

Potential on the Use of GIS Watershed Modeling for River Basin Planning _ Case Study of Attanagalu Oya Basin, Sri Lanka

K. R. J. Perera and N. T. S. Wijesekera

Abstract: Careful management for identifying and allocating available water resources is important, to preserve water for present as well as future users. Modeling at basin scale can provide necessary information on river basin planning and support policy makers in their decisions on allocating water resources in the basin. This study focused on identifying the potential of GIS for spatially distributed modeling of watersheds for river basin planning.

The spatially distributed GIS model represents the simulation of runoff in selected river basins. Selected river basins are characterized by nodal network approach and sub-catchment areas calculated using GIS tools. Runoff is assumed to be triggered by rainfall and mainly dependent upon land use, soil type and slope conditions. Spatially varied land use, soil and slope data for the selected catchments were digitized using GIS (vector format) and land parcels created by overlay operations in GIS showing different catchment characteristics were used in the model. All calculations were performed with standard GIS tools of ArcGIS software. A simple conceptual model was used to compute runoff from each land parcel. The model is capable of calculating runoff from catchment characteristics based on predetermined runoff coefficients at the presence of precipitation data. A nodal representation of case study basin was prepared using MIKE BASIN to estimate streamflow at each node. The runoff coefficient for Attanagalu Oya basin with the spatial variation of parameters was estimated as 0.51 using this approach. Model provides streamflow at any node provided in the model. The average streamflow identified to fluctuate between $10\text{m}^3/\text{s}$ to $60\text{m}^3/\text{s}$ without taking water extractions into consideration. Land use, soil, slope patterns can be changed in the GIS model to calculate new coefficients with new spatial variation and can be incorporated to the nodal model to visualize the changes in streamflow patterns. Model results indicate the potential of the use of spatially distributed model for decision making when carrying out river basin planning.

Keywords: River basin planning, modeling, ungauged basin, catchment characteristics, runoff coefficient, GIS, MIKE BASIN

1. Introduction

Rapid population growth, urbanization, drastic changes in land use and growing industrialization are threatening water resources with the increasing demand for water. Changes in aforementioned factors directly or indirectly affect the rainfall, and streamflow patterns. Hence, estimating streamflow with available rainfall to manage available water is important for water resources management.

Relationship between rainfall-runoff is a complex hydrological phenomenon. Rainfall runoff models have taken part in watershed modeling. During the past few decades rainfall-runoff modeling has attempted to establish major hydrologic concerns. For instance, Naden [10] and Troch et al. [16] present spatially distributed rainfall runoff models which include

channel flow routing and overland flow; Jothityangkoon and Sivapalan [8] developed a distributed rainfall-runoff model for extreme flood estimation. GIS based rainfall runoff models have also received similar attention and have shown their importance. Jain et al. [6] had introduced a GIS based distributed rainfall runoff model capable of handling the catchment heterogeneity in terms of distributed catchment characteristics and rainfall which was applied to isolated storm events in several catchments. In

Eng. (Dr.) (Mrs.) K.R.J.Perera, B.Sc. Eng. (Moratuwa), M.Phil. (Moratuwa), MS(USA), Ph.D. (USA), AMIE(Sri Lanka), College Assistant Professor of Civil Engineering, Department of Civil Engineering, New Mexico State University, NM, USA.

Eng. (Prof.) N.T.S.Wijesekera, B.Sc. Eng. (Sri Lanka), C. Eng., FIE(Sri Lanka), MICE(UK), PG Dip Hyd Structures (Moratuwa), M. Eng. (Tokyo), D. Eng. (Tokyo). Professor of Civil Engineering, Department of Civil Engineering, University of Moratuwa, Sri Lanka.



addition, rainfall-runoff modeling for ungauged basins is of great importance due to the limited data. Catchment characteristics such as land cover, soil, and slope have been identified as the major parameters which can be used to represent generated streamflow in ungauged basins since they govern the runoff [11, 12, 21]. This study focused on developing a GIS model to identify the potential of GIS for modeling watersheds using spatially distributed parameters.

Water resources are scattered unevenly indicating abundance and scarcity ranging from regional level to global level. Most of the basins in the world are ungauged and even in gauged watersheds sub-watersheds are ungauged. To manage a river basin, it is necessary to analyse them at spatial locations where there are extractions, diversions and joining of branches. The major objective of this study was to model ungauged watershed with the extrapolation of results from gauged watersheds, and to identify the potential of using GIS for the incorporation of spatially distributed physical characteristics, inputs, extraction and diversions.

2. Methodology and Study Area

2.1 Methodology

2.1.1 Model Description

This paper discusses the spatially distributed modeling of Attanagalu Oya basin using MIKE BASIN software to assess the water resources availability at a downstream station of the basin. Figure 1 shows the methodology flow chart of the study; including model development for gauged watersheds to establish runoff coefficients and extrapolated model simulations for Attanagalu Oya basin in order to analyze streamflow.

Available data were collected and checked for adequacy and consistency as data is very important for reliable river basin modeling [13, 15]. Details and methods given in Wijesekera et al, [20] were used as guidelines for data collection and processing. Rainfall data, streamflow data, evaporation data, demand data, and also land use, soil, contour and other digital data required for GIS layer preparations were collected for the study [11]. Data were checked for consistency and compatibility with different techniques such as visual examining, double mass curve method and statistical checks for homogeneity. In homogeneity checking it was assumed that the data are independent and with normal distribution though it may not always be satisfied by some data sets [3, 7].

