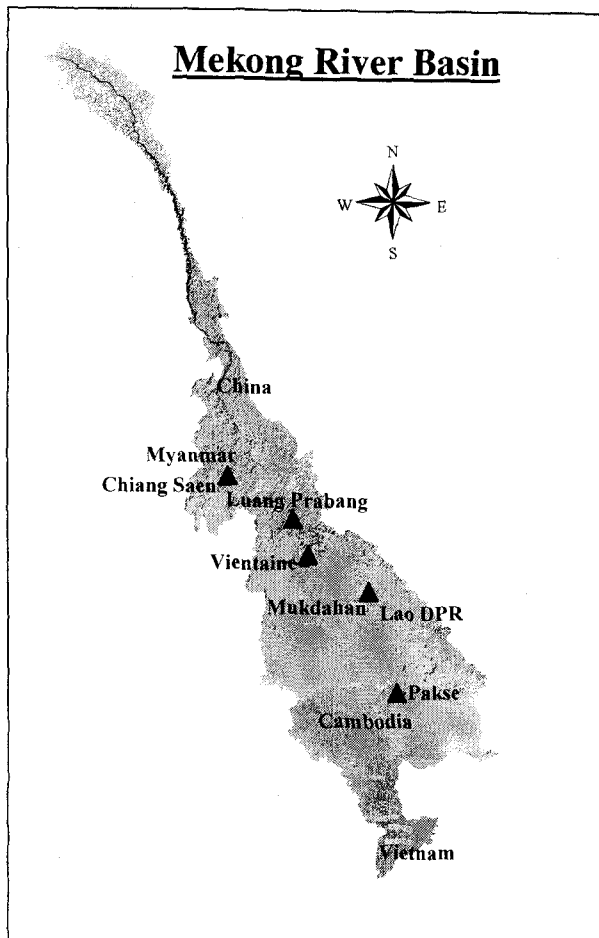


Fig. 1 Study Area

As the river passes through six countries with different ruling policies the necessity of a good watershed management in regional scale plays an important role. Furthermore pace of hydropower development in the region is accelerating and many dam sites are proposed in both main stream and the tributaries requesting a sound hydrological model, which can model water storage and reservoir operations.

### 3. Meteorological and Hydrological Data

Hydro-meteorological data sets were collected from Mekong River Commission (MRC) and from NOAA National Climate data center CD- ROM. Daily runoffs of five gauged stations: Chiang Saen (189000 km<sup>2</sup>), Luang Prabang (268000 km<sup>2</sup>), Vientiane (299000 km<sup>2</sup>), Mukdahan (391000 km<sup>2</sup>) and Pakse (545 000 km<sup>2</sup>) were used to simulate the runoff. These data were exacted from lower Mekong

hydrologic yearbooks published by MRC. Within the watershed 15 rainfall stations were chosen considering the availability of data sets. 1987 data from CD- ROM and 1993, and 1994 data from yearbooks were used in rainfall distribution estimation.

### 4. Structure of the BTOPMC

The BTOPMC is a physically based distributed hydrological model based on block wise use of TOPMODEL with Muskingum–Cunge flow routing method (Takeuchi et al., 1999) and can be used for runoff simulation in large watersheds. The model was developed in the Takeuchi/ Ishidaira laboratory, Yamanashi University, Japan. Digital stream network creation, runoff simulation from TOPMODEL and Muskingum–Cunge flow routing are the main components of this model.

#### 4.1 Digital Stream Network

The USGS EROS Data Center provides 30" grid digital elevation data (GTOPO30) that covers most of the world. Elevation data (34° 0' 0"N , 93° 0' 0"E to 9° 0' 0"N , 109° 0' 0"E) were extracted from global elevation data base. Scaling up was carried out due to computational limitations. A secondary DEM of grid size 3' × 3' was delineated from each 6×6 grids of the original DEM. The model has the capability of removing pits by its own automatic elevation modified method (Ao et al, 2000). Water at a grid point flows down to one of the eight neighboring grid points. The steepest slope determines the drainage line connecting two adjacent grid points. These drainage lines make the stream network of the basin.

