SIMULATING THE HYDROLOGIC RESPONSE OF GILGEL ABBAY WATERSHED WITH A SIMPLE SEMI-DISTRIBUTED WATER BALANCE MODEL

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ABSTRACT

Almost all previous hydrological studies for Gilgel Abbay watershed use parameter intensive models usually for climates and landscapes unlike the Ethiopian Highlands. In this study a simple distributed water balance model was used that runs in excel spread sheet to simulate the runoff processes in the Gilgel Abbay watershed. The watershed was divided up into potentially saturated excess runoff areas at the bottom of the hillsides near rivers, and hill lands. The hill lands were either degraded producing surface runoff or not degraded. In the non-degraded area all rain water infiltrates and released with a time delay as interflow and baseflow. The model simulates well the river discharge except for some peak flows. The discharge variation of the Gilgel Abbay river was explained well with the determination coefficient, R^2 = 0.75 and Nash Sutcliffe efficiency, NSE= 0.74. The results indicate that the simple site specific water balance model can be an important tool in identifying and addressing runoff generation mechanisms with the scarce data availability and can be easily refined when new and comprehensive data are accessible.

Key words: Gilgel Abbay watershed, water balance model, simulation, baseflow

BIOGRAPHICAL SKETCH

Aemiro Gedefaw was born in Adet, West Gojjam Zone, Ethiopia on June 17, 1984 to his father, Gedefaw Kassa, and his mother, Zina Gedib. He joined Abra Minch University in November 2001 and obtained a degree in hydraulic engineering in July 2006. After which, he has worked as an instructor at Bahir Dar College of Construction Technology from September 2006 – January 2009. From January 2009 onwards, he has been working in Amhara Design and Supervision Works Enterprise. In between, he joined a Cornell University master's degree program and continued to attend the program. His aspiration and professional career has made him to want to hold PhD degree.

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1 INTRODUCTION

The discharge of rivers such as GilgelAbbay does not only vary from season to season but over large time periods as well. This variation has direct implications on water resource management (Howell and Allan, 1990). Watershed models can simulate these variations based on longterm precipitation data. The capability to simulate river flows in large river basins is desirable for at least four reasons (Arnell, 1999 cited in Xu, 2003): 1) water resources managers need to estimate the spatial variability of resources over the regions for operational and planning purposes; 2) hydrologists and water managers are concerned about the effects of land use changes and climate variability over large geographic domains; 3) hydrological models are useful in estimating non-point sources of pollution; and 4) hydrologists and atmospheric modelers are conscious of weaknesses in the representation of hydrological processes in the regional and global atmospheric models.

Hydrologic prediction usually relies on incomplete and uncertain process descriptions that have been deduced from sparse and paucity data sets. Precipitation – runoff models, which combine conceptual descriptions of the flow system with a simplified characterization of the flow domain, have proven quite successful when used for operational forecasts of runoff. A severe drawback of these models, however, is that their structure is not directly related to the physical characteristics of the watersheds. Accordingly, it is expected that their applicability is limited to areas where runoff has been measured for some years and where no significant change of conditions has occurred (Beldring, 2001). Steenhuis et al. (2009) has proposed a semi distributed watershed model that has been used to simulate the flow in the Blue Nile. The basin was conceptualized into runoff contributing area and hillslope scale. Despite lumping hydrological processes over several kilometers in a watershed the model was able to simulate flows with Nash Sutcliffe efficiencies of 0.80 and greater on a daily basis. The hydrologic response is addressed through saturation excess runoff generation mechanism [Steenhuis et al., 2009].The runoff processes are conceptualized based on this single dominating slope of the catchment (over 90%) and the rainfall season as a hydrologic response unit (HRUs).The model constitutes of saturation excess overland flow and baseflow recession in each HRUs.

Model evaluation is required before it can be applied to an area (Wagener, 2003; Gupta et al., 2005). A good model meets the following requirements: (1) the model must be able to reproduce with accuracy and precision the observed system response, (2) model parameters must be identifiable easily with available data and (3) the model must be consistent with our understanding of reality.

Future climate change will impact on discharge which will further increase the uncertainties in Gilgel Abbay water resources planning and management. Long-term planning for water resource development becomes very difficult under such conditions, which call for an assessment of the sensitivity of discharge to a wide range of future precipitation scenarios. The sensitivity of river flow to precipitation fluctuations has implications on Lake Tana water level and water quality.

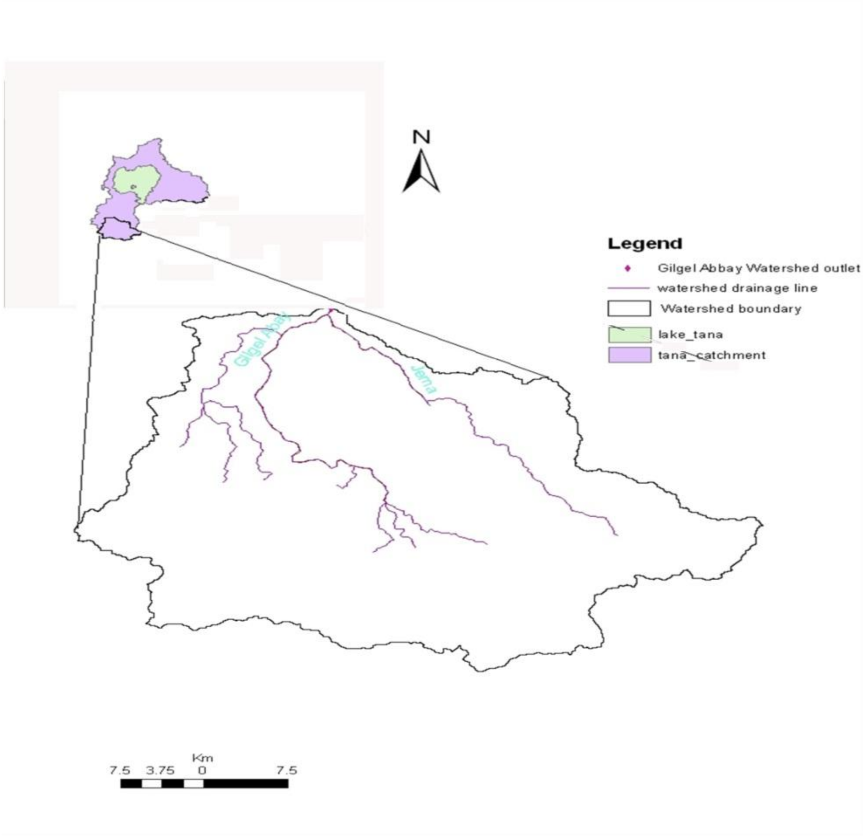

Figure 2-1: Location of Gilgel Abbay watershed

It is therefore imperative that simple models are developed based on readily available data that can simulate the river discharge. The general objective of the study is to assess the validity of the semi distributed water balance model developed for the Upper Blue Nile basin [Steenhuis et al., 2009] for Gilgel Abbay watershed for assessment of hydrological processes and model performance and model structure uncertainties.

2 BIOPHYSICAL DISCRIPTION OF GILGEL ABBAY WATERSHED

Gilgel Abbay watershed which is the largest of the four watersheds of Lake Tana is the main contributor of the flow to the lake. The area of the study watershed at Wetet Abbay gauging station is 1656 km^2 and it is located south of Lake Tana as shown in fig. 2-1. The elevation ranges from 1890 m to 3524 m above mean sea level (fig. 2-2).

From the slope map of the watershed (fig. 2-3) around (909 km^2) 55% of the area falls on0-8% slope range, and the rest (365 km^2) 22%, (258 km^2)16% and (124 km^2)7% of the watershed area respectively falls in the slope range of 8-15%, 15-30% and a slope greater than 30%.