The model used for the study is as follows [11, 12].

$$(Surface\ Runoff)_i = (Runoff\ Coefficient)_i * (Rainfall)_i \quad (1)$$

$$Runoff\ Coefficient_i = f(Land\ use_i, Slope_i, Soil_i) \quad (2)$$

where,

$i \in spatial\ entity$

$t \in time\ point$

Governing catchment characteristics namely the land use, soil, and slope were grouped into classes of five, two and three for land-use, soil and slope, respectively.

2.1.2 Determination of Basin Parameters

Spatially varied land use, soil and slope data which were collected and identified on maps were digitized using GIS (vector format). Three catchment characteristics for a given basin was overlaid using overlay operation in GIS. This activity creates different land parcels with different catchment characteristics. Required land parcel was selected using table operations for later applications.

A simple conceptual model was used to compute runoff from each land parcel using the concept presented in equations 1 and 2. The model assumed a linear function incorporating land use, slope and soil as major catchment parameters contributing to convert rainfall into surface runoff as illustrated in equation 3.

The cumulative runoff contributed from each land parcel in a catchment was taken as the surface runoff generated from the catchment.

$$Q = (P_{ijk} * A_{ijk}) * R \quad (3)$$

where,

$R = \text{Rainfall}$

$A_{ijk} = \text{Area of concern with given factors } i, j, k$

Coefficient $P_{ijk} = f(i_{(1-5)}, j_{(1-3)}, k_{(1-2)})$

Table 1 -Land use, slope and soil classification

Land use (i)		Slope (j)		Soil (k)	
i	Class	j	Class	k	Class
1	Forest	1	Flat	1	Red Yellow Podzolic
2	Garden	2	Average	2	Alluvial
3	Grass & Chena	3	Steep		
4	Cultivation				
5	Rocks, tanks & reservoirs				

P_{ijk} represents the coefficient for i^{th} land use type, j^{th} slope class and k^{th} soil type where i varies from 1-5, j varies between 1-3 and k from 1-2. For instance, P_{231} represents the coefficient for steep slope garden areas with red yellow podzolic soil type. Parameters of the model assigned by the above criteria are given in Table 2. Model parameters (P values) were estimated (optimized) using Mean Ratio of Absolute Error as the objective function [18, 19]. Parameter optimization was initiated with the literature values [1, 2, 4, 5]. Parameters at which minimum MRAE were selected as finalized parameters of the model.

Kelani Ganga at Glencourse and Kalu Ganga at

optimized by matching calculated and observed runoff. It was assumed that watersheds with similar catchment characteristics will produce similar pattern of runoff from rainfall. It was also assumed that for monthly time scale computations, the soil wetness would not have a significant impact. In order to minimize this factor, the case study selected wet zone basins only.

Representing river basins by nodal network approach is the common approach for computations of water allocation [9], where lines represent the stream segments and nodes represent water extractions and other necessary activities.

Table 2 - Classification of model parameters on land use, soil and slope

Land Use (i)	Slope Class (j)	Soil (k)	
		Red Yellow Podzolic (RYP) - (1)	Alluvial (AL) - (2)
Forest (1)	Flat (0-2 %) (1)	(P_{111})	(P_{112})
	Average Slope (2-7 %) (2)	(P_{121})	(P_{122})
	Steep Slope (over 7 %) (3)	(P_{131})	(P_{132})
Garden (2)	Flat (0-2 %)	(P_{211})	(P_{212})
	Average Slope (2-7 %)	(P_{221})	(P_{222})
	Steep Slope (over 7 %)	(P_{231})	(P_{232})
Grass & Chena (3)	Flat (0-2 %)	(P_{311})	(P_{312})
	Average Slope (2-7 %)	(P_{321})	(P_{322})
	Steep Slope (over 7 %)	(P_{331})	(P_{332})
Cultivation (4)	Flat (0-2 %)	(P_{411})	(P_{412})
	Average Slope (2-7 %)	(P_{421})	(P_{422})
	Steep Slope (over 7 %)	(P_{431})	(P_{432})
Rocks, Tanks & Reservoirs (5)	Any Slope	($P_{5,1-3,1-2}$)	

Putupaula gauging stations were used as supportive catchments to evaluate runoff coefficient soil, slope and land use relationships since the catchment at Karasnagala gauging station did not cover all the soil types of Attanagalu Oya basin. Attanagalu Oya basin soils fall into only two major soil groups as Red Yellow Podzolic and Alluvial (Table 4).

Twenty years monthly rainfall data were selected for the Kelani and Kalu Ganga sub basins. Data period from 1951-1960 were selected for calibration and 1961-1970 were selected for verification. Ten years of monthly rainfall runoff data from 1970-1980 were used for model calibration (1970-1975) and verification (1975-1980) at Karasnagala sub-basin. Initial runoff coefficient values were obtained from literature [4, 14, 17]. Runoff coefficients were then

Calculated streamflows from initial GIS model were incorporated to MIKE BASIN nodal network of Attanagalu Oya basin in order to identify flow at different nodes of interest. In the developed representation, nodes are located at stream segment connection points. Model requires specific runoff at each network branch. Sub-catchment area, relevant nodal points, flow direction, etc are the other inputs to the MIKE BASIN model. Moreover, in case of water extractions, such water extraction locations, any prioritization of water extractions, lag times, etc. would need to be added as input data.

