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HYDROLOGIE HYDROCHIMIE SOL ENVIRONNEMENT

TITLE: HYDROLOGICAL MODELLING OF RIO BENI WITH CONCEPTUAL MODELS.
TITRE: MODELISATION HYDROLOGIQUE DU RIO BENI A L'AIDE DE MODELES CONCEPTUELS

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Titre Title	Modélisation Hydrologique du Rio Beni à l'aide de Modèles Conceptuels. Hydrological modelling of Rio Beni with conceptual models.
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Résumé	Dans cette étude, nous exposons la première modélisation hydrologique du Rio Béni, grand bassin sédimentaire de la Cordillère des Andes. Du fait de la rareté des données disponibles, notre approche s'est orientée vers l'utilisation de modèles conceptuels, malgré l'hétérogénéité du bassin. La procédure d'optimisation des paramètres est basée sur des algorithmes génétiques, nouvel outil en hydrologie. Différents modèles conceptuels sont ainsi comparés en terme de cœfficient de Nash mais aussi en terme de représentation des processus physiques (débit de base, ruissellement superficiel).
Mots clés	Hydrologie du Rio Béni, Modèles pluie débits, algorithme génétique.
Abstract	An effort is made to model the hydrological processes of Rio Beni, a sedimentary basin of Cordillère of Andes, a large scale watershed. Because of the sparsity of available data, our approach leans towards conceptual models despite the natural heterogeneity of the basin. The optimisation procedure is based on genetic algorithm, which is not often used in hydrology. Based on monthly and weekly data, several conceptual models are compared in terms of Nash coefficient but keeping in mind a good representation of the basic physical processes (baseflow, surface runoff).
Key words	Rio Beni hydrology, Rainfall-runoff conceptual models, genetic algorithm.

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1 INTRODUCTION

Large-scale watershed models are required to estimate basin runoff to the lakes and other large-basin applications for use in long-term routing determinations, water resource operation decisions, operational hydrology studies, and long-term forecasting. Data availability over large areas, large-basin applicability, computation requirements, and model application costs often preclude the use of detailed watershed models, designed for small scales, for large-scale applications.

As a prerequisite for the implementation of the best suited models over an area understudy, the first step involves the selection of the most appropriate models from the acquired set of possbile rainfall-runoff modelling approaches for the available dataset. The models used in this study were selected to meet certain criterias; reliable in terms of stream flow simulation, be userfriendly and not too demanding in terms of input.

With the above criterias in mind, several conceptual models are used in this study. A tentative attempt is also made to model the catchment with a distributed model.

1.1 Objective

The objective of this study is to model the hydrological processes of the sedimentary basin of Cordillère of Andes. An effort is made to model a large scale watershed of about 60 000 km². The watershed constituting of mountainous zone, houses a variety of vegetation and soil types. Because of the variation in the topography, rainfall distribution is not even and varies with the altitude. The challenge here is to model the hydrological processes with sparsity of data.

2 DESCRIPTION OF WATERSHED

The study area is situated in South America, Bolivia. The watershed in question is the sub-basin of Rio Maderia, one of the most important southern affluent of Amazone (1.4 106 km²) which floods the Cordillère of Andes. The Rio Maderia with a surface area of 1.37 106 km² is the second largest sub-basin of amazone. It represents 23% of Amazone basin and drains 35%

of Andine channels in the Amazone bassin. The principal Andine tributaries of Rio Maderia are rios Beni, Madre de Dios and Mamoré which originates from the Cordillère oriental of Peru and Bolivia. [7]

Although Bolivia lies entirely within tropical latitudes, climatic conditions vary widely from tropical in the lowlands to polar in the highest parts of the Andes. Temperatures depend primarily on elevation and show little seasonal variation. In most locations, rainfall is heaviest during the Southern Hemisphere summer, and yearly amounts tend to decrease from north to south. Northern lowland areas have a tropical wet climate with year round high temperatures, high humidity, and heavy rainfall. Daytime highs average more than 30° C all year in most locations. The rain-bearing northeast trade winds, blowing across the Amazon Basin, bring significant rainfall amounts. Rain often falls in brief thunderstorms, sometimes accompanied by strong winds and hail.

