STREAMFLOW PREDICTION IN UNGAUGED CATCHMENT : A CASE STUDY OF “TIERS” SOUTH AUSTRALIA

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Abstract

Streamflow prediction in ungauged catchments is challenging. In this study we have applied hydrologically similar catchment modelling concept to predict streamflow from an ungauged catchment. Stormwater Management Model, EPASWMM was used to simulate the rainfall runoff process. First a model was set up for a nearby gauged catchment that was assumed hydrologically similar to the target ungauged catchment. The model was calibrated by using its gauged data. The calibrated model parameters were then used to set up the ungauged catchment model. The prediction of ungauged catchment model was verified with the uniform runoff loss rate, “ ϕ index” method and found similar values for both catchments. Further statistical analysis revealed that there is a strong temporal correlation in streamflow for both catchments. The developed ungauged catchment model can be used to study any post development scenario within the catchment. This paper provides a detail description of the modelling procedure.

Key Words : EPASWMM model, Ungauged catchment prediction, rainfall-runoff simulation.

1. Introduction

In Australia a majority of the catchments are ungauged [1]. Runoff prediction from ungauged catchment is important as it has direct impact on various practical applications such as design of drainage structure, runoff forecasting and water allocation etc. Prediction of ungauged catchment can be done by using a regional scale model or a catchment scale model. In regional scale modelling, streamflow data from gauged catchments are used to setup a regional scale model that is used to predict streamflow for any ungauged catchment within the region [2,3]. In catchment scale modelling, a rainfall-runoff simulation is done by using computerized modelling tools such as EPA SWMM, XP SWMM, PC SWMM, etc. According to this method, at first a model is made for a nearby gauged catchment and model parameters are determined by calibration. The calibrated parameters then used to construct the ungauged catchment model. This method is suitable when both catchments are hydrologically similar. The term hydrologically similar refers to three types of similarity: i) spatial proximity; ii) physical similarity; and iii) integrated similarity. Spatial proximity means the target ungauged catchment is located in close proximity to the gauged catchment. Physical similarity means most of the physical characteristics of the gauged and ungauged catchments are similar and integrated similarity means both spatial proximity and physical similarity are present [4].

The main purpose of this study is to predict runoff from an ungauged catchment. The outcomes of this study will

help to estimate the volume of runoff from an ungauged catchment. This information can be utilized in designing any hydraulic structures such as bridge, culvert, etc. at any location within the catchment. Furthermore, the constructed ungauged catchment model can be used to analyze a range of post development scenarios.

The next section of this paper provides a description of the study area, research methodology, derivation of initial model parameters, model setup, model calibration, validation and performance measurement. In the result and discussion section a descriptive and inferential statistical analysis of streamflow is given for both catchments. The last section provides a conclusion.

2. Study area

The study area is located at the southern part of Mount Lofty Ranges (MLR) watershed, about 50 km south from the city of Adelaide, South Australia. The ungauged catchment name is Tiers having an area of 22.1 km² (Fig. 1). The nearby gauged catchment is Myponga upstream catchment with an area of 72.6 km². Some of the streams in both catchments are intermittent [5]. The terrain pattern in the area is a rolling type terrain with some low lying marshy area at the mid-section of the catchment [6]. The aquifer in the region is made up of tertiary limestone and quaternary sediment [7]. A variety of soil category is found in the area but the dominant category is loamy soil. Rainfall in the area is winter dominated. The mean annual rainfall is approximately 820 mm/yr and the average wind velocity is 7 km/hr [8].

Fig. 1: Map of the study area

2.1 Land use

Myponga upstream and Tiers catchment are mostly used for broad scale grazing for cattle and sheep. Approximately 75% of the land is used for grazing, 16% covered by native vegetation, 7% covered by forest and 2.4% used as horticulture[6]. Fig. 2 shows the land use map of both catchments.

