International Journal of Progressive Sciences and Technologies (IJPSAT)
ISSN: 2509-0119.

http://ijpsat.ijsht-journals.org
Vol. 18 No. 2 January 2020, pp. 121-129

Runoff Prediction in an Ungauged Catchment of Upper Deduru Oya Basin, Sri Lanka: A Comparison of HEC-HMS and WEAP Models

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Abstract - Runoff prediction from ungauged catchment has always been a challenging task, requires transfer of hydrologic information from gauged to ungauged catchments. However, it is not clear whether information transfer among nearby catchments is suitable across a wide range of climatic and geographic regions. In this study, stream flow data of a gauged catchment (*Tittawella* tank) were used for calibration and validation of HEC-HMS (Hydrological model) and WEAP (Water resource model). Watershed area ratio technique was adopted to simulate runoff from an ungauged catchment (*Hakwatuna Oya*) and the results were compared. The simulated flows generated by both models in calibration and validation showed good agreement with observed flows. Monthly flows simulated by both models were quite similar. Although HEC-HMS enables runoff simulation on daily basis with better prediction of peaks, necessary for flood forecasting, monthly simulation is adequate for water managers to take management decisions. Therefore, WEAP as a single model can be used for both runoff simulation and taking management decisions in *Hakwatuna Oya* catchment.

Keywords - HEC-HMS, hydrological modelling, ungauged catchment, WEAP.

I. Introduction

Water is a precious natural resource essential for survival of living beings. A large-scale regional variability of water resources can be expected due to variations in rainfall and seasonal evaporative demands. Further, surface water and rainfall, apart from their spatial variability, are characterized by a random variability in time, conditioned by meteorological phenomena [1], [2]. Problems were further aggravated by continued climate change and variability [3]. It is also noted that climate change and variability have major implications for the discharge regime of rivers [4], [5]. Management of water resources has therefore become a big challenge, particularly for water stressed catchments.

The *Hakwatuna Oya* catchment is an ungauged catchment of upper *Deduru Oya* basin, feeds *Hakwatuna Oya* reservoir which supplies water to different user groups. Agriculture is the main water consumer, supports livelihoods of nearly 3500 farming families. It is a water stressed catchment, where frequent conflicts among user groups over limited water, crop failures and in some cases abandoning of cultivation seasons are very common due to inaccurate prediction of available water and poor management decisions. Better prediction of available water is, therefore, an urgent need for better planning and management of water resources. However, it is a challenging task to have a credible prediction of surface runoff in ungauged catchments or regions where no runoff data are available or runoff data are available sparsely [6].

Catchment modelling plays a vital role in assessing the seasonal water availability [7] and thereby helps to take better management decisions for sustainable water resources management. There are many hydrological models with unique and common characteristics developed for different purposes and, therefore, have many different forms. Selection of a model depends on modelling purpose, climate and physiographical characteristics of catchment, quality and availability of data, knowledge on modelling process, model performance and suitability observed in previous studies, etc. Most of the models have specific data requirements which are not available for many of the catchments worldwide [8].

The HEC-HMS is one of the most popularly known hydrological models widely used for runoff simulation. Previous studies showed the ability of HEC-HMS model to simulate and forecast stream flow based on different data sets and catchment types [9], [10]. However, a single modelling framework which incorporates a rainfall-runoff component, reservoir storage, water allocation priorities, return flows and abstractions, and a water quality component is highly desired rather than having separate model for each component. The WEAP is such a model that meets all these requirements and enables evaluation of planning and management issues associated with water resources management and development. This model can be applied to address a wide range of issues including sectoral demand analyses, water conservation, water rights and allocation priorities, stream flow simulation, reservoir operation, ecosystem requirements and project cost-benefit analyses [11]. There are studies [12], [13], [14] which have shown the usefulness of WEAP in water resources management. However, many studies [15], [16] have used separate model to simulate catchment hydrology. This study is, therefore, conducted (1) to simulate runoff from *Hakwatuna Oya* ungauged catchment, and (2) to evaluate the applicability of both HEC-HMS and WEAP models for runoff simulation from this ungauged catchment.