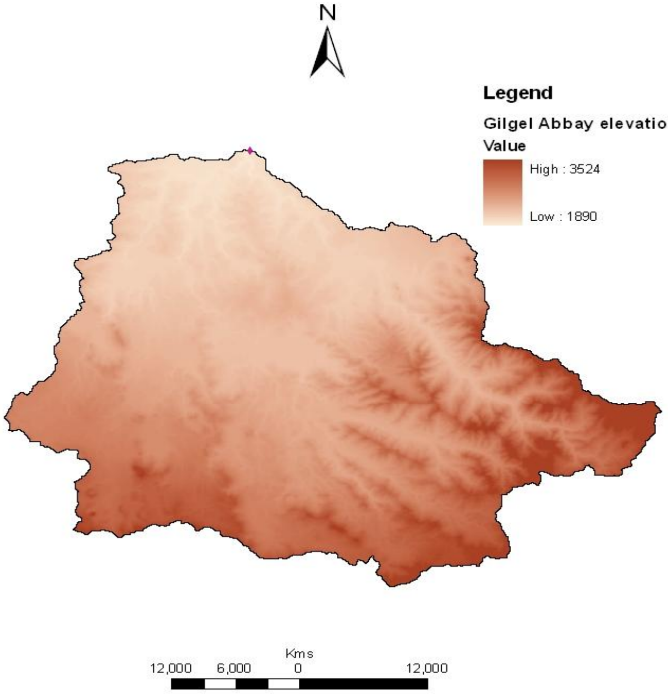

Figure 2-2: Digital elevation model of Gilgel Abbay

The dominant geologic cover of the watershed is quaternary volcanic rock characterized by basicular and fractured basaltic rock (Abdo, 2008). Land use/ land cover characteristics comprise mainly of crop land with other minor covers of grassland, forest and marshland (Abdo, 2008), while their distribution and uniformity remains characteristics of mainly the topography.

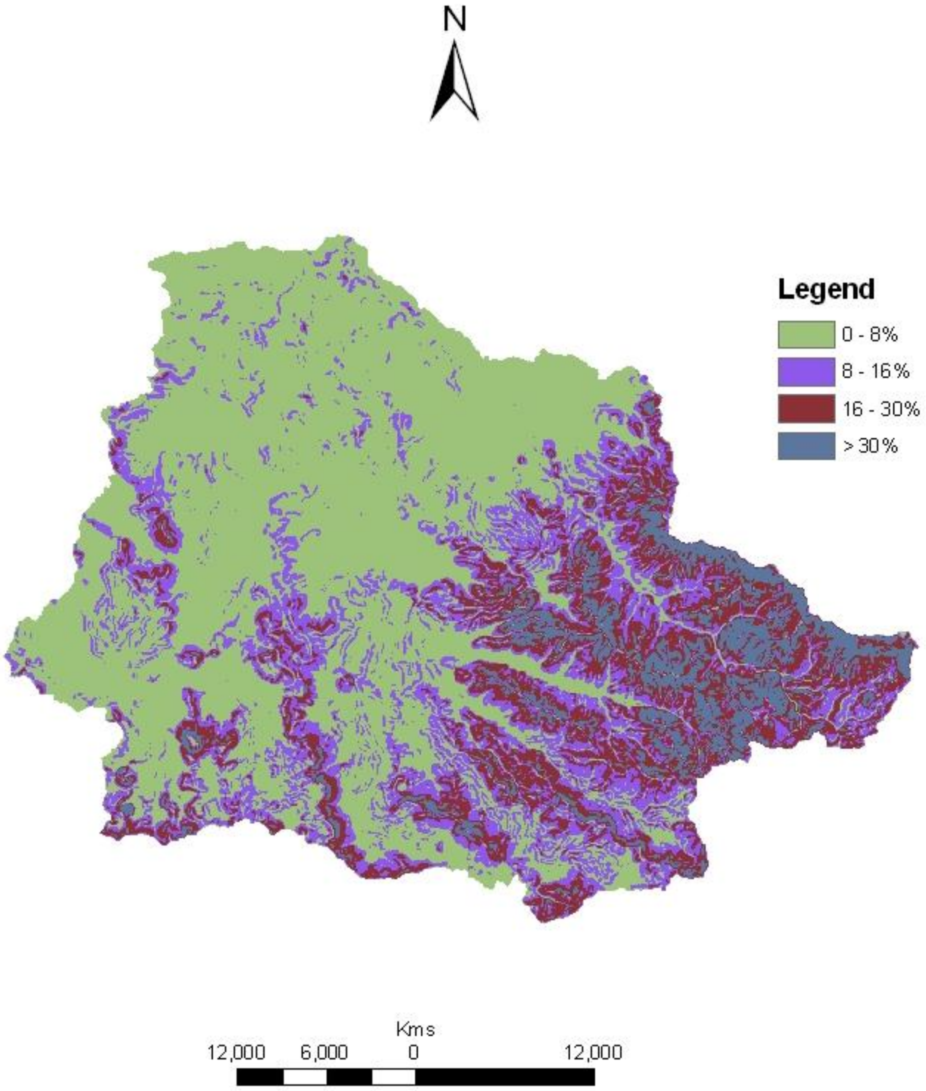

Figure 2-3: Topographic slope classes for the Gilgil Abbay watershed

Continuous and long data record period is very important for the watershed monitoring such as water quantity and quality estimation to be very accurate. The importance of watershed gauging increases or will be recognized more when pressure (such as water use competition) on watershed increases (Johnson, 1999). The characteristics (i.e., percent of missing data days and mean of the rainfall over the record period) of Gilgel Abbay watershed metrological stations have been summarized as tables 2-1 and 2-2. Only Sekela meteorological station has been found located within the study area boundary (fig. 2-4). The long term average rainfall of the watershed has been characterized by meteorological gauging stations of Dangila, Sekela, Kidamaja and Enjibara (see appendix).

Srinivasan et al. (2005) discussed the importance of seasonal hydrometric characteristics of watershed for understanding watershed behavior (e.g. runoff generation mechanism). Hence the seasonal hydro-metric characteristic for the Gilgel Abbay watershed is illustrated as in figure 2.5 and figure 2.6.

Table 2-1: Statistical summary of meteorological stations

Meteorology Station name	**Minimum mm**	**Maximum mm**	**Mean mm**	**Record period, year**	**% missing data days**
Enjibara	0.00	166.00	6.64	1985 - 2006	12
Kidamaja	0.00	92.20	6.04	1985 - 2006	60.9
Bahir Dar	0.00	124.7	4.00	`985 - 2006	3.1
Zege	0.00	97.3	4.21	985 - 2006	61
Adet	0.00	81.9	3.67	1986 -2006	71
Dangila	0.00	78.5	4.56	1985 - 2006	80.7
Sekela	0.00	103.5	5.42	1988 - 2006	22.5

Table 2-2: Location of meteorological stations

Station name	Easting (x)	Northing (y)
Enjibara	272684	1214798
Kidamaja	246960	1217535
Dangila	263023	1245068
Sekela	305531	1215764
Bahir Dar	323404	1281458
Adet	334835	1245552
Zege	315031	1293195