#### 4.2 TOPMODEL

Beven and Kirkby (1979) proposed the TOPMODEL (Fig 2) based on contributing area concept in hill slope hydrology. Since then, there have been many developments to the model. TOPMODEL is based on the original exponential transmissivity assumption that leads to the  $\ln(a/T_0 \tan \beta)$ , soil-topographic index, where  $a$  is the upstream catchment area draining across a unit length of contour line (m<sup>2</sup>m<sup>-1</sup>),  $T_0$  is the lateral transmissivity under saturated conditions (m<sup>2</sup>h<sup>-1</sup>), and  $\beta$  is the local gradient of ground surface. It is a combination of lumped and distributed models using soil-topographic characteristics. However, the application is limited to relatively small basins up to several hundreds km<sup>2</sup> (Beven, 1979).

The BTOPMC use TOPMODEL for flow generation module. BTOPMC is a semi-distributed model and applications are mainly open for watershed developments as well as ecological studies. It assumes the generation of identical discharge from any grid cell having identical soil-topographic index regardless of its location in a sub-basin. BTOPMC extend the usage of original TOPMODEL from few thousands km<sup>2</sup> to several ten thousands km<sup>2</sup> basins by its block wise use.

Discharge is composed of overland flow and base flow. Saturation deficit controls the discharge from local area. The local saturation deficit is determined from local soil-topographic index relative to its block average value  $\gamma$ . Thus, the soil-topographic index is the critical controlling factor in runoff generation and is a function of topography and soil type.

Over a block, an average saturation deficit  $S(t+1)$  is determined from equation 1.

$$S(t+1) = S(t) - Q_v(t) + Q_b(t) \quad (1)$$

Where,

$S(t)$  - previous average saturation deficit,

$Q_v(t)$  - input to groundwater from unsaturated zone

$Q_b(t)$  - groundwater discharge to the stream over all grids in the block in m.

The block average saturation deficit  $S(t)$  is distributed to local saturation deficit  $S(i,t)$  at grid cell  $i$ , according to the magnitude of local soil topographical index relative to its block average  $\gamma$ . Namely,

$$S(i,t) = S(t) + m (\gamma - \ln(a/T_0 \tan \beta)) \quad (2)$$

Where,  $m$  is the decay factor of lateral transmissivity with respect to saturation deficit in meters.

Rainfall on the  $i^{\text{th}}$  grid cell generated from Thiesen polygon method is first received by the root zone. The storage in root zone  $S_{rz}(I,t)$  changes over time as follows

$$S_{rz}(i,t) = S_{rz}(i,t-1) + R(i,t) - E(i,t) \quad (3)$$

Where  $R$  is precipitation and  $E$  is evapotranspiration.

The excess of root zone storage  $S_{rz}(i,t)$  goes in to the unsaturated zone and its storage  $S_{uz}(i,t)$  can be given as

$$S_{uz}(i,t) = S_{uz}(i,t-1) + S_{rz}(i,t) - S_{rzmax}(i,t) \quad (4)$$

Overland flow from grid cell  $i$   $q_{of}(i,t)$  can be given as follows

$$q_{of}(i,t) = S_{uz}(i,t) - S(i,t) \quad (5)$$

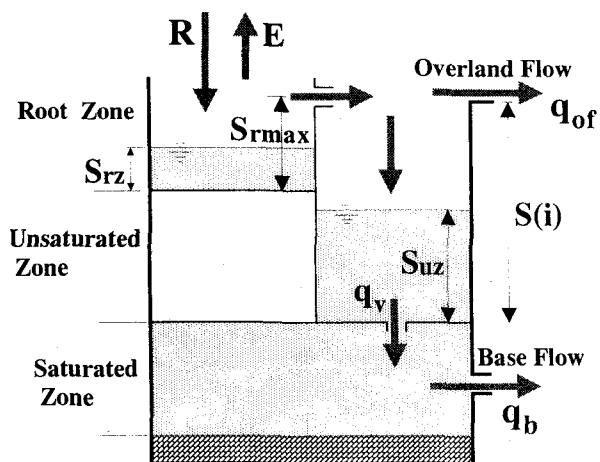


Fig.2 TOPMODEL Concept

Groundwater discharge is considered semi-steady depending on the saturation deficit. The hydraulic gradient is assumed parallel to the ground surface. Groundwater discharge from grid cell  $i$  is determined from equation 6.