II. Materials And Methods

2.1 Study Area

The *Hakwatuna Oya* catchment of upper *Deduru Oya* basin is located in Kurunagella district of Sri Lanka (Figure 1). The *Hakwatuna Oya* reservoir collects runoff water from its own catchment and is one of the four major reservoirs in the *Deduru Oya* basin. Total catchment area is 63.7 km^2. Rainfall is the only source of water and there is no any water diversion connected to this catchment. The annual average rainfall is around 1100 mm. The monthly mean maximum temperature ranges from 29.9^{0}C-33.4^{0}C while monthly mean minimum temperature varies from 21.8^{0}C-25^{0}C. The latitude and longitude of this watershed are 7.77^{0}N and 80.46^{0}E, respectively.

2.2 Data Collection

The *Hakwatuna Oya* catchment does not have any historical flow data to calibrate model parameters. Therefore, daily rainfall, runoff and evaporation data of *Tittawella* tank from 1995 - 1997 were collected [17] for model calibration and validation. The *Tittawella* tank has a small catchment which is hydrologically similar to that of *Hakwatuna Oya* catchment and located in the same agro-ecological region in Kurunegalla district. The catchment area of *Tittawella* tank is 2.95 km^2. The longest water course is 1800 m long and catchment slope is 0.82%. Daily rainfall data for the period from 2004-2014 was collected from Atharagalle gauging station for runoff simulation.

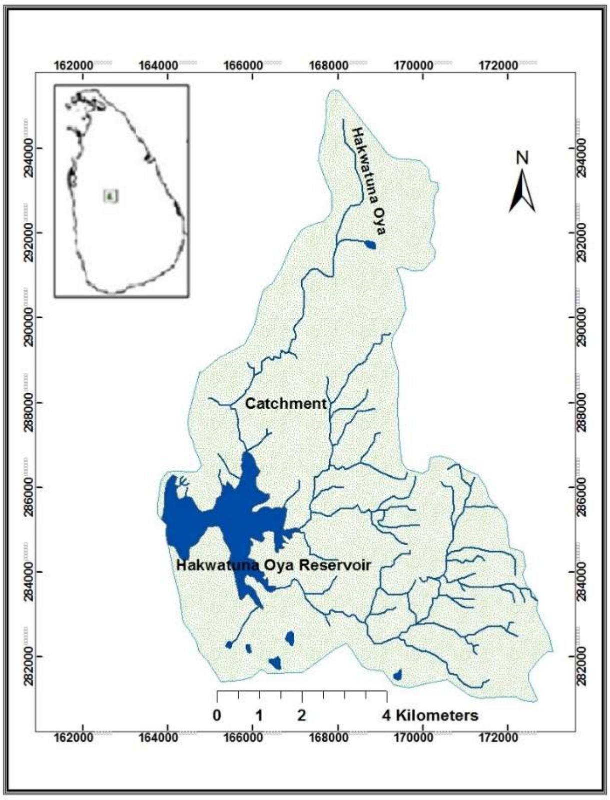


Figure 1. Map of *Hakwatuna Oya* catchment

Climate data such as daily temperature, humidity, sunshine hours, solar radiation, wind velocity and potential evaporation from 2004-2014 were collected from Natural Resources Management Centre, Peradeniya. Details of *Hakwatuna Oya* reservoir and reservoir storage data and water issues from 2005-2014 were collected from the irrigation department, Hiriyala division. Soil data was collected from SRICANSOL Resource Centre, University of Peradeniya.