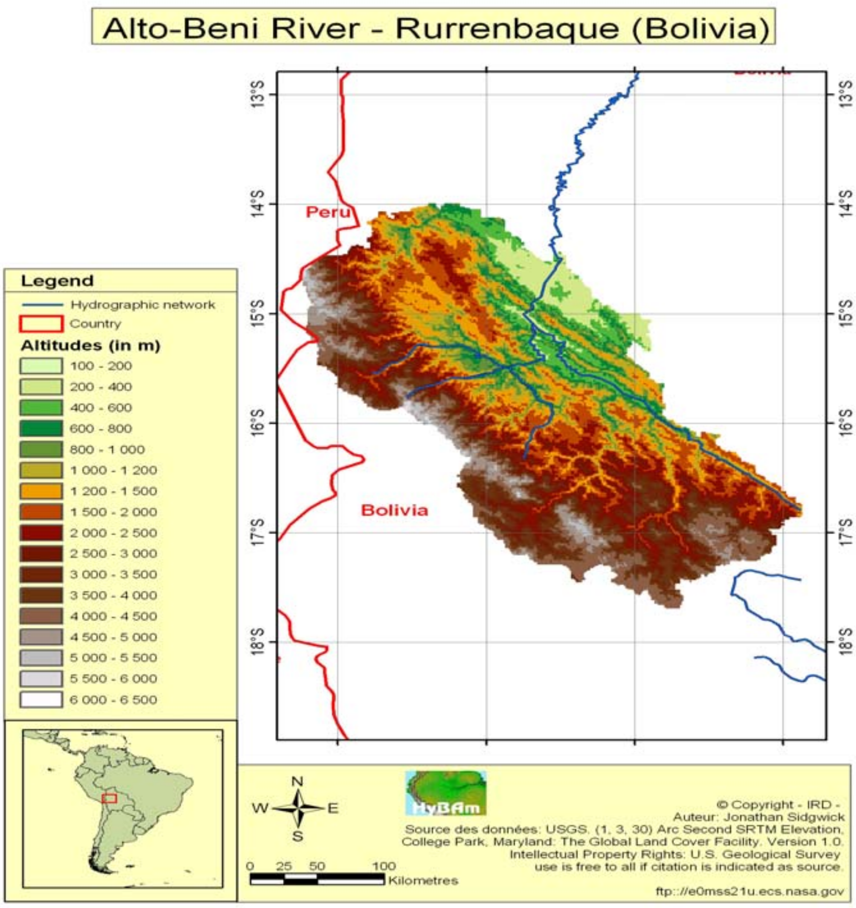


Figure 1 : Location of the watershed, in Bolivia. (The DEM of the watershed at 93m resolution.)

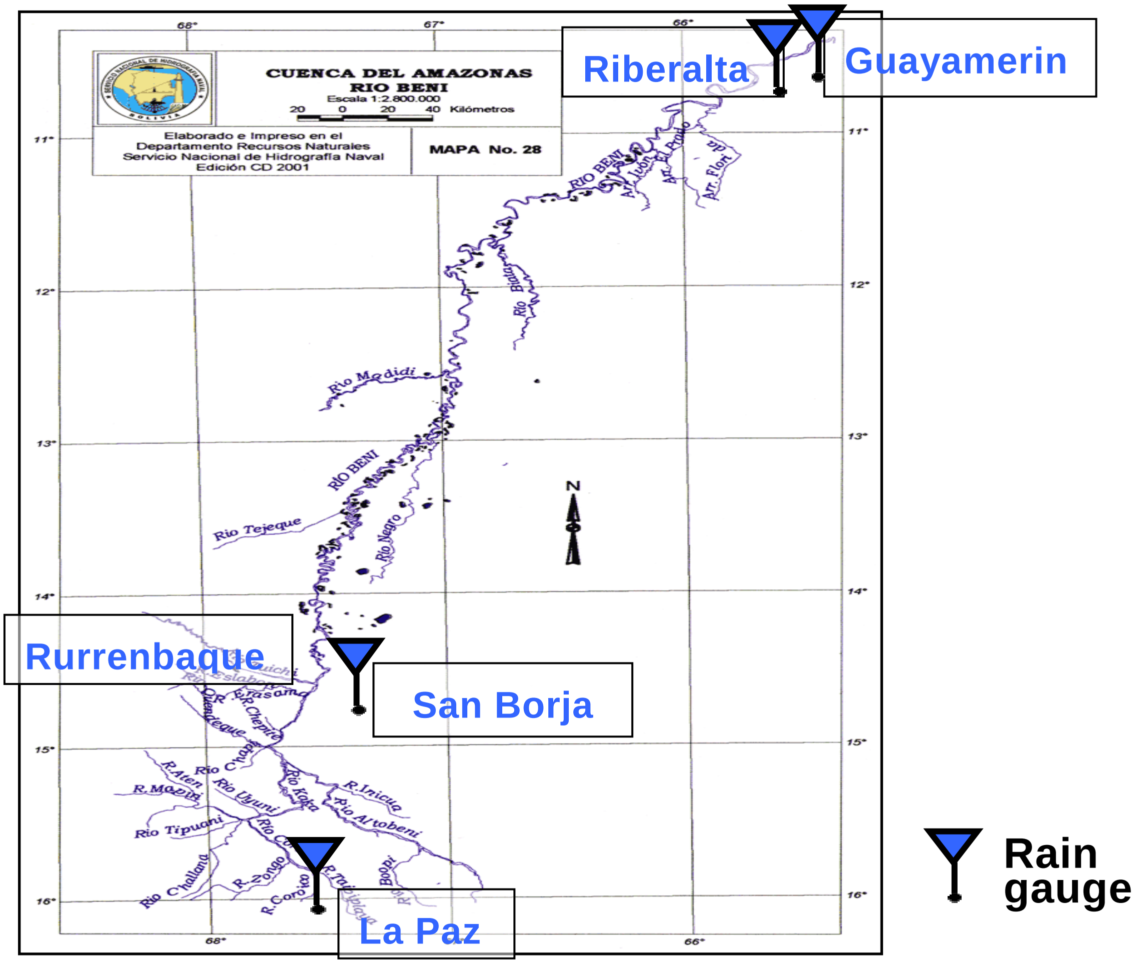


Figure 2: Drainge network of Rio Beni and localisation of the 5 rain gauge stations