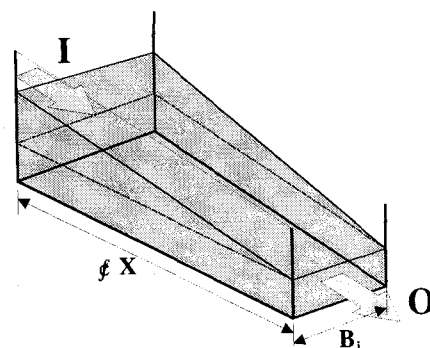
$$q_b(i,t) = T_0 e^{-S(i,t)/m} \tan \beta \quad (6)$$

The discharge from grid cell  $i$  to the stream per unit width is the sum of  $q_{of}(i,t)$  and  $q_b(i,t)$ .

#### 4.3 Muskingum-Cunge Flow Routing Method

In the BTOPMC model Muskingum-Cunge method (Fig.3) is selected as the flow routing technique. This is useful for a large stream network since it can successively calculate the flow rate everywhere along a stream at an instant. Although it cannot express the backwater effects, the flood wave diffusion and propagation can be taken into account.

The Muskingum-Cunge derivation begins with the continuity equation and includes the diffusion form of the momentum equation. These equations are combined and linearized to form the working equation.



$$O(t+1) = C_1 I(t) + C_2 I(t+1) + C_3 O(t)$$

Fig. 3 Muskingum-Cunge Method

Channel section is assumed to be wide rectangular shape with width  $B_i$  (m) proportional to the upper catchment area  $a_i$  ( $\text{km}^2$ ) as

$$B_i = \alpha a_i^c \tag{7}$$

Where  $\alpha$  and  $c$  are constants.

Manning's roughness  $n$  is determined by

$$n_i = n_0 (\tan \beta_i / \tan \beta_0)^{1/3} \tag{8}$$

Where subscript 0 indicates the average value of the block.

### 5. Model Calibration and Result Evaluation

Five model parameters ( $T_0$ ,  $m$ ,  $S_{rmax}$ ,  $n$  and initial saturation deficit  $S_{bar0}$ ) per each block were calibrated by trial and error method. The result evaluation is based on Nash Coefficient.

$$\text{Nash Coe.} = 1 - \frac{\sum (Q_{obs} - Q_{cal})^2}{\sum (Q_{obs} - Q_{obs})^2} \tag{9}$$

where,  $Q_{cal}$  is the Simulated daily discharge,  $Q_{obs}$  is the observed daily discharge and  $Q_{obs}$  is the annual mean observed daily discharge.

### 6. Results and Discussions

Runoff distribution was simulated from BTOPMC model. The model was calibrated for 1987 and the verification was done for the year 1993 and 1994. Simulation results at Mukdahan gauging station for the year 1994 is shown in the Fig. 4. Variations of Nash coefficient with effective drainage area for simulated years are shown in the Fig. 5. Nash efficiency coefficient increases with the drainage area.

Table 1 gives the sub watershed area comprises of irrigated crops and inland water areas. Most down stream sub basin mainly consists of irrigated crops lands where as upstream sub basin consists of very few irrigated lands and inland water areas. The area values are extracted from the USGS land use databases together with sub basins detect from the 1 km resolution watersheds drainage structure.