2.2 Study Area

2.2.1 Attanagalu Oya basin at Kotugoda.

Attanagalu Oya is located in the wet zone of Sri Lanka between the latitudes $7^{\circ} 00'$ and $7^{\circ} 17'N$, Longitudes $79^{\circ} 50'$ and $80^{\circ} 15'E$. Total catchment



area at Kotugoda is approximately 539 km². Figure 2 shows the Attanagalu Oya basin with the stream network of the sub catchment at the Karasnagala stream gauging point and at Kotugoda. Five rainfall gauging stations were selected to represent the spatial variability of rain in the basin. The station at Karasnagala maintained by the Irrigation Department of Sri Lanka, is the only available stream gauging station (non-recording).

The station has had a recorder at Karasnagala, but site visits revealed that this is not properly functioning. Department of Meteorology maintains a daily evaporation records at Katunayake, which is a principal meteorological station recording data once in every three hours.

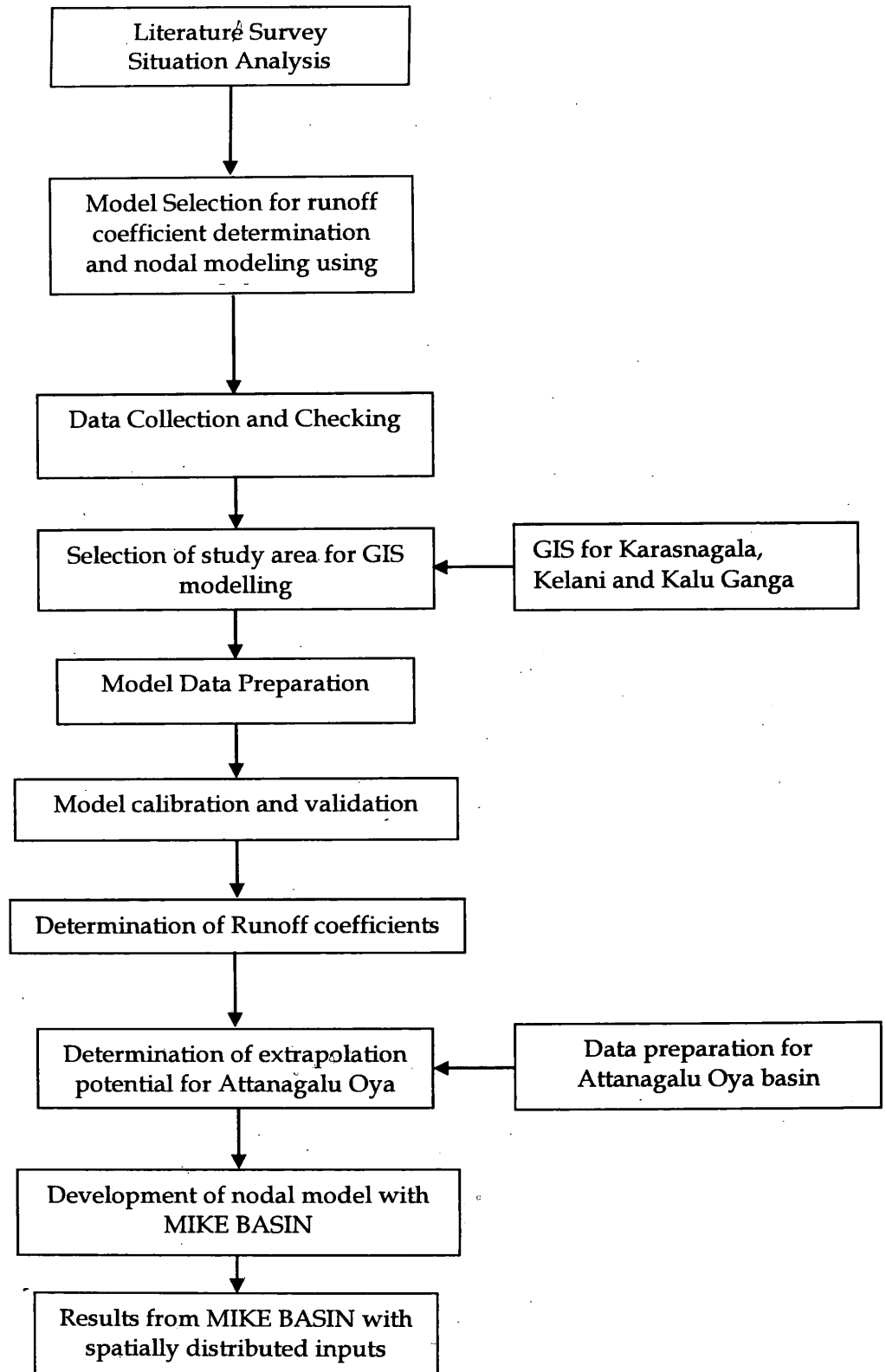


Figure 1 - Methodology flow chart

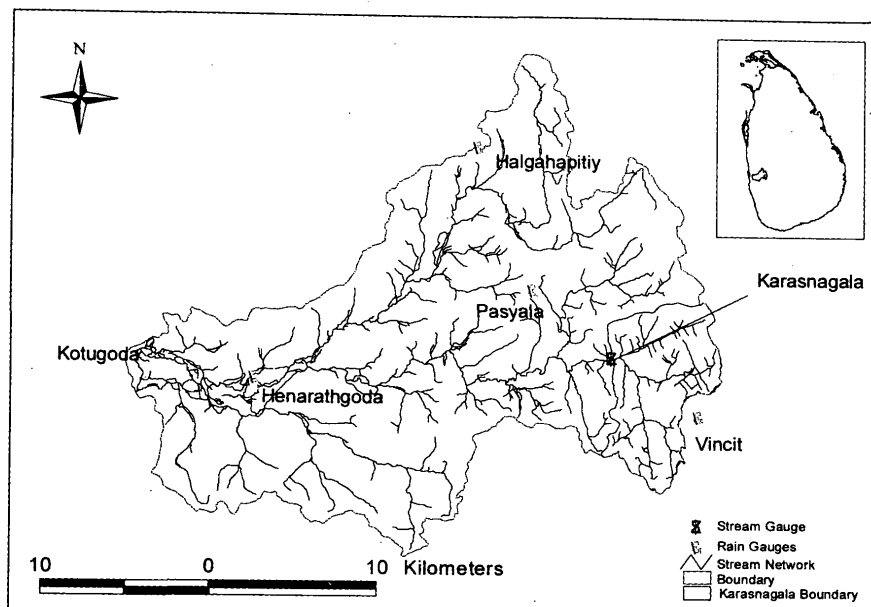


Figure 2 - Attanagalu Oya catchment at Kotugoda

2.2.2 Kelani Ganga basin at Glencourse (Kelani Ganga sub basin)

Kelani Ganga basin is located in the wet zone of Sri Lanka between the latitudes $6^{\circ} 45'$ and $7^{\circ} 15'$ N, Longitudes $79^{\circ} 50'$ and $80^{\circ} 45'E$. Sub basin of the Kelani Ganga at Glencourse