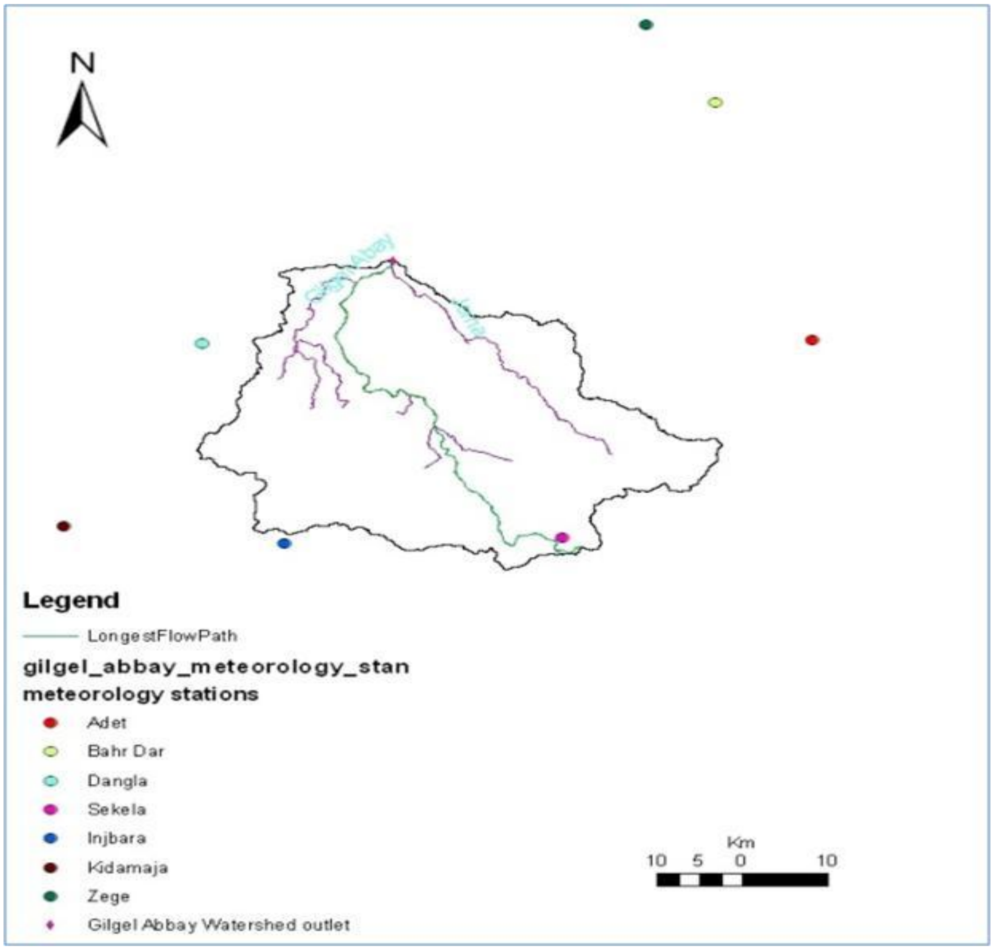

Figure 2-4: Geographical distribution of within and around Gilgel Abbay watershed hydro meteorological station

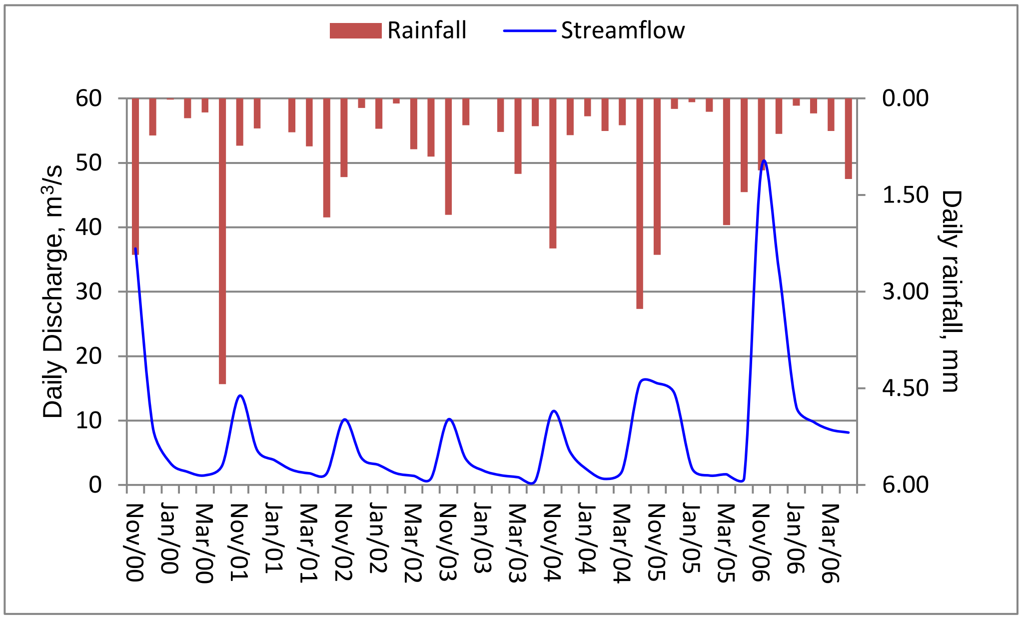

Figure 2-5: Low rainfall season hydrometric characteristics

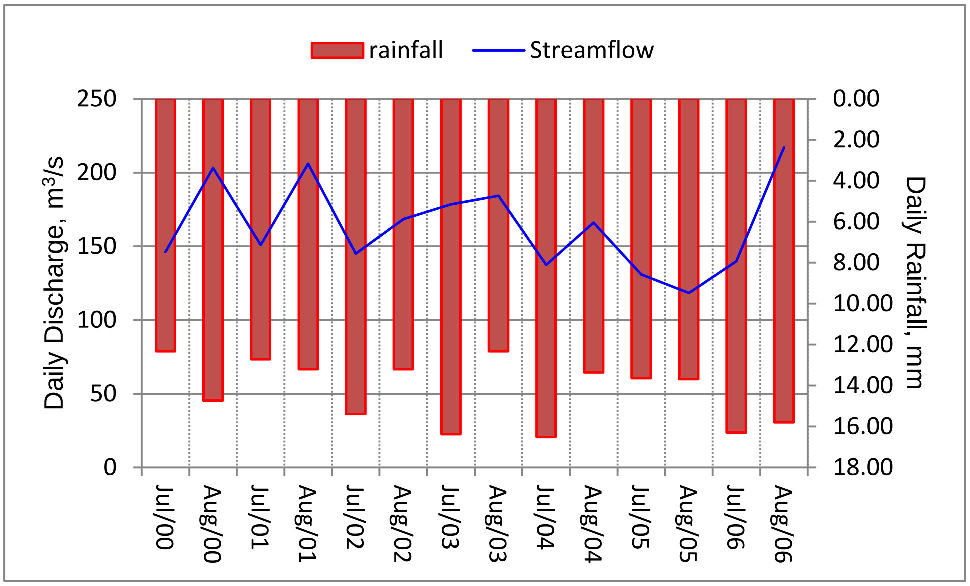

Figure 2-6: High rainfall season hydrometric characteristics

3 WATERSHED STUDY MATERIALS AND METHODS

Daily climatic data such as precipitation, temperature, and wind speed, and hydrological data i.e. daily stream flow have been collected from Regional Meteorological Agency and Ministry of Water Resources.

Models can take many different forms, from simple empirical relationships to complex three-dimensional spatially distributed representations of transport processes. They are constructed on the basis of limited experimental data and an imperfect understanding of the processes (National Research Council, 1990). Model development is an iterative process (Kolm, 1995; Nash and Sutcliffe, 1970; Fenicia et al., 2008). This thesis is the first iteration of a lumped distributed model (Steenhuis et al, 2009) for a small river basin; The Gilgil Ababy. The model was originally developed for the whole Ethiopian Blue Nile. To aid in further development the model is fitted against the data and the uncertainty of the model predictions is calculated for the Gilgil Abbay watershed.

A model consists of primarily two critical parts: 1) the model equation (structure), 2) model parameters. Many previous studies (e.g. Moges, 2008; Abdo, 2008) in Gilgel Abbay watershed considered model selection through evaluation of model performance at the outlet of the watershed. Some other studies (e.g. Setegen et al., 2008) provided insight into the internal catchment processes by addressing the dynamics of variable source contributing area as a basis for hydrologic response unit definition.