River Beni 1,600 km long rises in the Cordillera Real in Bolivia, flows NE through the Andean hills. It joins with the Mamoré to form the Madeira River. Of the 115200 km², 62% lies in the Beni Bassin and 38% lies in the Madre de Dios basin. Three tributaries Mapiri, Tipwani and Coroico rising in the Andes form the river Kaka. River Beni is a confluence of river Kaka and river Alto Beni (*Fig 2*). The width of the river varies from 100m at Alto Beni (in Cordillera Real) to 230 m at Rurrenbaque. The depth of the river is approximately 10m, with a slope of 1:1000.

The Beni River basin, in its Andean part, receives precipitation between some 800 and 1000 mm on the summit, and more than 4000 mm in the upper part of the hot valleys (Yungas). The most protected zones due to its western situation behind the upper summits of the Cordillera, such as the valleys of La Paz and Luribay, have rainfall in the range of 350 to 500 mm. The main rainfall in the Andean basin is estimated at 1720 mm. Rainfall in the plain ranges from 1650 to 2000 mm, with a mean precipitation evaluated at 1810 mm, and at 1755 mm in the entire Beni basin, at the confluence with the Madre de Dios River.

The natural vegetation of the zone is humid tropical forest that changes in composition and structure according to elevation. These forest formations are composed of different plant associations that relate to changes in soil, humidity, and successional state. These dense evergreens are stout, usually not exceeding 15 m, and are laden with epiphytes, moss, and ferns.

The forested tropical Andean slopes ("yungas" in Bolivia) form a continuous band along the eastern Andean slopes roughly between 500-3500 m. This forest band is usually subdivided into about three altitudinal zones: premontane or submontane forest extending up to 1000-1500 m, lower montane or tropical montane forest between 1500 m and 2300- 2500 m, and upper montane forest between 2500 m and 3200- 3500 m. Sometimes a fourth altitudinal zone is recognized, subpáramo or prepuna, consisting of the usually rather narrow shrub-dominated transition zone from forest to non-forest that generally occurs between 3000-3500 m. This shows the high heterogeneity of the study area.