2.3 Runoff Estimation from Ungauged Catchment

Modelling rainfall-runoff relationship of ungauged catchments is a challenging task, mainly due to lack of local runoff data necessary to calibrate the model parameters. Hydrologists have been attempting to develop strategies to estimate the parameters of their models without calibration since 1970s [18]. International Association of Hydrological Sciences (IAHS) launched an initiative of Predictions in Ungauged Basins (PUB) in 2003, which aims at predicting or forecasting the hydrological responses in ungauged or poorly gauged basins and their associated uncertainty [19]. Since then, many approaches which have been developed for estimating runoff in ungauged basins of which the earliest and most common technique for estimating daily flow in an ungauged catchment is the watershed area ratio method [20]. Flow at an ungauged catchment (receiver) is estimated by multiplying the measured flow at a nearby gauged catchment (donor) by the area ratio of the ungauged to gauged catchments [21]. Previous studies [20] [22], [23] have shown the ability of watershed area ratio technique for better estimation of runoff in ungauged catchments. This study used HEC-HMS model to simulate runoff from *Hakwatuna Oya* catchment by adopting watershed area ratio technique. The WEAP model was also used to simulate runoff from this ungauged catchment for the same time period for model comparison.

2.4 Model Description

2.4.1 HEC-HMS Model

A model HEC-HMS 3.5, developed by the United States Army Corps of Engineers, is designed to simulate the precipitation–runoff processes of dendritic watershed systems [24]. The model supports both lumped parameter based modeling as well as distributed parameter based modeling. This model was designed to simulate the rainfall-runoff processes in a wide range of geographic areas such as large river basin water supply and flood hydrology to small urban and natural watershed runoff [10]. It can be used to simulate a single watershed or a system of multiple hydrologically connected watersheds. The input data such as daily precipitation, long term average monthly potential evapotranspiration, runoff flow (for calibration and validation), and geographical information of the basin are required to get the simulated runoff as output [24]. HEC-HMS model setup consists of a basin model, meteorological model, control specifications, and input data (time series data). This model has capability to generate a continuous stream flow record for the sub-basin from the direct-runoff and base flow records [25]. Direct runoff is transformed to stream flow by a user-selected transform method.

2.4.2 WEAP Model

The Water Evaluation and Planning System (WEAP), developed by the Stockholm Environment Institute, is an Integrated Water Resources Management (IWRM) model that seamlessly integrates water supplies generated through watershed-scale hydrologic processes with a water management model driven by water demands and environmental requirements. It can be used to analyze a full range of water issues through a scenario based approach. Scenarios could include climate variability and change, watershed condition and changes, anticipated demands, ecosystem needs, the regulatory environment, operational objectives, and available infrastructure [12]. In addition, the ease of the use of the model and its user friendly interface make it useful for discussion and dialogue on water resources management among stakeholders [26]. There are four methods presented in WEAP for simulating catchment processes, of which WEAP-MABIA is a complete software package for modelling crop water requirements and the different water balance components. It is used by scientists, engineers and resource and asset managers to simulate runoff, infiltration and percolation processes. WEAP-MABIA also models flow and recharge in natural systems with groundwater interaction [27]. The time step for MABIA is daily while the normal time step for WEAP is monthly. Therefore, for each WEAP monthly time step, MABIA is run on a daily basis and then aggregated to the monthly time step [28].

2.5 Modelling Gauged Catchment

2.5.1 Model Calibration and Validation

Proper model calibration is important in hydrologic modelling studies to reduce uncertainty in model simulations. Time series data of a hydrologically similar catchment (*Tittawella* tank catchment), which has daily rainfall, runoff and evaporation data from 1995-1997, were used for model calibration and validation. The HEC-HMS model was calibrated against observed daily discharge data collected from Sep 1995 to Nov 1995. Flow data collected from Apr 1995 to Mar 1997 (2 years) were used for model validation. The WEAP-MABIA was calibrated and validated using stream flow data from Sep 1995 to Aug 1996 (1 year) and from Oct 1995 to Mar 1997 (18 months) respectively.

2.5.2 Model Performance Evaluation

In addition to graphical technique, statistical performance indices such as Coefficient of determination (iR^2), Index of agreement (id), Percent bias (PBIAS), RMSE-observations standard deviation ratio (RSR) and Nash-Sutcliffe model efficiency (NSE or EFF) were used to analyze the goodness of fit.