The main objective of this thesis is to re-consider catchment hillslope hydrology behavior (Steenhuis et al., 2009) as distinct from previous studies by considering the distribution of surface runoff, interflow and baseflow in the landscape. The watershed was divided up in to potentially saturated excess runoff areas at the bottom of the hillsides near rivers, and in to hill lands. The hillsides were either degraded producing surface runoff or not degraded. In the non-degraded area all rain water infiltrates and released with a time delay as interflow and baseflow. Base and interflow is based on streamflow recession analysis. Recession flow analysis is relatively well studied for the Gilgil Abbay (e.g. Moges, 2008; Setegn et al, 2008).

The model performance criteria were based on the Nash Sutcliffe (NSE), volume conversation index (VCI) and root mean squared error (RMSE). The sensitivity of model parameters was investigated for the model performance criteria using sensitivity index (SI) (Descroix et al., 2007) for the most sensitive parameter (eqn.3-1).

Eqn. 3-1

Where is the sensitivity index for a 10% change parameter value, is simulated discharge.

3.1 The Study Models

3.1.1 Water balance model for Upper Blue Nile basin

A lumped distributed water balance type rainfall runoff model was developed and tested by Steenhuis etal. (2009) to predict the stream flow for Ethiopia portion of the Blue Nile (Abbay) .The model was developed to predict the discharge as a function of surface runoff, interflow and baseflow. This model is applied to the Gilgel Abbay watershed at Wetet gauging station (a watershed of the upper Blue Nile catchment). The amount of water stored, S (mm), in the top most layer of the soil for hillslopes and the runoff source areas were estimated separately with a water balance equation of the form:

$$S_t = S_{t-\Delta t} + (P - AET - R - Perc)\Delta t \qquad \text{Eqn. 3-2}$$

where P is precipitation, (mm d^{-1}); AET is the actual evapotranspiration; $S_{t-\Delta t}$,previous time step storage, (mm); R, saturation excess runoff (mm d^{-1}); Perc is percolation to the subsoil (mm d^{-1}) and Δt is the time step.

During wet periods when the rainfall exceeds evapotranspiration (i.e., P>PET), the actual evaporation, AET, is equal to the potential evaporation, PET. Conversely, when evaporation exceeds rainfall (i.e., P<PET), the Thornthwaite andMather (1955) modified by Steenhuis et al., 2009) procedure is used to calculate actual evapotranspiration, AET (Steenhuis andVan Der Molen, 1986cited by Steenhuis et al. 2009).

$$AET = PET\left(\frac{S_t}{S_{\max}}\right) \qquad \text{Eqn. 3-3}$$

Where PET is the potential evapotranspiration (mm d^{-1}).

The available soil storage capacity, $S_{\max}$ (mm), is defined as the difference between the amount of water stored in the top soil layer at wilting point and the upper moisture content that is equal to either the field capacity for the hillslopes soils or saturation in runoff contributing areas. Based on Eq. 2 the surface soil layer storage can be written as:

$$S_t = S_{t-\Delta t}\left[\exp\left(\frac{(P-PET)\Delta t}{S_{\max}}\right)\right] \text{when } P < PET \qquad \text{Eqn. 3-4}$$

In the saturated runoff contributing areas when rainfall exceeds evapotranspiration and fully saturates the soil, any moisture above saturation becomes runoff, and the runoff, R:

$$R = S_{t-\Delta t} + (P-PET)\Delta t \qquad \text{Eqn. 3-5}$$

$$S_t = S_{\max} \qquad \text{Eqn. 3-6}$$

For the hillslopes the water flows either as interflow or baseflow to the stream. Rainfall in excess of field capacity becomes recharge and is routed to two reservoirs that produce baseflow or interflow. It was argued that the baseflow reservoir is filled first and when full the interflow reservoir starts filling. Clark et al. (2009) have also shown the hillslope outflow – storage relation as fill and spill process which is initialized by thresholds of; for instance, rainfall and storage. The baseflow reservoir acts as a linear reservoir and its outflow, BF, and storage, $BS_{t,}$ is calculated when the storage is less than the maximum storage, BS_{max}.

$$BS_t = BS_{t-\Delta t} + (Perc - BF_{t-\Delta t})\Delta t$$

Eqn. 3-7

$$BF_t = \frac{BS_t\left[1 - \exp(-\alpha\Delta t)\right]}{\Delta t}$$

Eqn. 3-8

When the maximum storage, BS_{max}, is reached then

$$BS_t = BS_{\max}$$

Eqn. 3-9

$$BF_t = \frac{BS_{\max}\left[1 - \exp(-\alpha\Delta t)\right]}{\Delta t}$$

Eqn. 3-10

4 RESULTS

4.1 Model Performance Evaluation and Sensitivity Analysis

It is of interest to analyse how closely the model predictions match the observed data. The analysis is done for two hydrologic regimes: lowand flowdischarge periods. The partitioning of regimes is due to the fact that the behavior of the catchment is inherently different during periods “driven’’ by high and medium rainfall and periods without or little rain (Wagener 2007).

The usual goodness of fit test using single value objective function of the Root Mean Square Error (RMSE) – it can address boththe bias or difference between the estimated and observed value and the variance and standard error or the spread of the error) is to be used for each different response modes of the watershed hydrological system (UNESCO, 2005). In reality it is difficult and impractical to achieve very accurate model performance indices (e.g., significance level) satisfying all requirements of factors in the process considered as a result of data mining (ample of data collection works, if possible and the challenge behind it of cost , time, sampling instruments availability and specification with regard to the environment considered as such calibration issues) problems at the spatial resolution or detail required, and as a result of temporal variation (Johnston and Dinardo, 1997). It may be in terms of some measure of variation as homoscedacticty/ heteroscedacticity (e.g., between calibration and validation scenario) of sample data characteristics even within its timeline of data collection. Performance measures of the estimated model (e.g., parameter constancy) should be tested against different criteria, the idea which is more emphasized by (Johnston and Dinardo, 1997). As far as the model outcome is of with "small" discrepancy with the observed phenomena, it is taken as multi-objective optimization criteria which could advantage the model delimitation of its parameters and structures (Beldring, 2002).

$$RMSE = \sqrt{\frac{1}{N}\sum_{t=1}^{N}\left(q_t^{sim} - q_t^{obs}\right)^2}$$

Eqn. 4-1

Stable and robust parameter values [Nash and Sutcliffe, 1970;] could even be attained using relevant objective functions (i.e. choosing the right objective function for the right scenario). Srinivasan, et al (2005) pointed out that Nash-Sutcliffe (NS) and Volume of error (D_v, i.e. cumulative difference between observed and simulated values) criteria worked efficiently for a daily time steps and for a specific length of time respectively. A bias measure, VCI is also used in the model performance assessment.

Eqn. 4-2

Eqn. 4-3

Where VCI is the volume conversation index; NSE is the Nash-Sutcliffe efficiency; Qobs, Qsim, and obs are observed discharge, simulated discharge and average observed discharge, respectively. The simulation output in respect of seasonal variation has also been shown using the general model structure which was usually proved sufficient (vandewiele, Xu and Ni, 1992).

Eqn. 4-4

Where, is residual or error.

The model result shows good prospects for future of more detailed investigation. It fits closely the observed streamflow phenomena (figs. 4.1a and4-1b). The statistical model performance measures (NSE_Nash-Sutcliffe and RMSE_root mean square error)of the model simulation are in good proximate [according to Johnston and Dinardo, 1997].