The effective watershed area for Chiang Saen consists of a big lake (Er Lake) and land use types are mainly mixed forest, scrub forest, grassland with only few farming lands, and few irrigated crop fields. Temporary storage in irrigated fields and reservoirs is low compared with the runoff values. This leads low values of minimum and maximum in difference between simulated and observed runoff values (Fig. 10). However, due to complexity in physical properties in the area, it is very difficult to calibrate the model accurately. Nawarathna, et. al, (2001) pointed out the reasons for the differences between the observed and simulated runoff. To

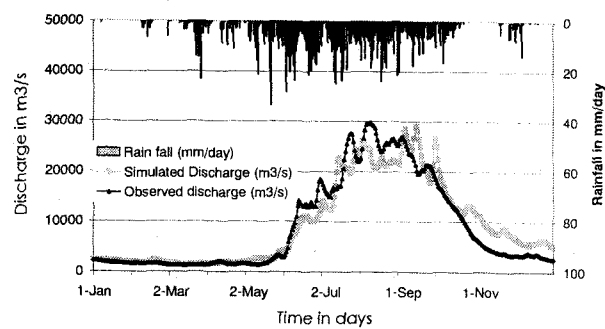


Fig. 4 BTOPMC results in the year 1994 at Mukdahan.

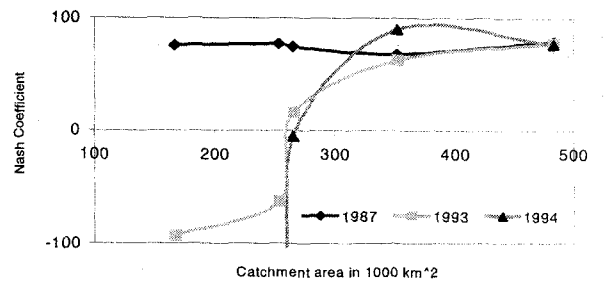


Fig. 5 Variation of Nash coefficient with basin area

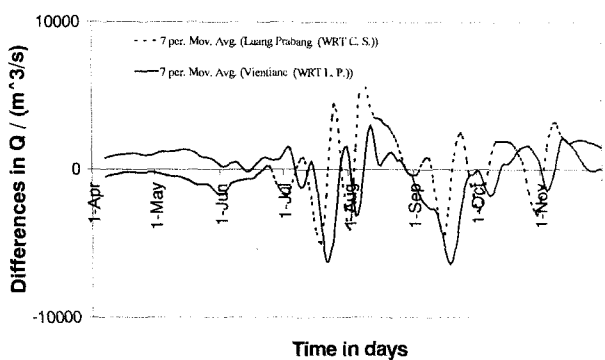


Fig. 6 Shifted differences in runoff in the year 1993 (upstream)

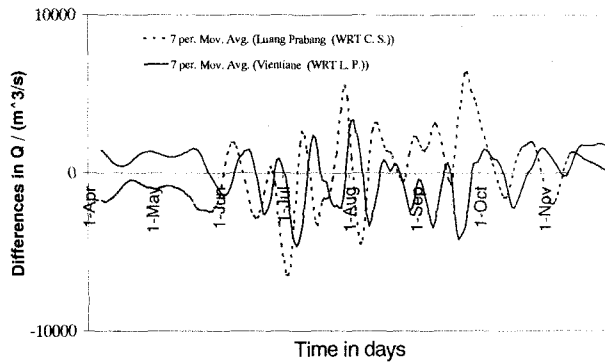


Fig. 7 Shifted differences in runoff in the year 1994 (upstream)

Table 1 Land use distribution in sub basins

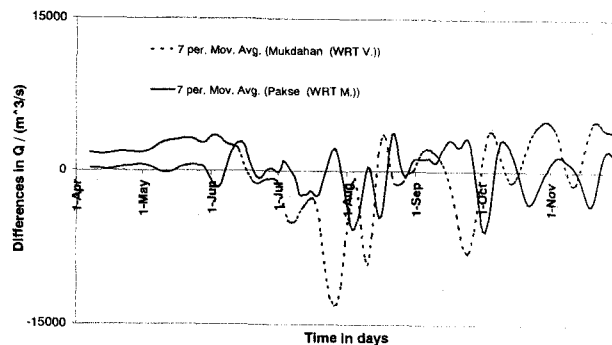
Land Use type	Mukdahan to Pakse	Vientiane to Mukdahan	Luang Prabang to vientiane
Irrigated Crops	107800 (70%)	21421 (23.3 %)	3694 (11.9 %)
Inland Water	1849 (1.2 %)	1607 (1.8 %)	360 (1.2 %)
Total in km <sup>2</sup>	154000	92000	31000

avoid errors in upstream stations accumulating to down stream stations differences between simulated and observed runoff values were modified from the following equation.