was selected for this study. Total catchment area is about 1537 km² at Glencourse (Kelani Ganga sub basin). Data from six rainfall-gauging stations and one streamflow gauging were available for the study [11, 12].

2.2.3 Kalu Ganga basin at Putupaula (Kalu Ganga sub basin)

Kalu Ganga basin is located in the wet zone of Sri Lanka between the latitudes $6^{\circ} 20'$ and $6^{\circ} 55'$ N, Longitudes $79^{\circ} 55'$ and $80^{\circ} 45'E$. Sub basin of the Kalu Ganga at Putupaula was selected for this study [11, 12].

3. Data Analysis

Out of the five gauging stations selected, for the Kotugoda sub-catchment, two stations are within the Karasnagala sub-catchment. Daily rainfall data were analysed to obtain the results. Highest annual rainfall has been observed in 1975 while minimum was observed in 1976. According to the computations the highest rainfall of 4322 mm has been observed at Vincit. Lowest rainfall of 1640 mm was observed at Henarathgoda when averaged over the 10 year analysis period.

Streamflow and average rainfall variation in the basin are given in Figures 3 and Figure 4 for two time segments (1971-1980, 1981-1990). Land use and soil type within the basin are given in Table 3 and Table 4 respectively.

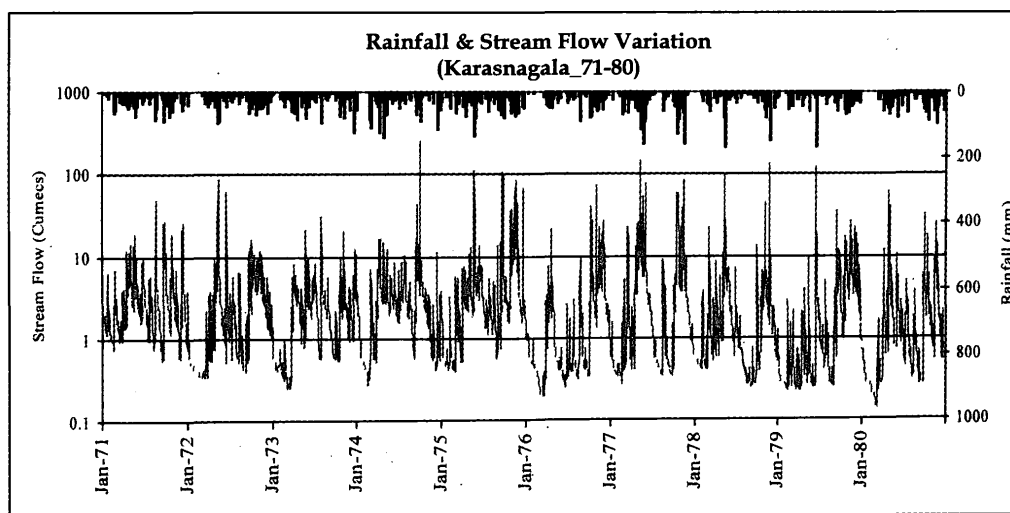


Figure 3 - Thiessen averaged catchment rainfall variation with streamflow at Karasnagala for the period of 1971-1980.