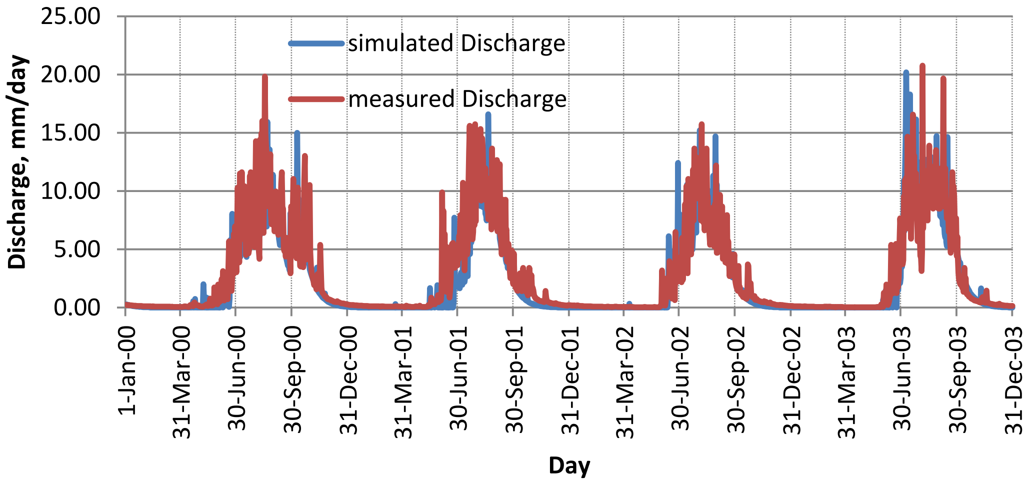

Figure 4-1a: Simulated discharge vs observed discharge for 2001 and 2003

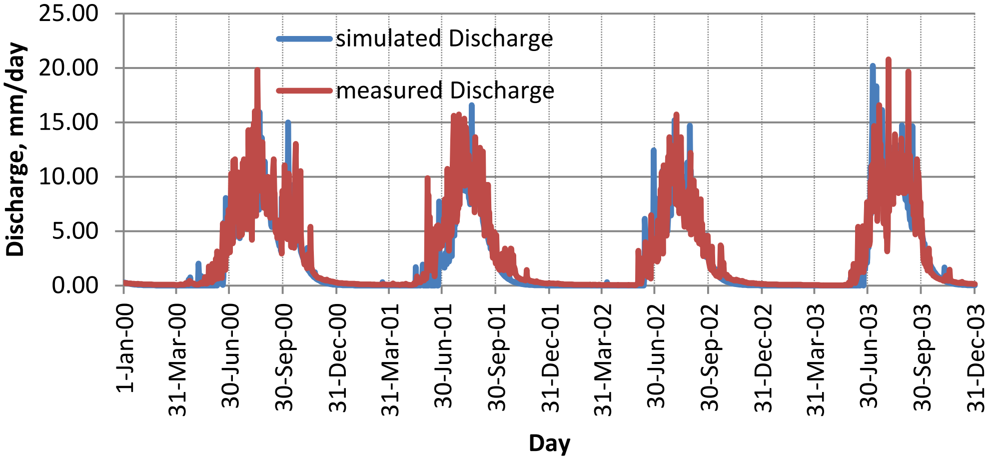

Figure 4-1b: Simulated discharge Vs observed discharge for 2003 to 2006

The result shows the model is predicted to be reasonable with the criteria NSE of 0.74and with the root mean square error (which is a measure of both bias and variance (UNESCO, 2005) is of 1.93 mm/day (Table 4.1).

Table 4-1: Statistical result of model simulation

Criteria	Performance
NSE	0.74
VCI	0.86
R^2	0.754
RMSE	1.93

The model residual behavior also shows the model error to be concentrated between 1.5 and -1.0 mm/day with some errors to reach extremes in both the positive direction (i.e., up to 2.50 mm/day) and negative direction (i.e., up to -2.0mm/day) (figs. 4-2a and 4-2b).

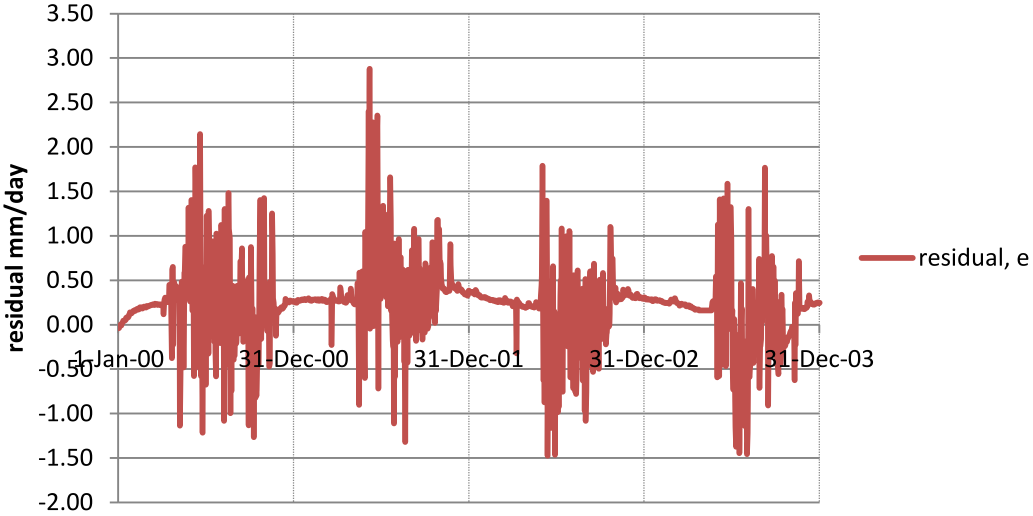

Figure 4-2a: Residual characteristics of the model

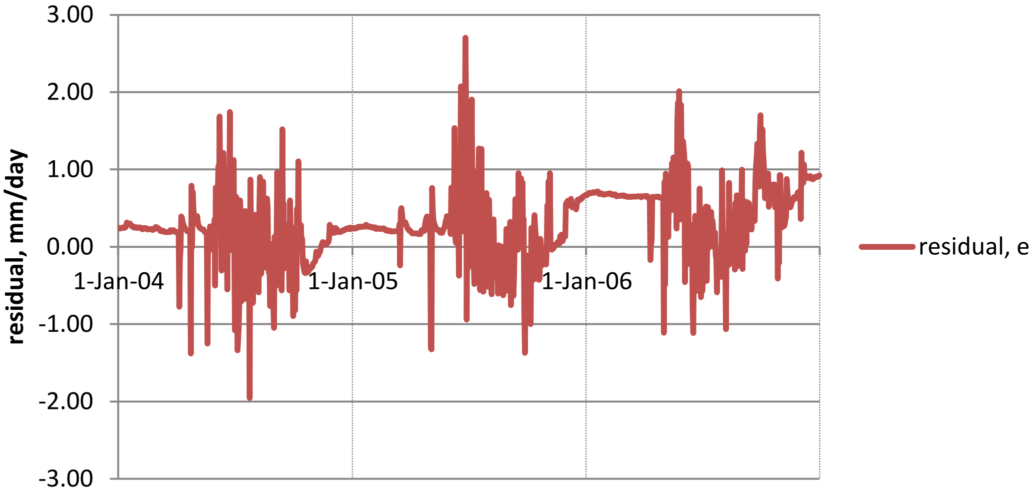

Figure 4-2b: Residual characteristics of the model

Another statistical in particular measure of bias, volume of conversation index, VCI has result in a model performance of 0.86 for the simulating period. It indicates the total volume difference between the simulated and observed discharge within the given period of model run.