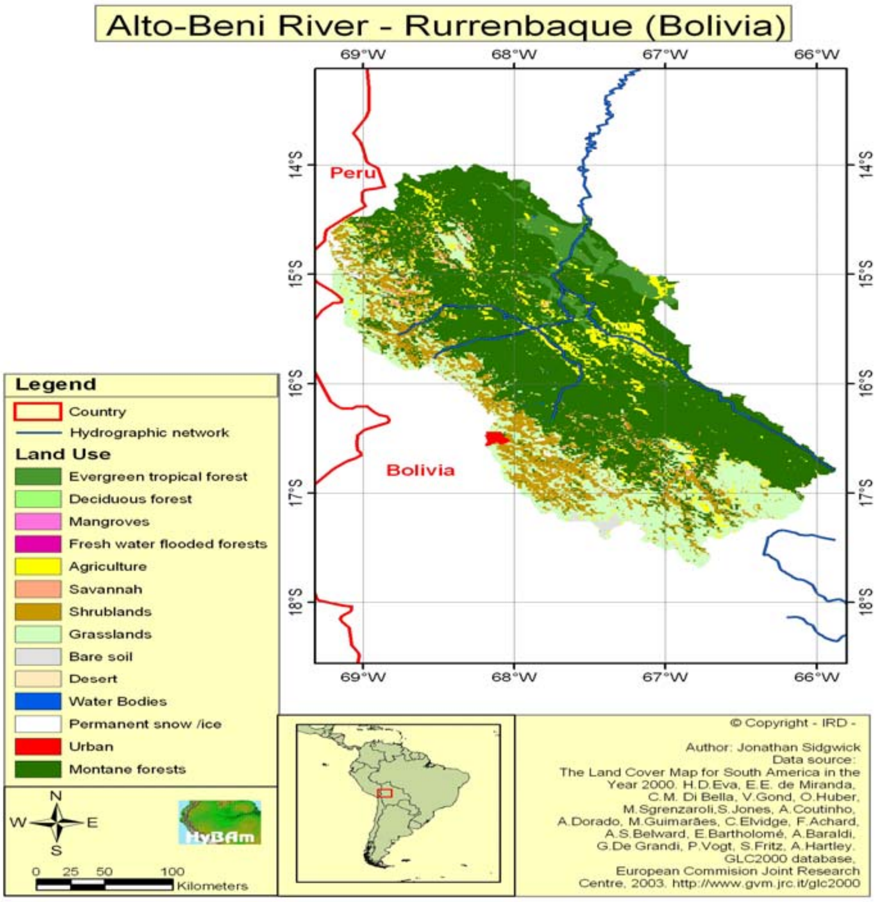


Figure 3: Landuse of the watershed

Soils in the region vary depending upon geomorphology (Fig 4). Steep-sided mountain ridges have shallow soils with numerous sandstone outcrops; these soils are susceptible to erosion and vary from strongly acidic to neutral. Lower hills with tertiary substratum have deeper soils and are only moderately acidic. Valleys, abandoned terraces and the alluvial plains are characterized by deep soils that vary from heavy clays to sandy loams and are strongly to slightly acidic.

With the information about the topography, soil types and land use of the watershed, it can be deduced that the study area is heterogeneous, thus increasing the complication for modelling the watershed.

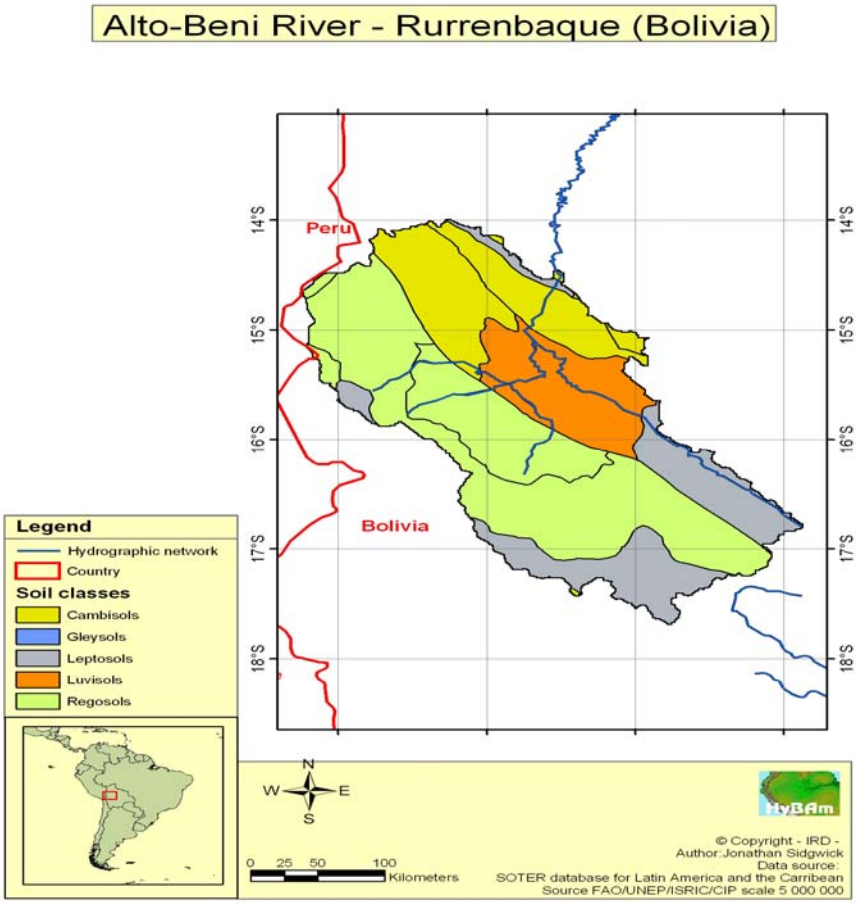


Figure 4: Soil map of the watershed

2.1 Data available

Daily rainfall and discharge measurements from a single gauging station (Rurrenbaque), situated at the outlet of the watershed were at our disposal (*Fig 5*). Also daily measured rainfall from 4 other stations; La Paz, San Borja, Riberalta and Guayamerin located outside the watershed are used (*Fig 6*). All the data are from database of HyBam. A DEM (Digital Elevation Model) map with a 93m resoultion was used to calculate the area of the watershed, the flow direction and accumulation of water. Spatial data: landuse, soils and digital elevation maps are presented using an ArcView GIS system.

2.2 Importance of data quality

It is necessary to check the quality of the data before and while running the models. It should be remembered that (a) hydrometric measurements were not necessarily made, and (b) datasets were not necessarily prepared initially, for calibrating rainfall-runoff models. For the type of model being used here the prime requirement is for unbroken and concurrent time series of rainfall, runoff that are consistent through time.