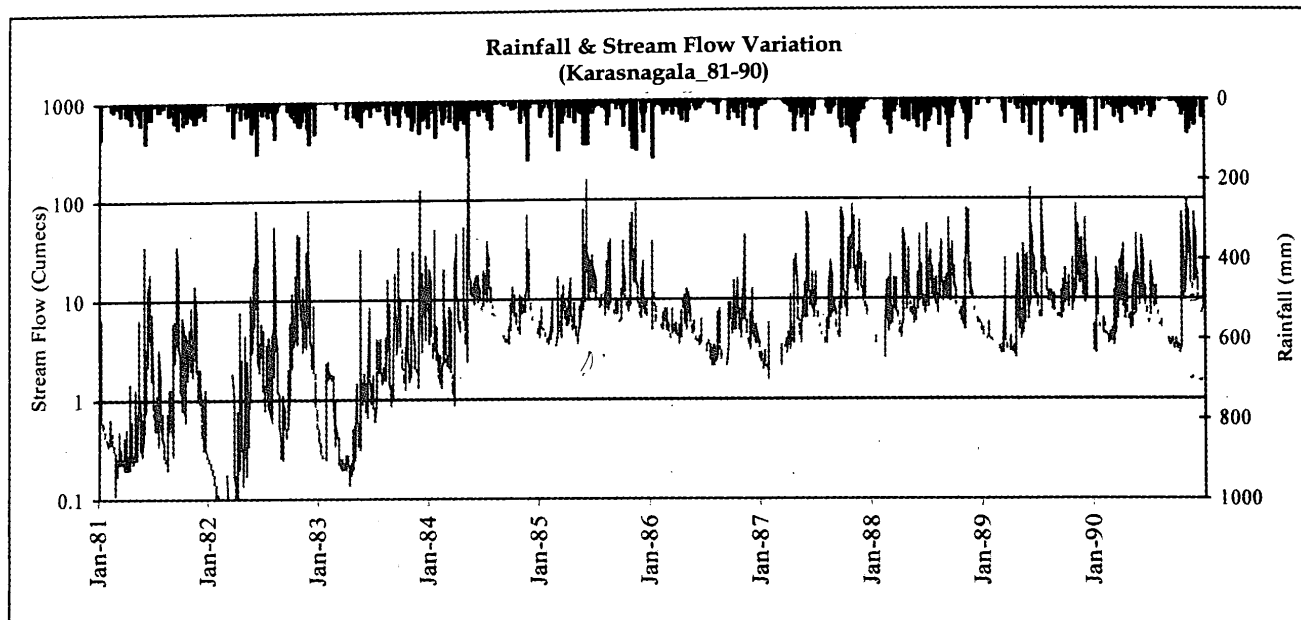


Figure 4 - Thiessen averaged rainfall variation with streamflow at Karasnagala for the period of 1981-1990.

Table 3 - Land use data of Kotugoda sub basin of Attanagalu Oya

Land Use Type	Area (km ²)	Percentage of Area (%)
Cultivation	300.30	55.67
Forest	4.85	0.90
Garden	216.29	40.10
Grass and Chena	14.47	2.68
Rock, Tanks and Reservoirs	3.48	0.65

Table 4 - Soil data of Kotugoda sub basin of Attanagalu Oya

Soil Type	Area (km ²)	Percentage of Area (%)
RYP	480.44	89.12
Alluvial	56.97	10.57
Latosols and Regosols	1.71	0.32

Ten major irrigation water extractions (anicuts) and few minor extractions (pickup anicuts) are available within the basin. Further, water extractions for drinking water supply by the National Water Supply and Drainage Board

(NWS&DB) were observed. Those are the two main water extractions in addition to the ecological consumption and domestic activities within the basin.

4. Results and Discussion

4.1 Spatially Variable Basin Parameters

Data checks provided agreeable results with an error record at Karasnagala streamflow data in year 1975. Annual average rainfall for Attanagalu Oya basin is within the range of 2000mm-3500 mm. Typical dry month for the Attanagalu Oya basin is January. Average runoff coefficient was found as 0.40 for Attanagalu Oya basin at Karasnagala considering Karasnagala rainfall and streamflow without considering spatial variation over the catchment. Averaged optimized runoff coefficients from the study were obtained as 0.51 for Attanagalu Oya basin at Karasnagala under spatial considerations.

Comparing the covering area, latosol and regosol soil areas were neglected (0.3% of total catchment area). Hence, only red yellow podzolic soil (89.1% of total area) and alluvial soil (10.6% of total area) areas were considered in this study. Cultivations are the higher percentage of land use for the basin. Cultivations include coconut, rubber, paddy and other cultivation [4]. In case of the cultivations optimized runoff coefficients are 0.61, 0.57 and 0.20 for steep, average and flat slopes respectively for red yellow podzolic soils while for alluvial soils the runoff coefficients are 0.50 and 0.55 for average and steep slopes respectively. Residential areas generate higher amounts of runoff from rainfall. Such areas showed higher runoff coefficients values of 0.65, 0.60 and 0.55 for red yellow podzolic soils for steep, average and flat slopes respectively. Run off coefficients in residential areas with alluvial soils are 0.52, 0.56 in case of average and steep slopes respectively. Lowest runoff coefficient

obtained for forest areas with alluvial soils followed by that for red yellow podzolic soils. Optimized runoff coefficients are given in Table 5.

4.2 Spatially Variable Stream Network

The nodal network prepared for Kotugoda sub basin with the incorporation of spatially variable inputs to MIKE BASIN model is given in Figure 5. In the Attanagalu Oya model simulation, water extractions could not be considered due to unavailability of data. Model demonstrations assessed water resources without extractions.