For the model to be good it should have to also satisfy a requirement in most cases of a small range of parameter space [National Research Council, 1990]. The sensitivity of the model has been tested for the parameters thought to have spatial and temporal variations. Subsequently the watershed maximum water holding capacity, $S_{max}$and the maximum length of period, tstar for the interflow to stop has been varied for the 10%, 20% and 30% of the parameters values (table 4-2). Except for the hillslope hydrologic unit maximum water holding capacity (S_{max}), the study shows very small change to most parameters of the hydrologic response units for the model performance of Nash Sutcliffe efficiency (NSE), root mean squared error (RMSE), the determination coefficient (r2) and volume conversation index (VCI). The performance of Nash Sutcliffe efficiency NSE has been changed for the hillslope S_{max}-30, S_{max}-10, S_{max}+10 and S_{max}+30 respectively from (0.74 – 0.73), (0.74 – 0.74), (0.74 – 0.73) and (0.74 – 0.72). Sensitivity analysis based on the 10% (SI_{10}) and 30% (SI_{30}) sensitivity index for the S_{max} of hillslope hydrologic area has resulted in -0.035 and- 0.103 for SI_{10} and $SI_{30,}$ respectively.

Table 4-2: Sensitivity analysis result

Degraded area S_{max}							
Perform-ance unit	S_{max}-30	S_{max}-20	S_{max}-10	S_{max}	S_{max}+10	S_{max}+20	S_{max}+30
VCI	0.86	0.86	0.86	0.86	0.86	0.86	0.86
NSE	0.74	0.74	0.74	0.74	0.74	0.74	0.74
r^2	0.754	0.754	0.754	0.754	0.754	0.754	0.754
RMSE	1.93	1.93	1.93	1.93	1.93	1.93	1.93
Saturated area Smax							
Perform-ance unit	S_{max}-30	S_{max}-20	S_{max}-10	S_{max}	S_{max}+10	S_{max}+20	S_{ma}x+30
VCI	0.86	0.86	0.86	0.86	0.86	0.86	0.86
NSE	0.74	0.74	0.74	0.74	0.74	0.74	0.74
r^2	0.754	0.754	0.754	0.754	0.754	0.754	0.754
RMSE	1.93	1.93	1.93	1.93	1.93	1.93	1.93
Hillslope area S_{max}							
Perform-ance unit	S_{max}-30	S_{max}-20	S_{max}-10	S_{max}	S_{max}+10	S_{max}+20	S_{max}+30
VCI	0.91	0.89	0.88	0.86	0.85	0.83	0.82
NSE	0.73	0.74	0.74	0.74	0.73	0.73	0.72
r^2	0.751	0.753	0.754	0.754	0.753	0.75	0.746
RMSE	1.94	1.93	1.93	1.93	1.94	1.95	1.97
Groundwater Bs_{max}							
Perform-ance unit	BS_{max} -30	BS_{max}-20	BS_{max}-10	Bs_{max}	BS_{max}+10	BS_{max}+20	B_{Smax}+30
VCI	0.84	0.85	0.86	0.86	0.86	0.86	0.86
NSE	0.73	0.73	0.74	0.74	0.74	0.74	0.74
r^2	0.751	0.752	0.753	0.754	0.754	0.754	0.754
RMSE	1.95	1.94	1.93	1.93	1.93	1.93	1.93
Interflow tstar							
Perform-ance unit	tstar-30	tstar-20	tstar-10	tstar	tstar+10	Tstar+ 20	Tstar + 30
VCI	0.86	0.86	0.86	0.86	0.86	0.86	0.86
NSE	0.73	0.73	0.74	0.74	0.74	0.74	0.74
r^2	0.751	0.752	0.753	0.754	0.755	0.755	0.757
RMSE	1.94	1.94	1.93	1.93	1.93	1.92	1.91

5 CONCLUSION AND RECOMMENDATION

Goodness of fit cannot be a sound and sufficient measure for a valid model in itself (Vogel and Sankarasubramania, 2003) when the input parameters vary in time (Cheng, 2008). Rather physically interpretable development of watershed model parameters through successive iteration is vital especially in the assessment of ungauged watersheds. It may even be helpful in regionalizing such physically based developed models at local level (Franchini and Pacciani, 1991). In this thesis it is shown that the model sensitivity varies for each parameter. The model's Nash Sutcliffe NSE changed relatively little for a 30% increase or decrease for the following input parameters: the degraded area maximum water holding capacity, S_{max}saturated area S_{max}, and maximum baseflow storage BS_{max}. The hillslope S_{max} was relatively more sensitive parameter which caused the model NSE and VCI (volume conversation index) to be changed by about 2% and 6% respectively for a change in $S_{max}$of 30%. It is recommended that the predictions can practically be improved through integration of well planned and managed projects like water resource developments and specific research works.

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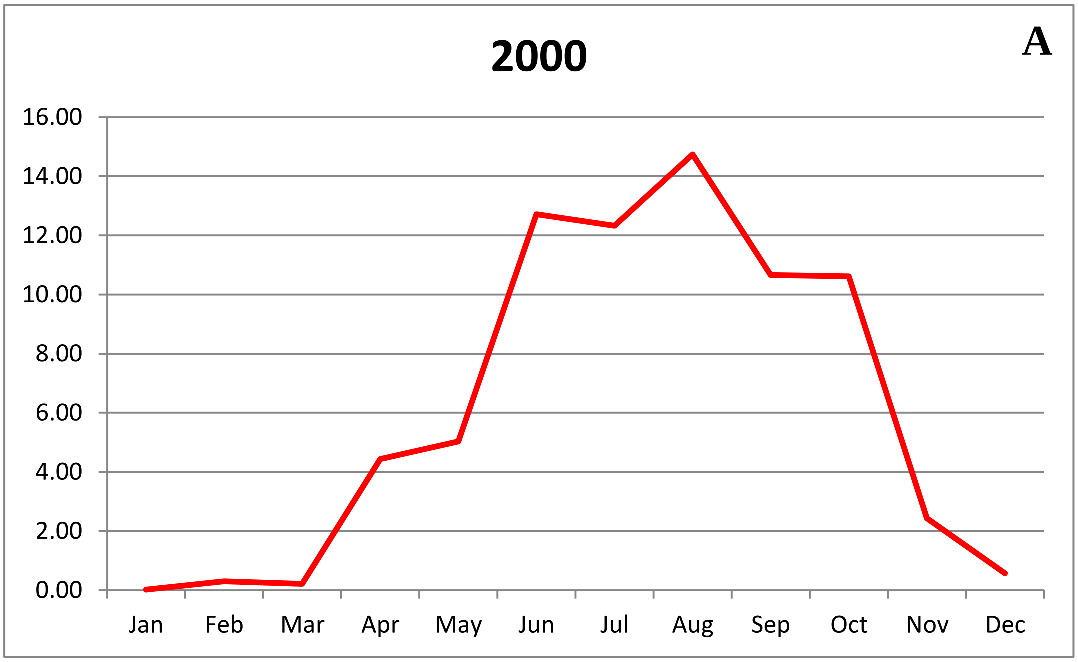
7 APPENDIX