3 MODELS AND APPROACH

3.1 Conceptual model

Conceptual models are mathematical models applied for real-time hydrological forecasting. Here conceptual model is lumped, i.e the watershed is considered as a whole. The input being the mean areal precipitation over the watershed and the output being the discharge measured at the outlet. In a lumped *conceptual* type model the internal descriptions of the various subprocesses are modelled attempting to represent, in a simplified way, the known physical processes. The input (precipitation values) is partitioned into components that are routed through the subprocesses either to the watershed outlet as streamflow or to the surface and deep storages or to the atmosphere as evapotranspiration. Even if not applying the exact differential laws of conservation, conceptual models attempt to describe large spatial and temporal scale conservation and response laws that are in accordance with the observed large-scale behaviour of water in hydrologic drainage basins. Conceptual approaches were recognised to be able to improve the description of the hydrological response of a basin in comparison with black-box modelling and this generally implies a better performance in discharge forecasting.

In conceptual models the catchment is divided into two stores: the upper store produces surface and subsurface runoff, having rainfall and potential evapotranspiration as input . The lower store produces base runoff. [12]

3.2 Monthly and weekly timescales

The conceptual models used in this study are based on the thesis of Perrin (2000). Measured monthly rainfall is used as input for models working on monthly time scale to simulate runoff and calibrated against the discharge measurements. The monthly time scale models used here are as follows along with the number of parameters for each model,

1. ABCD (6 parameters)
2. CATP (7 parameters)
3. GEOR Georgakakos and Baumer (9 parameters)
4. HAAN (8 parameters)
5. SDIO (9 parameters)

Measured weekly rainfall is used to simulate runoff with the following models. The models used here are

1) GR5J (6 parameters)
2) GR (4 parameters)
3) GRHUM (6 parameters)
4) TOPMODEL (7 parameters)

Flowchart of TOPMODEL is shown here *(Fig 8)* to get an idea of the general structure of a conceptual model [10]. The aim and application, along with the parameters optimized for each model are briefly highlighted in the tables 1 and 2.

3.3 Modelling periods

In order to evaluate the efficiency of a model, for a wide range of hydrological conditions over a catchment, it is necessary to perform simulation tests for different periods. Here monthly and weekly measurements are used in the conceptual models for duration of 4 years (1996 – 2000). Daily measurements for one year (1996) are used for the physical distributed model