Model results provide the streamflow values at the Kotugoda outlet point as well as streamflow values at each node of interest. Calculated streamflow over time for Attanagalu Oya at Kotugoda outlet is shown in Figure 6. Flow duration curve for the calculated streamflow is given in Figure 7. Calculated zero flows are replaced by minimum flow of the basins at zero rainfall record periods because model results with zero streamflow with zero rainfall even though river flow has not gone zero.

According to the hydrograph, every year low flows can be observed in January while higher flows are observed in May and October. The average streamflow fluctuates between 10m³/s to 60m³/s. The model computations were done with the varied runoff coefficients [11, 12]. However due to non-availability of streamflow, these values could not be verified. However the representative result showed that the GIS approach well demonstrated the potential of water resources management with the incorporation of the spatial variability of soil, slope and land use.

Table 5 - Finalized Runoff Coefficient Matrix

Land Use	Slope Class \ Soil	Red Yellow Podzolic	Alluvial
Forest	Flat (0-2 %)	0.10	NA
	Average Slope (2-7 %)	0.20	0.05
	Steep Slope (over 7 %)	0.25	0.10
Garden	Flat (0-2 %)	0.55	NA
	Average Slope (2-7 %)	0.60	0.52
	Steep Slope (over 7 %)	0.65	0.56
Grass & Chena	Flat (0-2 %)	0.45	NA
	Average Slope (2-7 %)	0.52	0.35
	Steep Slope (over 7 %)	0.55	0.40
Cultivation	Flat (0-2 %)	0.20	NA
	Average Slope (2-7 %)	0.57	0.50
	Steep Slope (over 7 %)	0.61	0.55
Rocks, Tanks & Reservoirs	Any Slope	1.00	



NA- parameter not available within study areas.

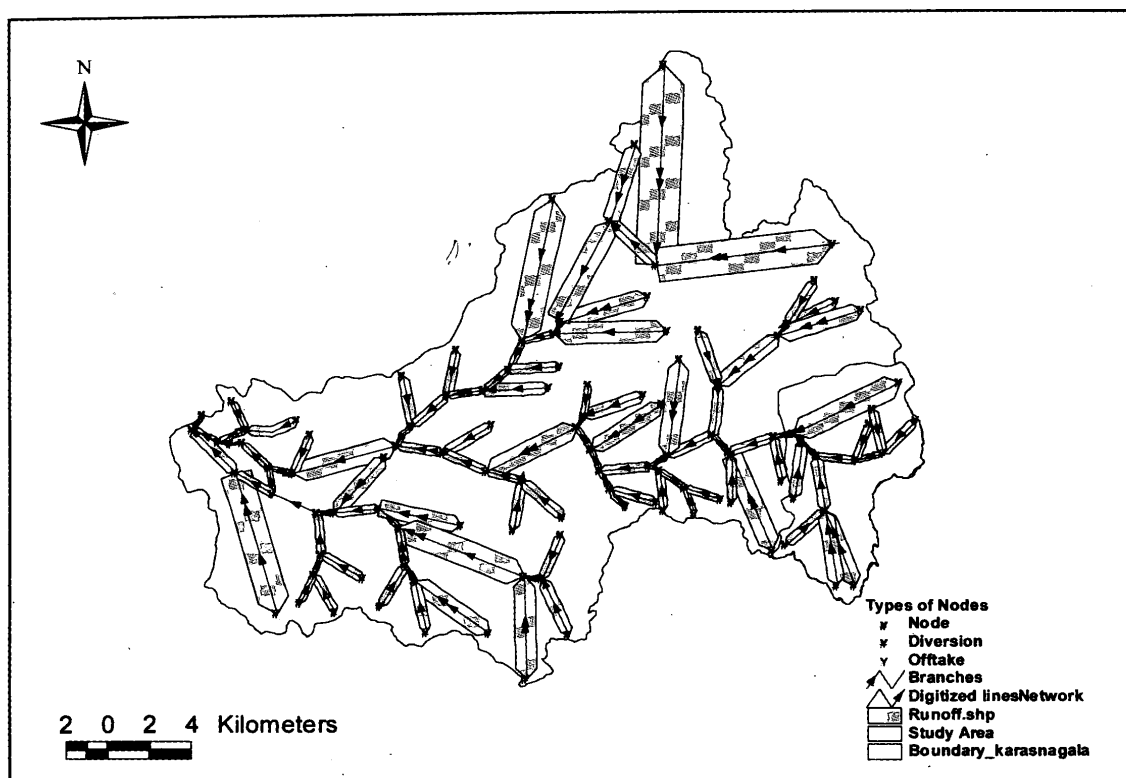


Figure 5 - Nodal network for Attanagalu Oya at Kotugoda.