The iR^2 (Eq.1) estimates the combined dispersion against the single dispersion of the observed and predicted series and ranges between 0 and 1. A value of zero means no correlation at all whereas a value of 1 means that the dispersion of the prediction is equal to that of the observation.

$$iR^2 = \left[\frac{\sum_{i=1}^{n}\left(y_i^{Obs}-y_{mean}^{Obs}\right)\left(y_i^{Sim}-y_{mean}^{Sim}\right)}{\sqrt{\sum_{i=1}^{n}\left(y_i^{Obs}-y_{mean}^{Obs}\right)^2}\sqrt{\sum_{i=1}^{n}\left(y_i^{Sim}-y_{mean}^{Sim}\right)^2}}\right]^2 \quad \text{Eq. (1)}$$

The id (Eq.2) represents the ratio of the mean square error and the potential error [29]. The id varies from 0.0 to 1.0, with higher values indicating better agreement between the model and observation.

$$id = 1 - \left[\frac{\sum_{i=1}^{n}\left(y_i^{Obs}-y_i^{Sim}\right)^2}{\sum_{i=1}^{n}\left(\left|y_i^{Sim}-y_{mean}^{Obs}\right|+\left|y_i^{Obs}-y_{mean}^{Obs}\right|\right)^2}\right] \quad \text{Eq. (2)}$$

The PBIAS (Eq.3) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. Positive values indicate model underestimation bias while negative values indicate model overestimation bias [30].

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(y_i^{Obs}-y_i^{Sim}\right)\times 100}{\sum_{i=1}^{n}\left(y_i^{Obs}\right)}\right] \quad \text{Eq. (3)}$$

The RSR (Eq.4) is calculated as the ratio of the RMSE and standard deviation of measured data. RSR varies from the optimal value of 0, to a large positive value. The lower RSR, the lower the RMSE and the better the model simulation performance.

$$RSR = \frac{RMSE}{STDEV_{Obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n}\left(y_i^{Obs}-y_i^{Sim}\right)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}\left(y_i^{Obs}-y^{Mean}\right)^2}\right]} \quad \text{Eq. (4)}$$

The NSE (Eq.5) criterion was recommended by ASCE Task Committee in 1993. It is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information"). The NSE ranges between −∞ and 1. It indicates a perfect match between observed and predicted values when NSE = 1. Values between 0 and 1 are generally viewed as acceptable levels of performance, whereas values less than 0 indicate that the mean observed value is better than the simulated value, which indicates unacceptable performance.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(y_i^{Obs}-y_i^{Sim}\right)^2}{\sum_{i=1}^{n}\left(y_i^{Obs}-y^{Mea}\right)^2}\right] \quad \text{Eq. (5)}$$

In which, y_i^{obs} is the ith observed value, y_i^{sim} is the ith simulated value and y_{mean} is the mean of observed values.

2.6 Estimation of Runoff from Ungauged Catchment

The HEC-HMS model, calibrated for a hydrologically similar gauged catchment, was used to estimate runoff from *Hakwatuana Oya* catchment by transferring model parameters. It is assumed that catchment size is the dominant factor that affects the runoff hydrograph and that runoff may be rescaled by area ratio conversions [23]. Daily rainfall collected from Atharagalle rain gauge station for the period from 2004 to 2014 was used for runoff simulation. Runoff simulation was also carried out using calibrated WEAP-MABIA for the same time period.

Simulated runoff was compared with reservoir inflows estimated by simple water balance model using available data. Due to lack of continuous reservoir storage data, it was not possible to compare flows for all years. Data such as surface area of reservoir, water release, evaporation, rainfall along with reservoir storage, estimated using level-storage relationship, were used to estimate reservoir inflow. Deep percolation was assumed as 0.05% of reservoir storage [31]. The following simple water balance equation was used for this study.