Fig. 2: Land use map during the study period

3. Methodology

For this study, we applied catchment scale modelling concept. Storm Water Management model EPA SWMM was used to simulate the rainfall-runoff process. As the ungauged Tiers catchment is a neighbour of the gauged catchment (Fig. 1), we assumed that both catchments are hydrologically similar. All the necessary rainfall and streamflow data was collected from the Bureau of Meteorology[8]. Using the collected data, a model was setup and calibrated for the gauged catchment. The

calibrated model parameters were then used to set up another model for the ungauged catchment. The major steps in modelling are discussed next.

3.1 Catchment delineation

According to many researchers including Blöschl and Sivapalan [9], catchment processes are highly variable at both spatial and temporal scales. In order to represent the spatial variability in the model, a catchment is divided into a number of subcatchments which is termed as delineation. In the study we delineated both catchments by using watershed tools in ArcMap software and Digital Elevation Model (DEM) of the catchment. The gauged catchment was divided into thirty subcatchments and the ungauged catchment was divided into 14 subcatchments as shown in Fig. 3.

Fig. 3: Delineation of Myponga and Tiers catchment

3.2 EPASWMM model parameter acquisition

EPA SWMM is a highly parameterized model. Some of these parameters can be extracted directly from GIS and DEM. The width and slope of subcatchments, conduit length and junction invert elevation were extracted from GIS and DEM. Percentage of impervious area of subcatchments were estimated by interpreting the land use map during the study period (Fig. 2). Manning's roughness for impervious and pervious area were obtained by interpreting the aerial photograph of the catchment. Aerial photo of the catchment showed that most of the catchment was covered by light to medium underbrush. Therefore, the recommended values for Manning's n for light to medium underbrush given in EPASWMM manual[10] was used in the model. The initial values of the depression storage parameters were assigned based on the values recommended by Huber and Dickinson [11] for various land-use types. For conduits,

trapezoidal cross section was assigned and initial depth was assigned as 3 meter. Conduit roughness was initially assigned as 0.15 based on the recommended values in EPASWMM manual [10] for a range of channel types. The depth of junction invert was assigned as 4 meter. For infiltration modelling, Horton infiltration method was selected and the initial values of the infiltration parameters were assigned by interpreting the hydrological soil group map and the recommended values by Akan [12].

Aquifer bottom elevation was obtained from the geological cross-section map of the area. Initial aquifer water table depth for each subcatchment was assumed equal to junction invert elevation. Initial values of aquifer properties such as field capacity, wilting point, hydraulic conductivity, etc. was obtained from EPASWMM manual [10] for a range of soil texture. Initial soil moisture content in the aquifer was assigned an arbitrary value between the field capacity and the wilting point of the subsoil. Conductivity slope and lower groundwater loss rate was assigned an arbitrary value within the range specified in EPA SWMM manual [10]. Tension slope was initially assigned as default value and the initial value of upper evaporation fraction was assigned an arbitrary value. The initial value of ground surface elevation was assigned 4 meter higher than node invert elevation. The groundwater flow equation in EPASWMM model is a user defined power function [6]. Therefore, initial values of groundwater flow coefficients were assigned as default values.

3.3 Model setup and run for Myponga upstream

Rainfall and evaporation data during the period of 1993-1998 was assigned to the model. As the data came from three different rain gauge stations, the contributing area for each gauge station was determined by Thiessen-polygon method and the subcatchments within a gauge station's Thiessen-polygon boundary was assigned rainfall from that station. The model was set up on daily time step as the rainfall and evaporation data time steps were on daily basis. For flow routing, dynamic wave routing option was selected and the routing time steps was set to 60 seconds. The EPA SWMM model allows to assign realistic value of surface runoff based on hydrological condition. Therefore, for dry period, a time step of 10 minutes and for wet period, a time step of 5 minutes were assigned to compute surface runoff. The model output was set to report on daily basis. After the completion of setup and defining all parameters, the model was run for the period of 1993-1998.