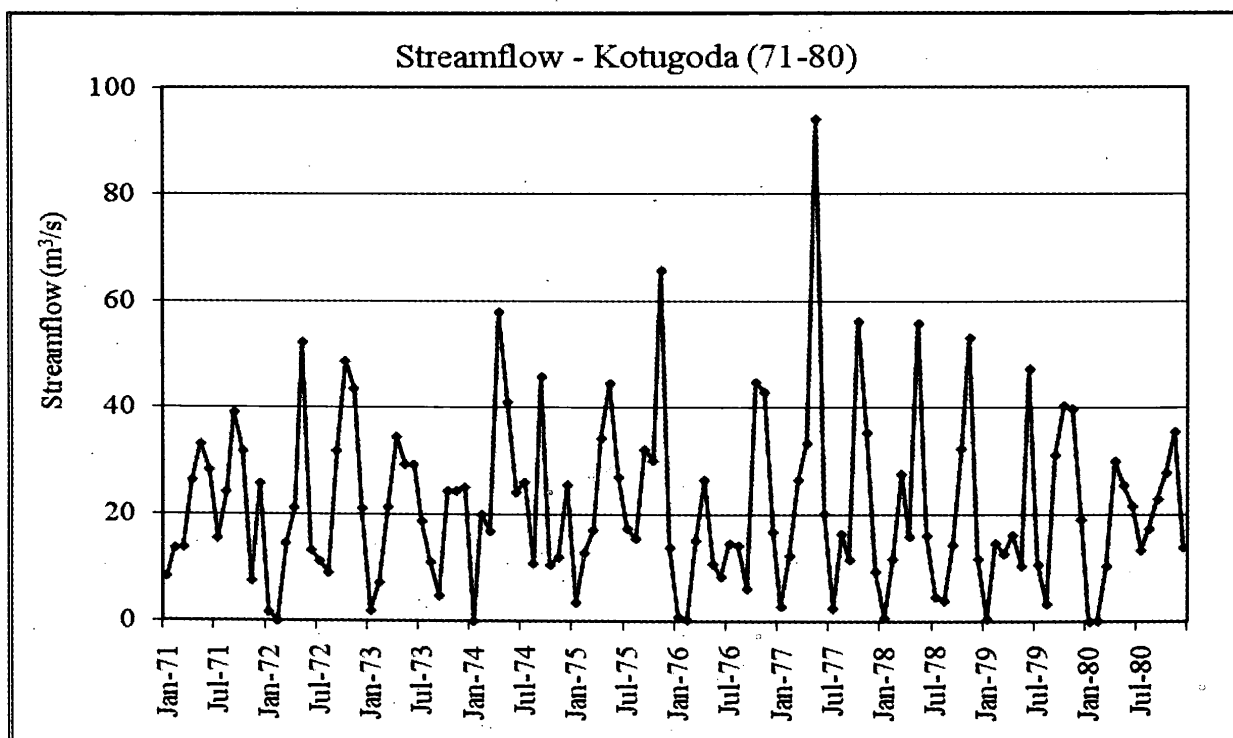


Figure 6 - Hydrograph for Attanagalu Oya at Kotugoda (through GIS based modelling)

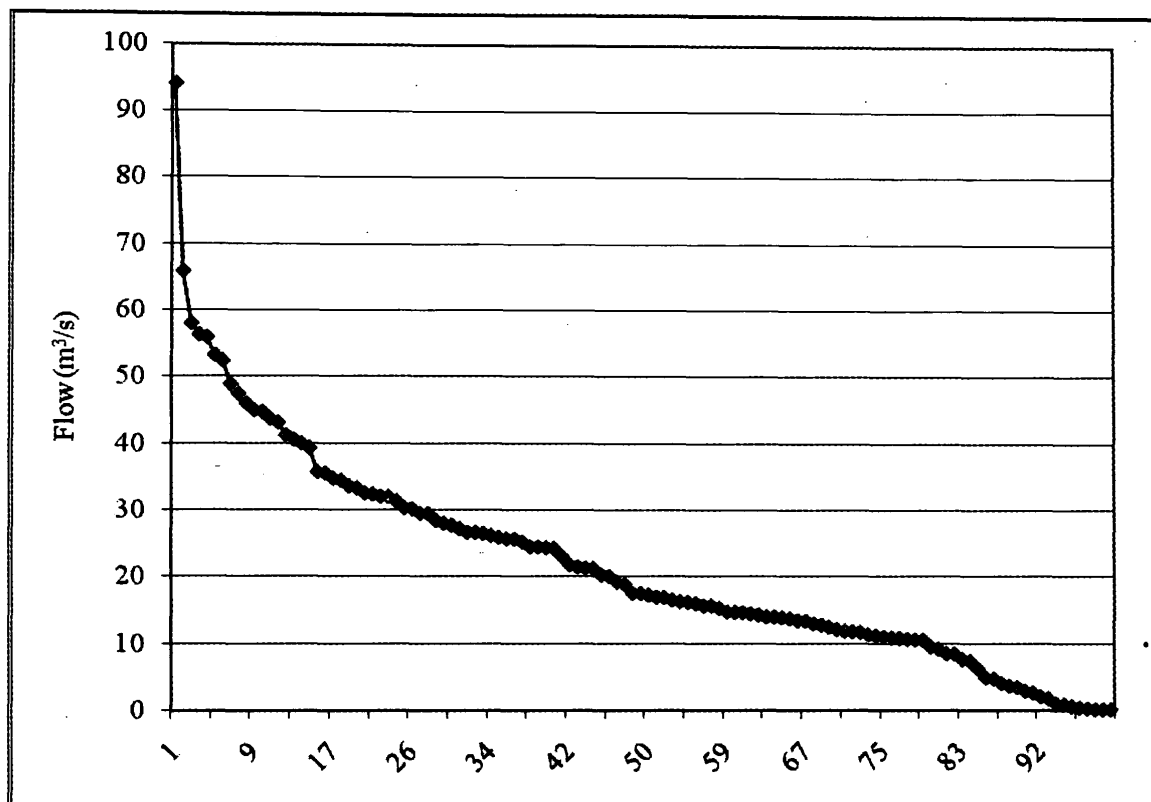


Figure 7 - Flow Duration Curve for Attanagalu Oya at Kotugoda.