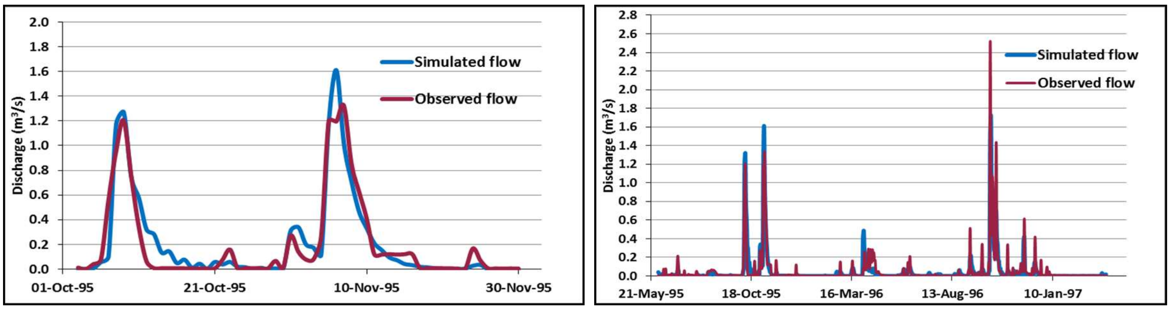
$$\Delta S = (IF + RFY) - (I + E + D)$$

Where; IF is Inflow (m^3), RFY is Rainfall yield to reservoir (m^3), I is Water issues (m^3), E is Evaporation from reservoir (m^3), D is Deep percolations and seepage losses (m^3) and ΔS is Storage difference (m^3).

III. Results And Discussion

3.1 Model Calibration and Validation

Model calibration and validation were done using available stream flow data. Graphical technique was used for visual comparisons of simulated and observed flows as well as for first overview of model performance [32]. Models closely simulated the observed flow for the entire simulation periods, however there is a slight under or over prediction of peaks (Figure 2). Spatial variation of rainfall and data errors, in addition to modelling error, might have attributed for these slight variations [33]. Model parameters used in this study are given in Table 1.



(a) (b)

Figure 2. Calibration (a) and validation (b) of HEC-HMS model using gauged catchment data

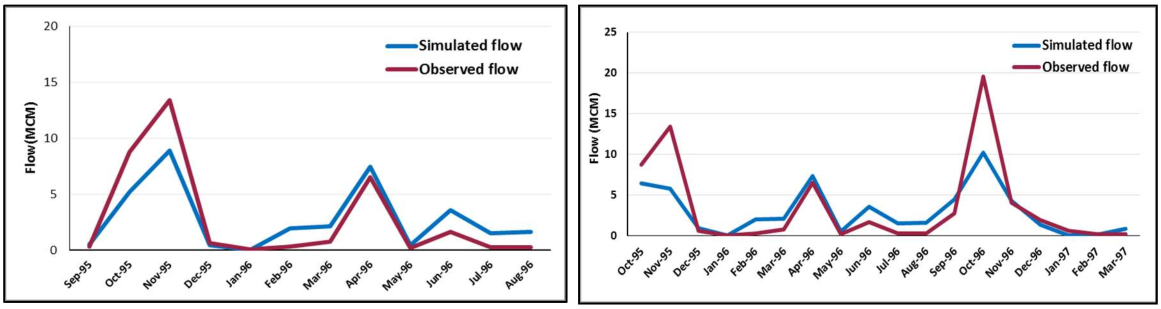
Table 3 shows the values of statistical performance indices. Better model performance can be realized if the NSE, iR^2, and id are closer to unity and PBIAS and RSR have small values [34]. The HEC-HMS showed satisfactory results with NSE > 0.6 and PBIAS <+ 25% for both calibration and validation. This model is therefore well calibrated and can be used to simulate runoff from this ungauged catchment by transferring gauged catchment model parameters.

WEAP also simulated monthly flows which showed good agreement with observed flows (Figure 3). Variations in peaks were observed. It was found that WEAP is not very sensitive to rainfall intensity. The runoff coefficient was almost constant over the simulation periods, irrespective of rainfall intensity. Table 2 shows model parameters used in WEAP model.