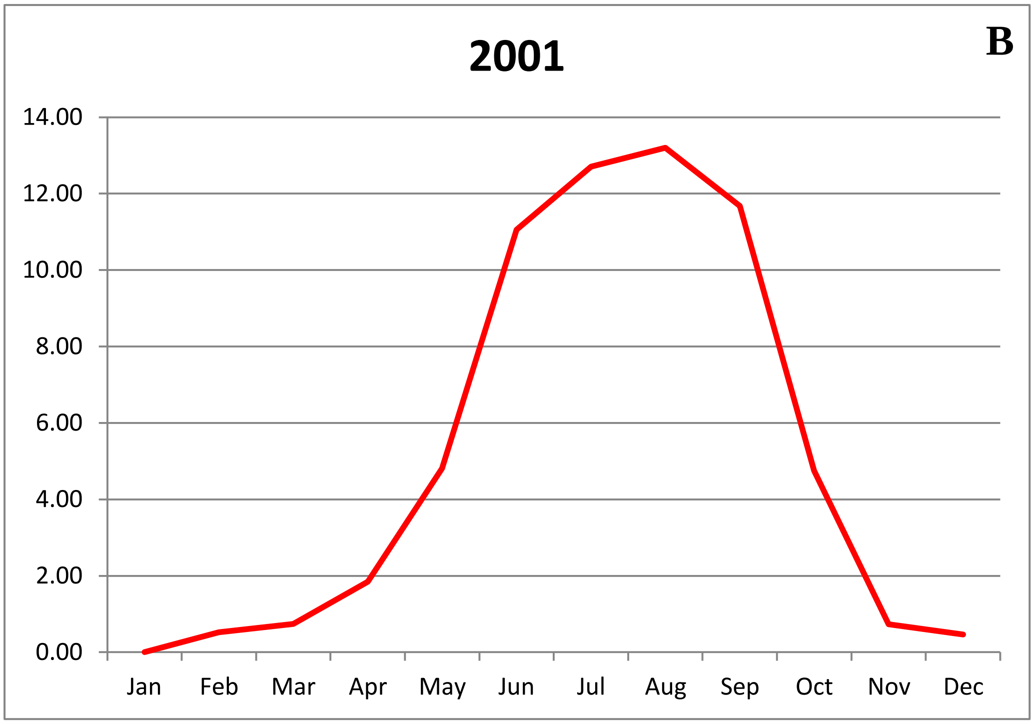
Long-term mean daily rainfall

The following tabular long term rainfall is calculated as

where i refers to the year and j refers to meteorological station. Graphs A to G below illustrate the rainfall distribution from years 2000 to 2006.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.02	0.30	0.22	4.43	5.03	12.72	12.33	14.74	10.66	10.62	2.43	0.57
2001	0.00	0.52	0.74	1.85	4.81	11.06	12.71	13.20	11.68	4.75	0.73	0.46
2002	0.47	0.08	0.79	0.90	1.96	9.52	15.39	13.19	8.29	4.14	1.22	0.15
2003	0.00	0.52	1.17	0.43	1.78	12.23	16.38	12.33	12.03	3.13	1.81	0.41
2004	0.28	0.51	0.41	3.27	2.27	10.09	16.51	13.36	11.72	4.49	2.33	0.57
2005	0.06	0.21	1.96	1.45	3.65	14.76	13.64	13.68	11.98	4.25	2.43	0.16
2006	0.11	0.23	0.50	1.25	9.06	11.57	16.29	15.79	11.53	7.72	1.12	0.55