5. Conclusions

- The present case study demonstrated the potential of the use of GIS to incorporate the spatial variability of catchment characteristics and rainfall to manage water resources of river basins. Such techniques require runoff coefficients, which have been verified for similar conditions.
- This GIS application enable a river basin manager to analyze the behavior of surface water once the catchment characteristics are changed at various locations of given watershed.
- The overall runoff coefficient for Attanagalu Oya basin with the spatial variation of parameters was 0.51. Model provides streamflow at any node provided in the model. The average streamflow identified to fluctuate between 10m³/s to 60m³/s without taking water extractions into consideration. Land use, soil, slope patterns can be changed in the GIS model to calculate new coefficients with new spatial variation and can be incorporated to the nodal model to

visualize the changes in streamflow patterns.

- To improve the model outputs, gauged streamflow data is needed for Attanagalu Oya basin. The study can be improved further by adding gauged water extraction scenarios, which is more helpful for river basin planning and management.

Acknowledgement

This study was funded by a Senate Research grant at University Moratuwa.

References

1. Andy, D., Stanley, W., Environmental Hydrology, 2nd ed., Boca Raton, FL, USA: CRC Press, 2004.
2. Bedient, P., Huber, W., Hydrology of Floodplain Analysis, 2nd ed., New York, USA: Addison-Wesley, 1992.
3. Buishand, T. (1982). Some Methods for Testing the Homogeneity of Rainfall Records. Journal of Hydrology 58(1-2): 11-27.
4. Chow, V., Maidment, D., & Mays, L. (1964). Handbook of Applied Hydrology. New York : McGraw-Hill.



5. Glenn, O., Frevert, R., Kenneth, K., Edminster, T., Elementary Soil and Water Engineering, 3rd ed., New York: John Wiley, 1985.
6. Jain, M., Kothiyari, U., & Raju, K. (2004). A GIS Based Distributed Rainfall Runoff Model. *Journal of Hydrology* 299(1-2):107-135.
7. Jayawardena, A. (1990). Homogeneity Tests for Rainfall Data. *Hong-Kong Engineer*: 22-25.
8. Jothityangkoon, C., & Sivapalan, M. (2003). Towards Estimation of Extreme Floods: Examination of the Roles of Runoff Process Changes and Floodplain Flows. *Journal of Hydrology* 281(3): 206-229.
9. Letcher, R., Croke, B., & Jakeman, A. (2006). Integrated Assessment Modelling for Water Resources Allocation and Management: A Generalized Conceptual Framework. *Journal of Environmental Modelling and Software* 22(5): 733-742.
10. Naden, P. (1992). Spatial Variability in Flood Estimation for Large Catchment: The Extrapolation of Channel Network Structure. *Journal of Hydrol. Sci.* 37: 53-71.
11. Perera, K.R.J. (2010). Model Development using Geographic Information Systems for River Basin Planning - A Case Study of Attanagalu Oya. MPhil dissertation: University of Moratuwa.
12. Perera, K.R.J., & Wijesekera, N.T.S. (2010). Identification of the Spatial Variability of Runoff Coefficients of Three Wet Zone Watersheds of Sri Lanka for Efficient River Basin Planning. ASCE: EWRI Conference on International Perspective on Current and Future State of Water Resources and the Environment. Chennai, India.
13. Pilgrim, D. (1975). Model Evaluation, Testing and Parameter Estimation in Hydrology. In: T. G.Chapman and F. X. Dunin (eds.), *Australian Academy of Science, Canberra*: 305-333.
14. Schwab, G., Frevert, R., Edminster, T., & Barnes, K. (1981). *Soil and Water Conservation Engineering* (3rd ed.). New York: John Wiley and Sons.
15. Silberstein, R. (2005). Hydrological Models are so Good, do we still need Data? *Environmental Modelling and Software* 21(9): 1340-1352.
16. Troch, P., Smith, J., Wood, E., & De Troch, F. (1994). Hydrologic Controls of Large Floods in a Small Basin. *Journal of Hydrology* 156: 285-309.
17. Ward, A., & Trimble, S. (1995). *Environmental Hydrology*. United States of America: CRC Press.
18. Wijesekera, N.T.S., "Parameter Estimation in Watershed Model: A Case Study Using Gin Ganga Watershed, Transactions". Annual Sessions of the Institution of Engineers, Sri Lanka, October 2000.
19. Wijesekera, N.T.S., Abeynayake, J.C., "Watershed Similarity Conditions for Peakflow Transposition - A Study of River Basins in the Wet Zone of Sri Lanka". *Engineer Journal of the Institution of Engineers, Sri Lanka*, April 2003.
20. Wijesekera, N. T., Malone, D. C., & Ranwala, D. A. (1998). Status of Water Data Collection, Processing and Management: Sri Lanka. National Conference, Colombo, Sri Lanka.
21. Yu, P., & Jeng, Y. (1997). A Study on Grid Based Distributed Rainfall Runoff Models. *Water Resources Management* 11: 83-99.