3.4 Model calibration, validation, parameter sensitivity and goodness of fit measures

Calibration is done in order to adjust the observed and simulated hydrograph. We utilized automatic calibration method by a parameter optimization tool (PEST). The

calibration with PEST requires to setup three files to run the calibration. These are: i) PEST instruction file; ii) PEST template file; and iii) PEST control file[13]. The instruction file tells PEST how to read data from the model output file. For each model run PEST writes new values of calibration variables using the template file to the model input file. PEST control file contains calibration data, initial values and upper and lower boundary of calibration parameters.

Since EPASWMM model contains a number of parameters, the most sensitive parameters to calibrate can be found by a sensitivity analysis. Fortunately, during the optimisation, PEST provides a parameter sensitivity report. From the first couple of PEST run, we identified the most sensitive parameters and calibrated them. Insensitive parameters were excluded from calibration. The calibration parameters in our model are listed in Table 1.

Table 1: List of calibration parameters

Model parameter name	Initial value	Calibrated value
Manning's n for pervious area	0.47	0.444521
Depression storage (pervious area)	9.6	15.0000
Manning's n for conduits	0.1	0.256348
Hydraulic Conductivity (mm/hr)	97	186.703
Conductivity slope (mm/hr)	460	452.795
Rate of percolation (mm/hr)	0.02	3.76E-02
Unsaturated zone moisture	0.22	0.301701
Ground water flow coefficients	3E-06	1.41E-07
Ground water flow exponents	2.27	5.00000

The performance of calibration was measured by using goodness of fit measures, R2 and N-S efficiency[14, 15]. In our model, we got a R2value of 0.61 and NSE value of 0.54. while calculating R2and NSE, model output of the first year (1993) was not counted. It was considered as model warm up period[6]. The observed and simulated flow after calibration is presented in Fig. 4.

Fig. 4 : Observed and simulated flow hydrograph

Fig. 4 indicates that our model is capable of capturing most of the hydrologic events.

After calibration, model's validity was tested by using rainfall and runoff data for the period of 1999-2001 and found $R^2 = 0.48$ and $NSE = 0.43$ which was within the acceptable range. Hence it was considered that the calibration was sufficient.

3.5 Creating a model for Tiers catchment

After getting the calibrated parameters from the gauged catchment model, we constructed another model for Tiers catchment using the calibrated parameters. Rainfall and evaporation data during the period of 1993-1998 was assigned to the model and the model was run. The simulation output was counted from 1994-1998 and the first year (1993) was considered as model warm up period.

4. Result and discussion

Using the model simulated flow series, a statistical analysis was performed for both catchments. The descriptive statistics of observed and simulated flow for gauged catchment is given in Table 2.

Table 2: Myponga u/s obs. and sim. flow statistics

Q-observed (ML/D)		Q-simulated (ML/D)	
Mean	19.303	Mean	20.2465
Std. Error	1.611	Std. Error	1.25902
Median	4.122	Median	6.9750
Mode	.000	Mode	.00
Std. Deviation	63.442	Std. Deviation	49.567
Variance	4024.991	Variance	2456.94
Skewness	8.631	Skewness	5.026
Kurtosis	96.076	Kurtosis	26.673
Range	962.852	Range	336.86
Minimum	.000	Minimum	.00
Maximum	962.852	Maximum	336.86

The coefficient of variation for observed flow series was found 328% which was higher than the simulated flow series (245%). This indicates that the observed flow has a high variability than simulated flow. As the observed flow is a natural process, it is highly variable compared to model simulated flow.

Since a time-series data is affected by time effect, it is important to find the temporal correlation in the time series data. For this purpose, we constructed a matrix scatterplot as shown in Fig. 5.

Fig. 5: Myponga obs. & sim. flow lag-1 correlation matrix

Pearson's correlation between Flow and Flow lag by 1 day for observed flow series was 0.609 whereas for simulated flow series, it was 0.869. This small difference is acceptable. Since both series have a similar temporal behaviour, the calibration was considered reasonable.

For ungauged Tiers catchment, simulated flow statistics is presented in Table 3 and lag-1 correlation matrix is presented in Fig. 6.