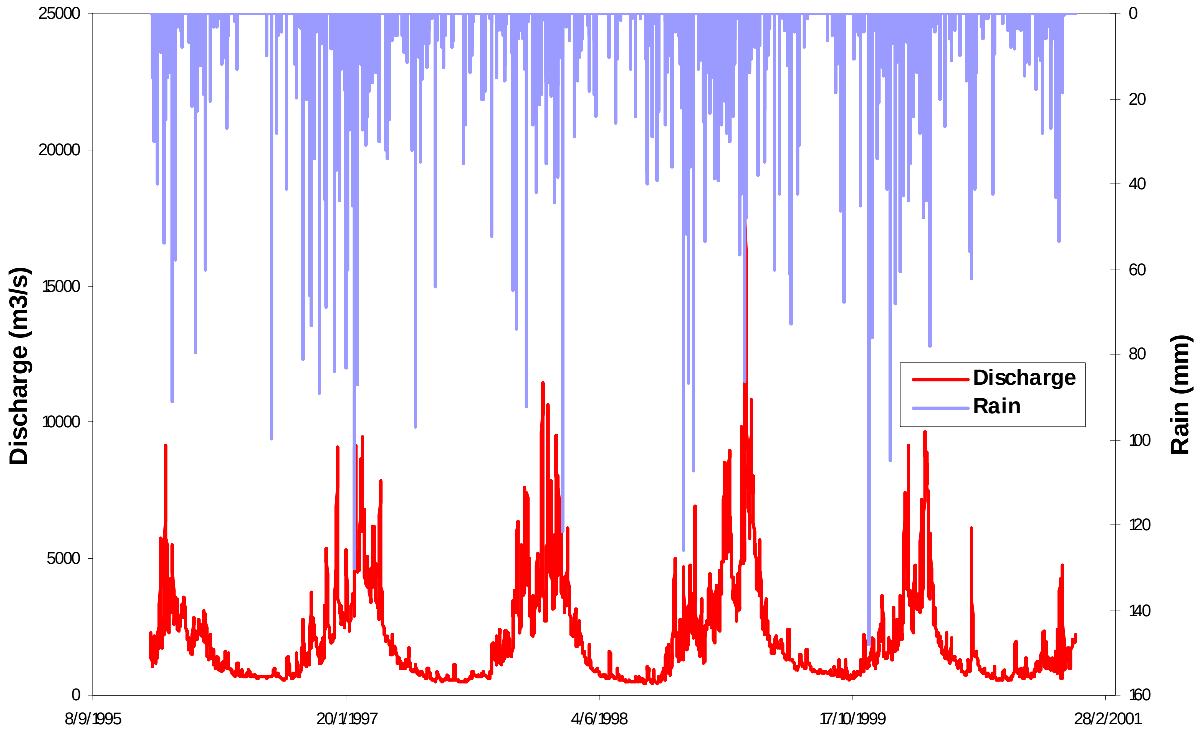


Figure 5: Daily measured discharge and rainfall at Rurrenbaque from 1996 – 2000

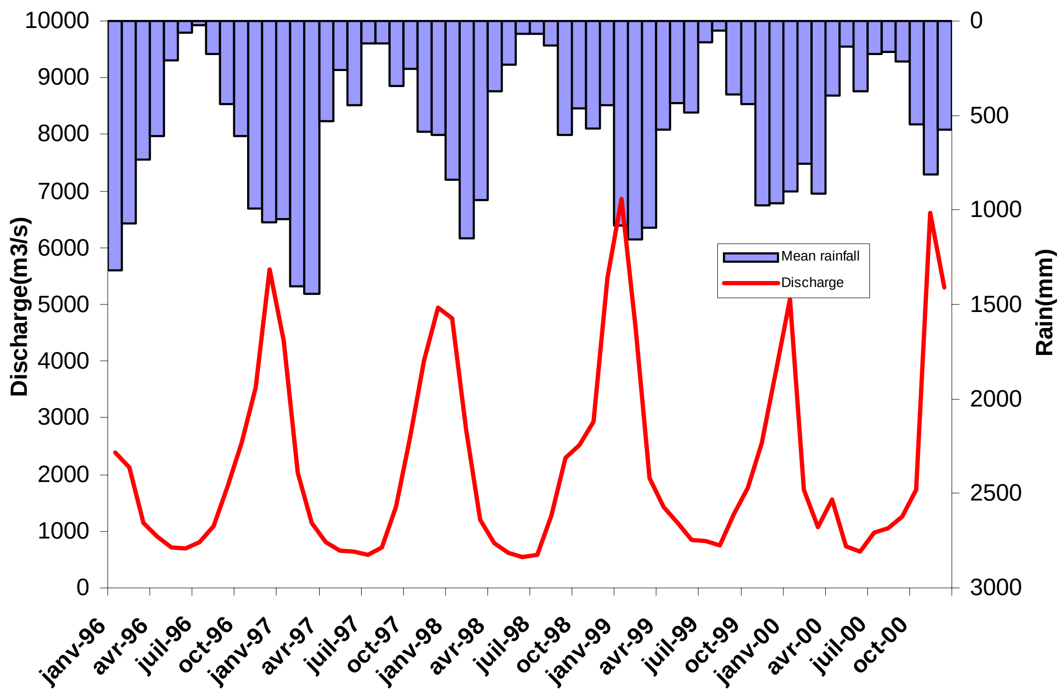


Figure 6: Mean monthly measured rainfall at 5 stations and measured discharge at Rurrenbaque from 1996 – 2000