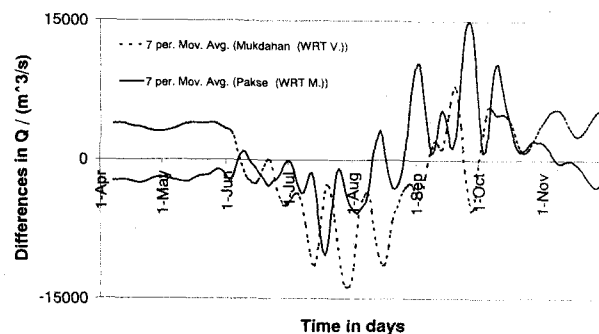
$$\text{Difference in } Q = (\text{Simulated } Q - \text{Observed } Q)_x - (\text{Simulated } Q - \text{Observed } Q)_y \quad (10)$$

Where y is the nearest upstream simulating station to x. From Chiang Saen to Luang Prabang 353 km Mekong river reach of 79 000 km<sup>2</sup> consists of very few farming or irrigated croplands and there are not any reservoirs with significant storage capacity in that channel reach. The watershed from Luang Prabang to Vientiane (530 km long, 31 000 km<sup>2</sup>) is quite similar to the earlier section without significant temporary water storage devises (**table 1**). Assuming that the errors in runoff simulations are only due to incapability of modeling of temporary storage devises, temporal variation of differences in Q with similar land use types for these two sections needs to be quite similar and it should have good agreement with the result obtained at Chiang Saen station. Temporary storage and releases in a watershed are prominent in the rainy seasons. Shifted difference values in the years 1993 and 94 for the first two channel reaches are shown in the **Fig. 6** and **7**. The pattern depends on rainfall variation and it easy to detect the water storing periods and releasing periods from those graphs. There is a time lag of 7 days between the moving average curves. Downstream curve has a lag of about 5 days to the upstream stations. This complies with the early storage and release in the upstream watersheds.

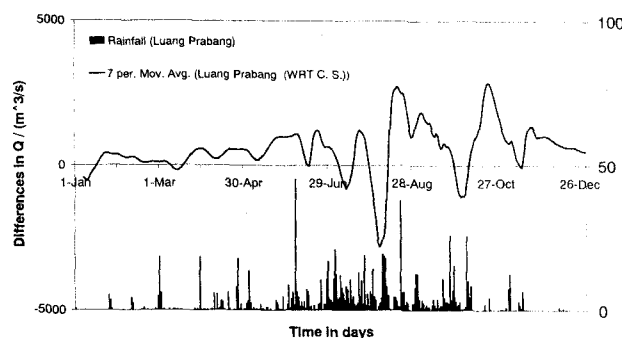
From Vientiane to Mukdahan there are four major reservoirs. Which are: Nam Ngun, Huay Luang, Nam Un and Nuong Han. Effective watershed for the 452 km main stream is about 92 000 km<sup>2</sup> containing high percentage of forest and paddy fields. From Mukdahan to Pakse 259 km main stream is fed from about 154 000 km<sup>2</sup> catchment area. This sub basin is full of paddy fields (70%). There are several reservoirs: Which are Shirinthorn, Lam Nang Rong, Lam Tha Kong, Chulaphorn, Ubon Rai and lam Pao. The water storage and release activities in these effective watersheds depend on climate, reservoir operations, as well as the cultivation pattern. It is not an easy task to separate different water storage activities from the result due to distinct cultivation patterns and reservoir operations. However, as a whole we can understand the reasons for the differences in observed and simulations runoff results. Shifted differences in runoff values in the years 93 and 94 with respect to up stream station are depicted in **fig.**



**Fig. 8** Shifted differences in runoff in the year 1993 (downstream stations)



**Fig. 9** Shifted differences in runoff in the year 1994 (downstream stations)



**Fig. 10** Differences in runoff at Luang Prabang in the year 1987

**8** and **9**. Both downstream stations have similar patterns but different from the upstream. Interestingly we can see the time lag of the down stream station. The time lag is also varying in the case of down stream stations depending on rainfall distributions because of the large water storage capacities.