Table 3: Tiers catchment simulated flow statistics

Q-simulated (ML/D)	
Mean	7.0032
Std. Error	.73529
Median	1.8950
Mode	.000
Std. Deviation	28.948
Variance	838.00
Skewness	11.830
Kurtosis	175.20
Range	526.41
Minimum	.000
Maximum	526.41

The coefficient of skewness for Tiers catchment was found 11.83, which indicates that the simulated flow series is highly positively skewed and most of the time Tiers catchment is subjected to low flow with a high flow variability that causes high skewness. Coefficient of variation was calculated as 414% which was comparatively higher than Myponga upstream catchment.

Fig. 6: Tiers catchment simulated flow lag-1 correlation matrix

Pearson's correlation between Flow and Flow lag by 1 day was 0.610, which was comparatively lower than Myponga upstream catchment simulated flow but similar to Myponga upstream observed flow. This indicates a chance that flow prediction from Tiers catchment would be better than Myponga upstream catchment.

To understand the occurrence of streamflow events, flow duration curves were plotted for both catchments as shown in Fig. 7.

Fig 7: Flow duration curves

From Fig. 7, it is seen that in Myponga upstream catchment, most of the time simulated discharge is higher than the observed discharge. For flow intensities less than 30 ML/D, simulated flows have a higher exceedance probability than observed flow. For flows greater than 8 ML/D, the calibration has a good agreement with the observed flow. The graph also indicates that our model is unable to predict any flow values less than 0.01 ML/D.

For Tiers catchment, the flow duration curve indicates that streams in Tiers catchment experience cease to flow conditions often than Myponga upstream catchment although simulated flow from Tiers catchment may sometimes reach higher than Myponga upstream catchment.

4.1 Verification of model prediction for Tiers catchment

To verify the Tiers model output, we used ϕ index method. ϕ index is a constant rate of water loss from land surface. Since we assumed that both catchments are hydrologically similar, therefore, ϕ index was expected to be similar for both catchments. We selected a 14 days' streamflow event started from 26-06-1995 to 03-07-1995. From the gauged catchment's observed streamflow data, baseflow was separated and net rain depth was calculated by dividing the direct runoff volume by the catchment area. The net rain depth was subtracted from gross rain depth and converted it on hourly basis which was the hourly loss rate " ϕ index". For Tiers catchment ϕ index was calculated for the same event using its simulated flow series. For Myponga upstream catchment ϕ index was calculated 0.1424 mm/hr and for Tiers catchment it was 0.155 mm/hr. Since these two loss rates were close, the prediction of ungauged Tiers catchment model was considered reliable.

5. Conclusion

In this study, Storm Water Management Model, EPASWMM was used to predict streamflow of ungauged Tiers catchment which is located in South Australia. First a model was made for a nearby gauged catchment. The necessary data was collected from the Bureau of Meteorology [8]. The model was calibrated and validated using observed streamflow data. The calibrated model parameters were then used to setup another model for the ungauged Tiers catchment. The ungauged catchment model output was tested in terms of ϕ index method and found that ϕ index for Tiers catchment was 0.155 mm/hr which was close to Myponga upstream catchment ($\phi = 0.1424$ mm/hr). Hence the prediction of ungauged streamflow was acceptable.

Apart from these, a statistical analysis was performed and found that in Myponga upstream catchment, average observed discharge was 19.3 ML/D and average

simulated discharge was 20.25 ML/D. The skewness of the observed and simulated discharge was 8.63 and 5.03 and the coefficient of variation was 328% and 245% respectively. For Tiers catchment average simulated discharge was 7 ML/D and the coefficient of skewness and variation was 11.83 and 414%. The reason of high skewness in streamflow of Tiers catchment was found caused by very low flow in most times. Unlike observed flow at Myponga upstream catchment, the simulated flow of both catchments was found highly correlated with previous days' flow. Finally, it can be said that the model we made for the ungauged Tiers catchment is reliable for predicting streamflow.

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