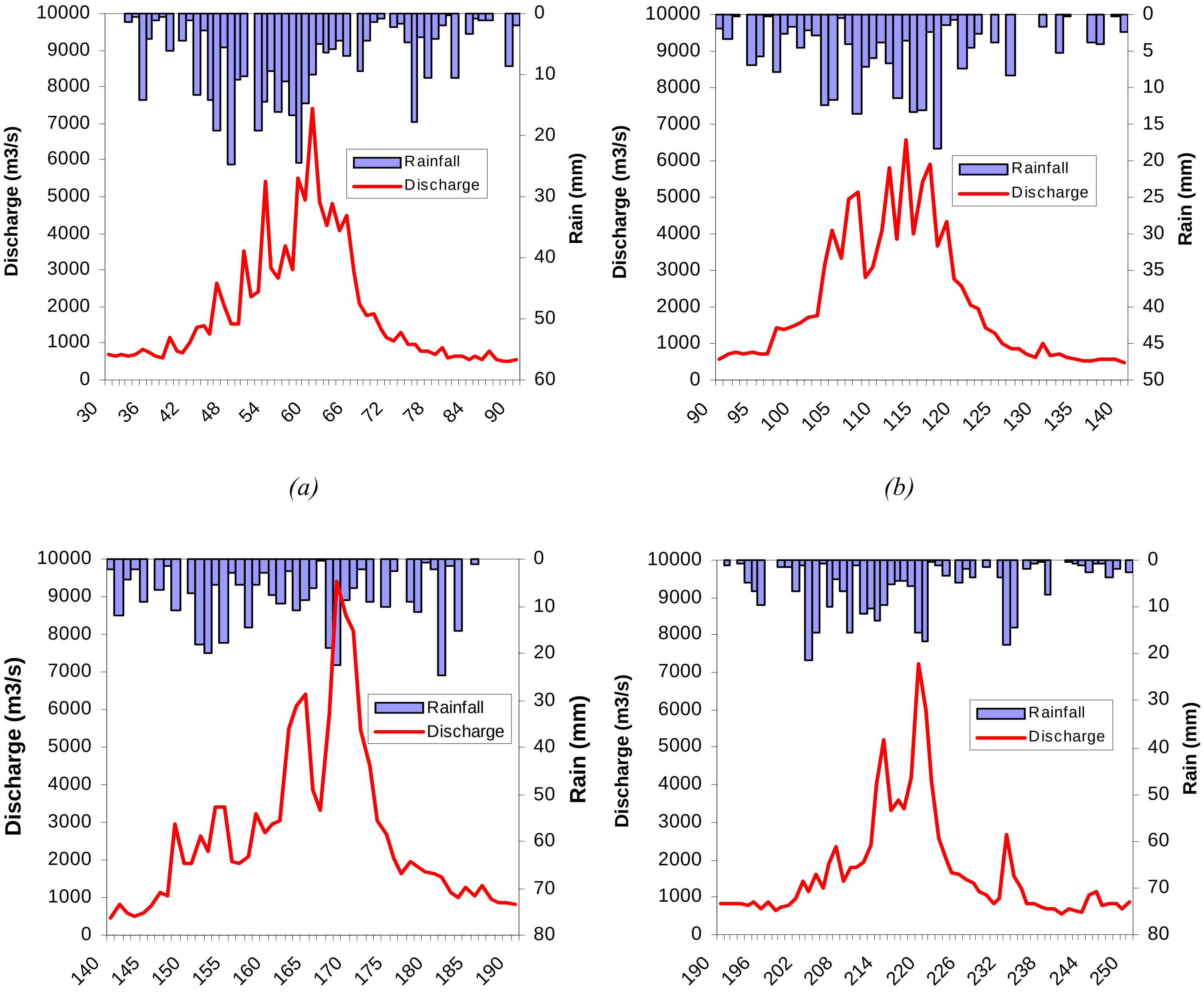
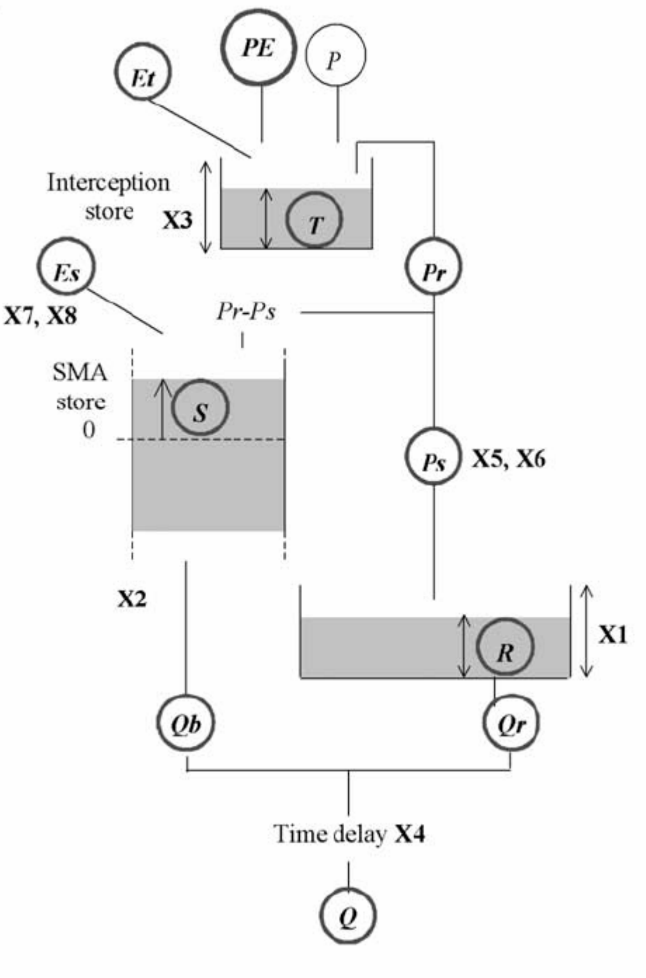


Figure 7: Mean weekly measured rainfall at 5 stations and measured discharge at Rurrnbaque from 1996 – 2000



Parameter	Definition
Model Inputs	
P	rainfall
PE	potential evapotranspiration
Internal State Variables	
Et	evaporation during the interception phase
T	water content of the interception reservoir
Pr	effective rainfall after interception
Es	evaporation from soil moisture accounting reservoir
S	water content of the soil moisture accounting reservoir
Ps	amount of water that reaches the routing reservoir
R	water content of the routing reservoir
Qb	percolation flow from the soil moisture accounting reservoir
Qr	outflow from the routing reservoir
Q	streamflow
Model Parameters	
X1	capacity of the quadratic routing reservoir (mm)
X2	outflow parameter of the exponential store
X3	capacity of the interception reservoir (mm)
X4	pure time delay (day)
X5, X6	parameters defining the distribution curve of the topographic index
X7, X8	actual evaporation computation coefficients

Figure 8: Structure of conceptual TOPMODEL (after Perrin 2000)