**Fig. 10** depicts the differences in runoff for the year 1987 in Luang Prabang. This figure can be use to understand the influence of rainfall on errors in simulations. Large negative value in the middle of August can be due to water release of big lake.

The discussion about water storage from reservoirs and paddy cultivation has been done assuming that BTOPMC has the capability to simulate hydrological processes accurately. All graphs individually show similar patterns for the

years 87, 93 and 94. Modeling incapability of human activities such as paddy cultivation and reservoir operations might be the possible reason for similar seasonal variation of model output.

Generally, rainy season starts in May and continues until October. First paddy cultivation season starts in the beginning of May and harvesting is in the month of August. The other cultivation season is from the end October to February. In the preparation stage farmers need to store water in the paddy fields. This leads to positive values in the graphs especially for the sub basin from Mukdahan to Pakse due to large percentage of paddy field (Fig. 8 and Fig. 9). From the preparation stage until the middle of farming season paddy fields need a large amount of water (Fig. 12). The observed runoff values in the watersheds of high farming lands like Mekong are less than simulated runoffs during these seasons. As the water level is in its minimum by the end of dry season reservoir regulating authorities, like to store water to their capacity in rainy season (Fig. 11). The reservoir operational curves depend on rainfall and the purposes of reservoir such as hydropower generation, flood control, water supply and irrigation. Early water release from reservoirs and excess water release from paddy fields in the months of July and August contribute to large observed runoff than simulated (Fig. 10, Fig. 8, Fig. 9). During the second cultivation season, rainfall amount is less and the farmers like to store maximum amount of water starting from October to December. This leads to a lesser quantity of observed runoff than simulated (Fig. 8, Fig. 9).

Fig. 11 shows the typical water level variation of reservoir in the Mekong river basin. Fig. 12 is a conceptual water storage diagram for paddy field of two cultivation seasons. Combined effect of these two curves controls the temporary water storage capacities. When there is insufficient water for paddy fields during preparation and growing stages, water from the nearest reservoir is diverted to the paddy fields. Observed runoff shows high values during the reservoir spilling periods (Fig. 10).

Although the BTOPMC model results reflect the incapability of modeling temporary water storage devises. Large-scale watershed modeling needs to consider the reservoir operations as well as the temporary water storage in paddy fields. Modeling capability of such changes will encourage decision-makers in watershed developments and planning activities.

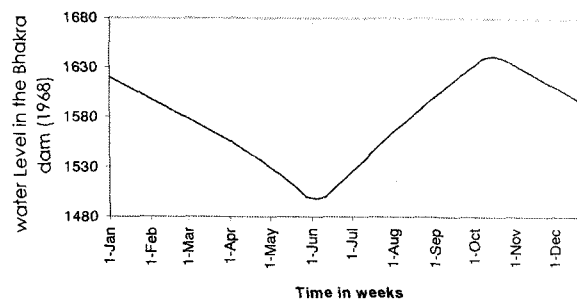


Fig. 11 Water level variation in the Bhakra Dam

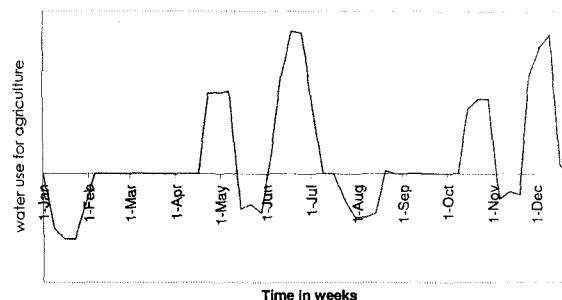


Fig. 12 Temporary water storage in paddy fields

## 7. Conclusions

Block-wise use of TOPMODEL with the Muskingum–Cunge flow routing method can be applied to simulate runoff in large-scale basins. Nash coefficient increases with effective drainage area. This concludes applicability of BTOPMC for large-scale basins. Water storage and release by reservoirs and paddy fields depend on the water availability and the amount of rainfall. Yet the model is not capable of handling such activities within the basin itself.

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