Table 1: Model parameters used in HEC-HMS model

Basin and Reach	Parameters	Values
Simple canopy	Initial Storage (%)	0
	*Max. Storage (mm)	4
Simple surface	Initial Storage (%)	0
	*Max. Storage (mm)	10
Initial and constant loss	Initial Loss (mm)	30
	Constant rate	1.28
	*Impervious (%)	10
Recession Base flow	Initial discharge	0.05
	*Recession constant	0.68
	*Ratio to peak	0.9
Clark Unit hydrograph	Time of	3.5
	Storage coefficient	2.3
Muskingum routing	*Muskingum K (hr)	0.8
	*Muskingum X	0.18
Constant Loss/Gain	Flow rate (m^3/s)	0.001
	*Fraction	0.18

** Sensitive parameters*



(a) (b)

Figure 3. Calibration (a) and validation (b) of WEAP model using gauged catchment data

Table 2. Model parameters used in calibration and validation processes.

Parameters	Forest	Agriculture
Area (%)	40	60
Surface layer thickness (m)	0.4	0.3
Total soil thickness (m)	2.0	2.0
Soil water capacity (%)		
Saturation	21.0	21.0
Field capacity	20.2	20.2
Wilt point	12.8	12.8
Coarse fragment	0.0	0.0
Available water capacity	7.4	7.4
Maximum infiltration rate (mm/day)	200	244
Maximum percolation rate (mm/day)	100	100
*Effective precipitation (%)	66	70

**Sensitive parameters*

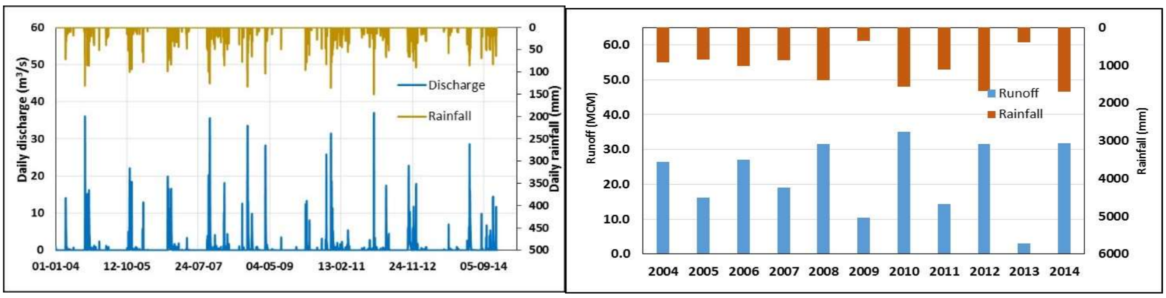
Performance of a model is considered as good for flow if monthly NSE ≥ 0.65, PBIAS ≤ ±15% and RSR ≤ 0.60 [35]. Accordingly, WEAP was also well calibrated and can be used for runoff simulation (Table 3).

Table 3. Calibration and validation statistics for HEC-HMS and WEAP

Model		NSE	RSR	PBIAS (%)	iR^2	id
HEC-HMS	Calibration	0.88	0.35	-4.1	0.97	0.97
	Validation	0.79	0.46	13.2	0.99	0.94
WEAP	Calibration	0.78	0.46	-2.5	0.98	0.92
	Validation	0.66	0.58	14.2	0.97	0.85

3.2 Runoff Simulation from Ungauged Catchment

In order to enable runoff estimation by HEC-HMS, gauged catchment model parameters were transferred to ungauged catchment. Daily discharge, and monthly and annual flows were simulated by HEC-HMS. High variations in daily discharge were observed over the simulation period due to high temporal variations in rainfall. The highest annual flow of 35.2 MCM was observed in 2010 while lowest annual flow of 2.9 MCM was in 2013 (Figure 4).