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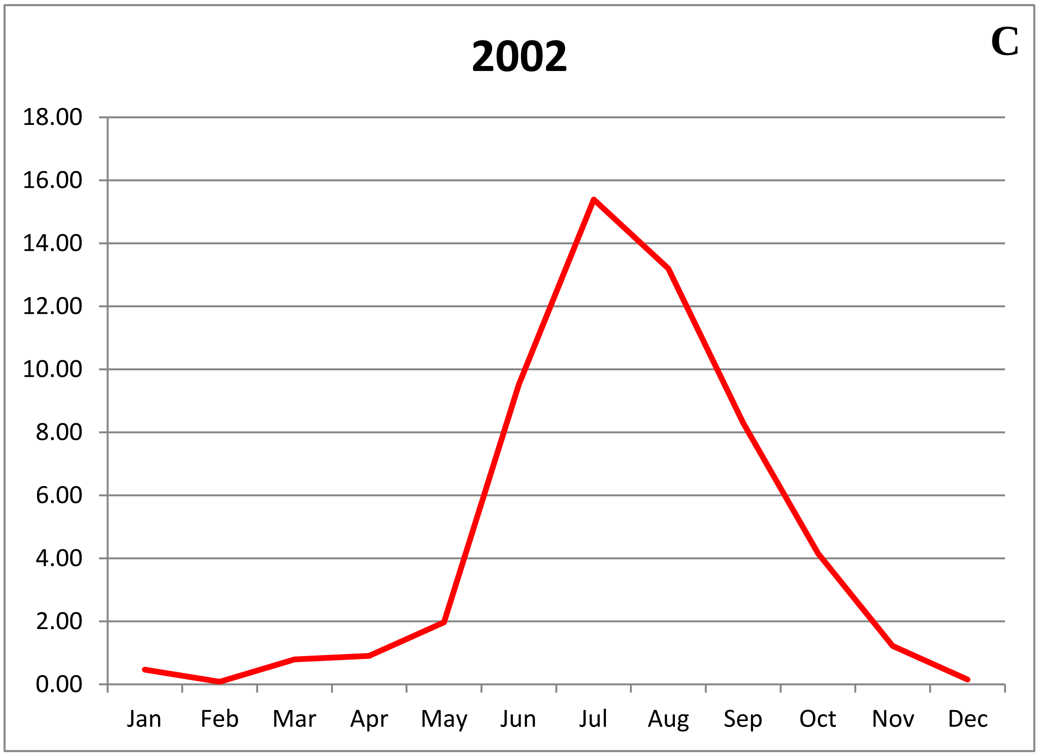
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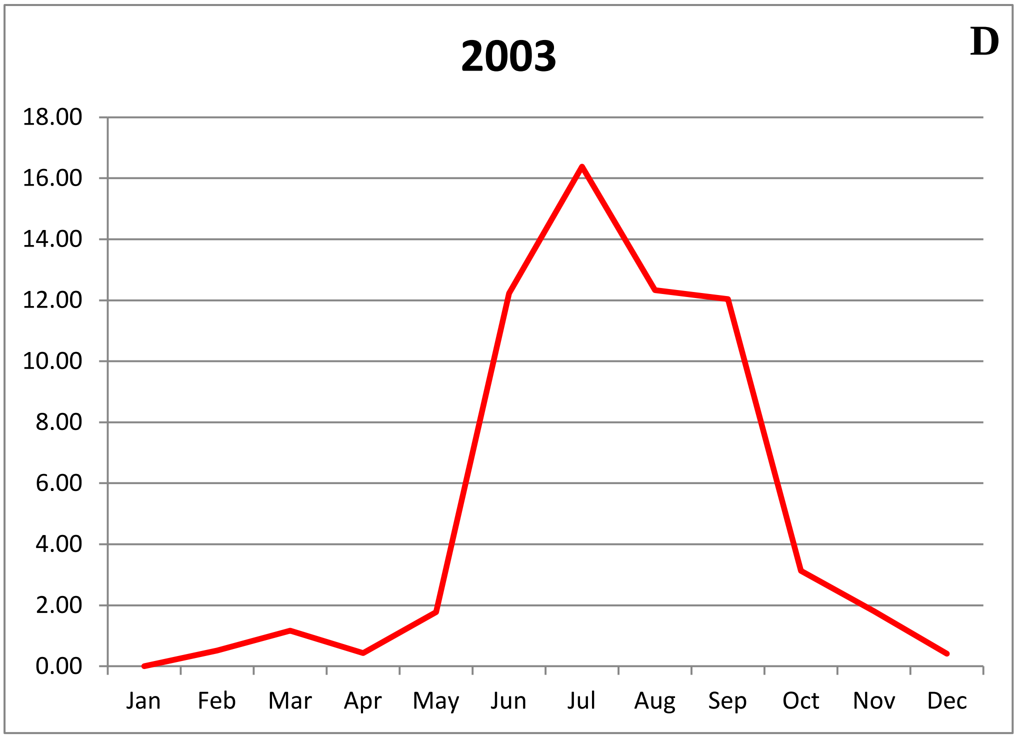
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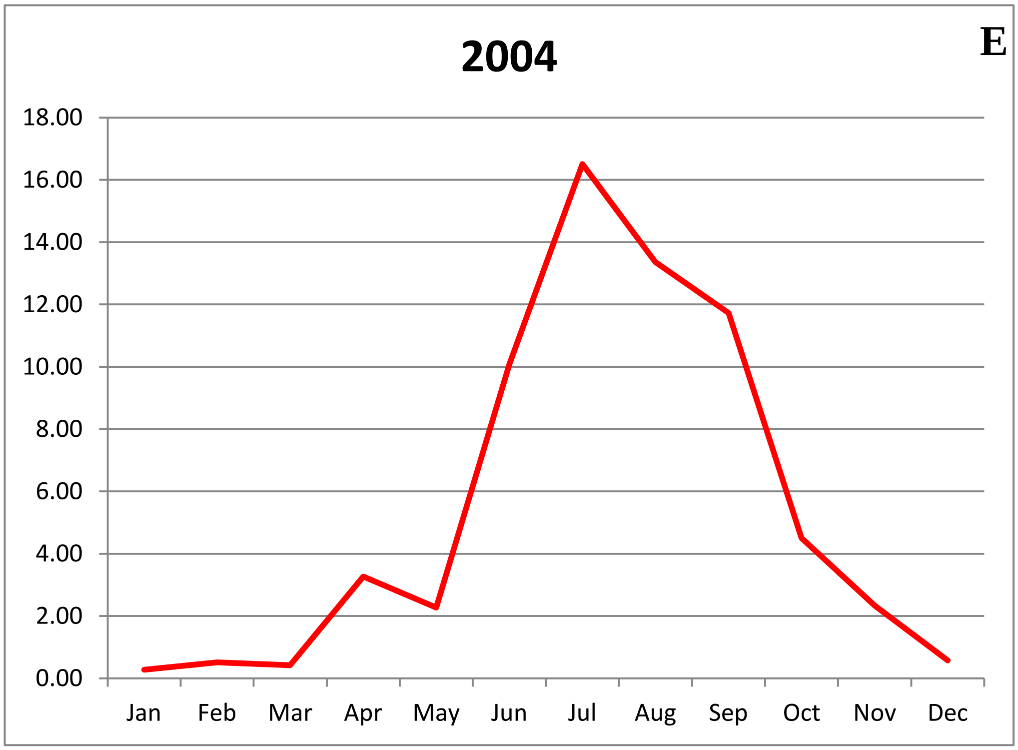
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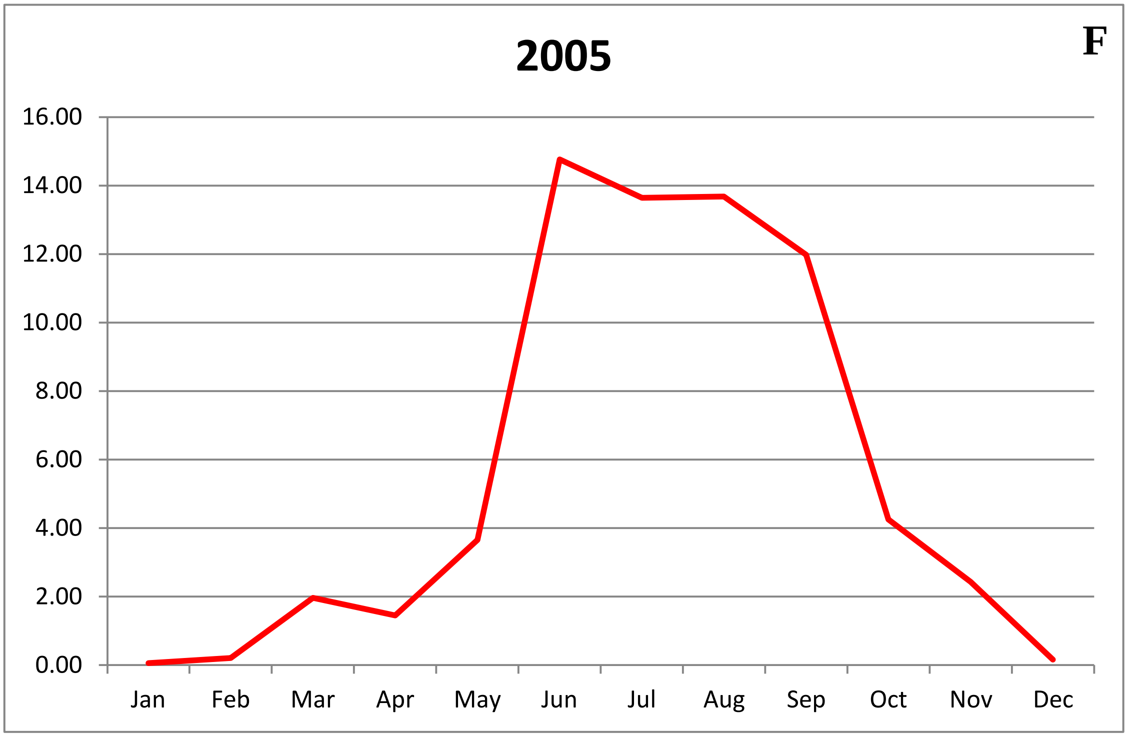
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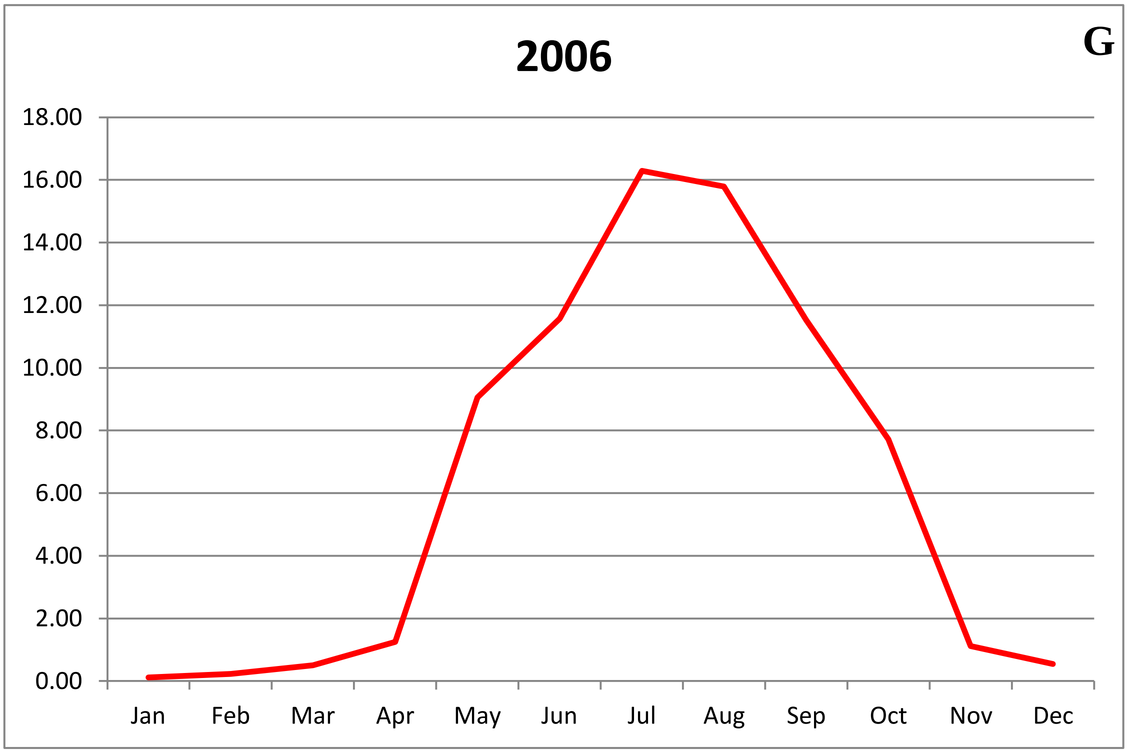
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