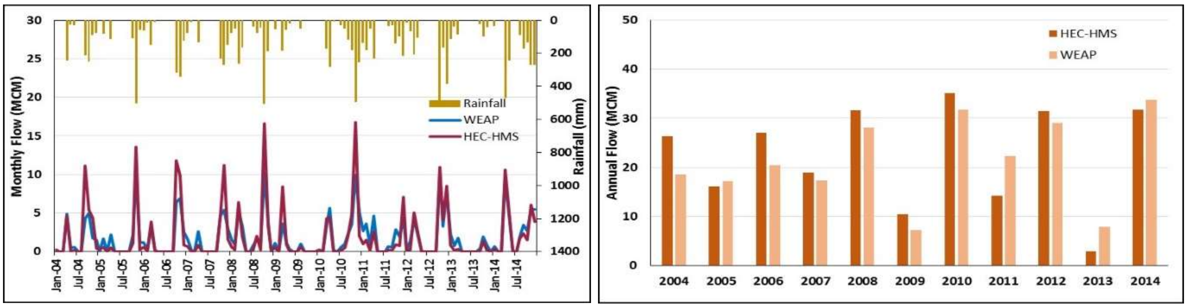


(a) (b)

Figure 4. Daily discharge (a) and annual flow (b) from *Hakwatuna Oya* catchment for the period from 2004 to 2014.

3.3 Comparison of HEC-HMS and WEAP

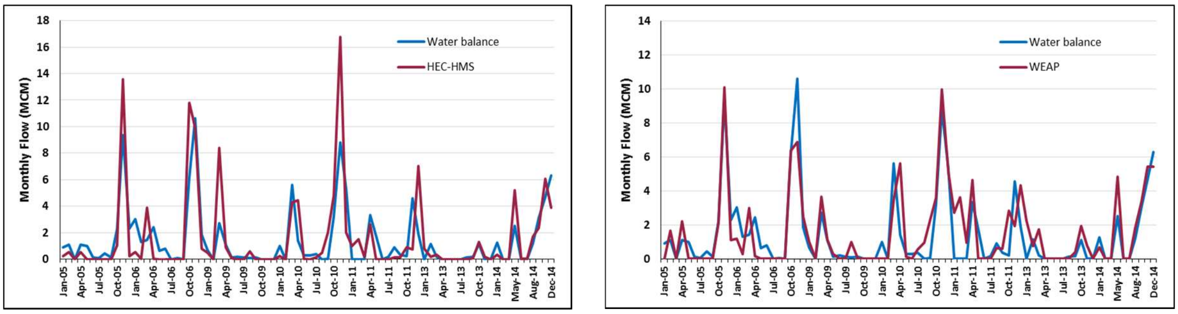
Both models were compared for monthly and annual flows. The qualitative analysis showed similarity of both models in predicting monthly flows from ungauged catchment (Figure 5). However, HEC-HMS slightly over estimated flows during simulation period. This might be due to inability of WEAP to respond to rainfall intensity. The correlation coefficient R^2 values for both monthly and annual flows were 0.84 and 0.80, respectively. The flows simulated by both models were quite similar. The average annual volume flow variation between both models was only 5.1%.



(a) (b)

Figure 5. Comparison of HEC-HMS and WEAP models for simulated monthly (a) and annual (b) flows

In addition, monthly simulated flows of both models were compared with reservoir inflows estimated by simple water balance model (section 2.6). Flows simulated by both models showed fairly good agreement with estimated reservoir inflow (Figure 6). HEC-HMS and WEAP showed correlation coefficient R^2 values of 0.69 and 0.71, respectively. Further, NSE values for HEC-HMS and WEAP were 0.67 and 0.69, respectively. However, water balance model used in this study is not adequate to account for all hydrological components. Lossess from seepage and percolation were not estimated due to lack of data. Instead, assumption was made to account for seepage and percolation lossess. Further, there is a large uncertainty in reservoir operational rules.



(a) (b)

Figure 6. Comparison of *Hakwatuna Oya* reservoir monthly flows simulated by HEC-HMS (a) and WEAP (b) with reservoir inflows estimated by water balance model

IV. CONCLUSIONS

Both HEC-HMS and WEAP adequately simulated runoff from the catchment. The selection of model depends on modelling purpose. It is desired to use HEC-HMS particularly for flood forecasting as it predicts peaks better than WEAP and runs on a daily basis. However, WEAP model provides useful information for decision makers to evaluate various policy interventions in water resources management.

ACKNOWLEDGMENTS

This work was carried out with the aid of a grant from the International Development Research Centre, Ottawa, Canada. Their financial support is gratefully acknowledged.

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