3.4 Efficiency criterion

To asses the model performances over the Beni catchment, Nash-Sutcliffe criterion to stream flows [8] will be used. This criterion gives more importance to flood than to low flows, which seems appropriate in this context. This criterion shows the discrepancy between simulated runoff and observed runoff

$$Nash = 100\left(1 - \frac{(Q_{obs} - Q_{sim})^2}{(Q_{obs} - \overline{Q})^2}\right)$$

Where Q_{sim} and Q_{obs} are the simulated discharge and the observed flows respectively. $\overline{Q}$ is the average observed discharge during the calibration period

Model	Aim and Application	Optimized Parameters
ABCD **(Thomas, 1981)**	Model the budget and longterm prevision. Handle water ressources and longterm hydrological evolution.	Soil saturation capacity Soil humidity and evapotranspiration Recharge of groundwater Groundwater emptying constant
CATPRO **(Raper and Kuczera, 1991)**	Study of hydrosalinity and exchange between the groundwater tables of rivers.Characterization of changes in environment.	Interception parameters Maximum capacity of the soil reservoir Maximum hypodermic discharge Maximum recharge of the groundwater Saturation constant Groundwater emptying constant Evapotranspiration coefficient
GEOR (Georgakakos and Baumer, 1996)	To use the humidity of the soil to simulate monthly timestep.	Maximum capacity of two soil layers Exponent Runoff parameters
HAAN **(1972)**	Hydrological model for small rural watersheds and for the prevision of monthly water budget.	Secondary capacity of soil reservoir Maximum infiltration capacity Maximum percolations Proportion of the percolation forming the base flow
SDIO (Langford and O'Shaughnessy, 1977)	To account humidity of soil for modelling rainfall-discharge.	Interception parameters Slope of the field Rapid runoff parameters Evapotranspiration parameters Ground water reservoir constant Exchange parameters

Table 1: Brief description of monthly hydrological models

Model	Aim and Application	Optimized Parameters
GR5J	Model rainfall-discharge with few parameters	Maximum capacity of the soil reservoir Maximum capacity of the routage reservoir Unit hydrogram duration Percolation to saturation Groundwater emptying constant
GR	Model rainfall-discharge in non-gauged watersheds	Maximum production capacity of reservoir Maximum routage capacity of the reservoir Duration for the unit hydrogram Underground exchange parameters
GRHUM	To account the interface between soil-vegetation-atmosphere in a rainfall-discharge model	Constant function of the drainage model of Thomas Constant time of the unit hydrogram Underground exchange parameter Maximum routage capacity Evaporation parameters, to be determined based on the physical characteristic of the watershed
TOPMODEL	Use of the topgraphy index and the notion of the variable contributive area for modelling rainfall-discharge.	Maximum capacity of interception and infiltration reservoirs Infiltration parameters Groundwater emptying constant Routage parameters Parameter dependent on topography index

Table 2: Brief description of weekly hydrological models

3.5 Approach

Conceptual model: Monthly time scale

For representative of the areal daily rainfall from the available rain gauges, two approaches are used here.The mean areal precipitation computation by Thiessen polygon method is not applicable for this study area, as the variation in the topography is very high and would not be representative of the area.

In the first approach, the daily rainfall input for simulation is got by multiplying rainfall from each of the 5 stations by weighted factor which are optimized and then summing it, as shown in figure 9a. With this global rainfall, discharge is simulated and calibrated against the measured discharge.

In approach 2, discharge obtained for each station from the model is multiplied by the weighted factors and is summed to get the final discharge. And this discharge is calibrated against the measured discharge form the Rurrenbaque (outlet).

Conceptual model: Weekly time scale

Weekly time scale was chosen in order to simulate the runoff better. The measured data for 4 years i.e from 1996 – 1999 are used here. After which simulation for each individul years are carried out.

4 RESULTS

The meteorological precipitation data used as input to the lumped conceptual model produces catchment runoff. The resulting catchment runoff is split conceptually into overland flow or surface runoff, interflow and baseflow components. For simplicity, the catchment runoff is divided into surface runoff and baseflow flow components. There was no evapotranspiration data available. Therefore we are not accounting the volume of precipitation and runoff i.e water budget established by other methods. So, we tried to relate directly normalized precipitation to normalized runoff. Both the signals range between 1 and 0. This assumption seems realistic in this case, with constant temperature throughout the year. The simulations of which can be seen in the graphs.

4.1 Optimization procedure

Genetic algorithm is a search procedure based on the mechanics of natural selection and natural genetics, which contribute an artificial survival of the fittest with genetic operators abstracted from nature. In this work a genetic algorithm for function optimization is introduced and applied to the calibration of conceptual rainfall-runoff models for data from a particular catchment. All the parameters of the model are optimized. Genetic algorithm has known to be efficient and robust [13]. The simulated runoff and model parameters are obtained by minimizing the deviation from actual runoff, by optimizing the given objective function using genetic algorithm, as reported by Wang in the application of genetic algorithm for calibration of Xinan Jiang model.

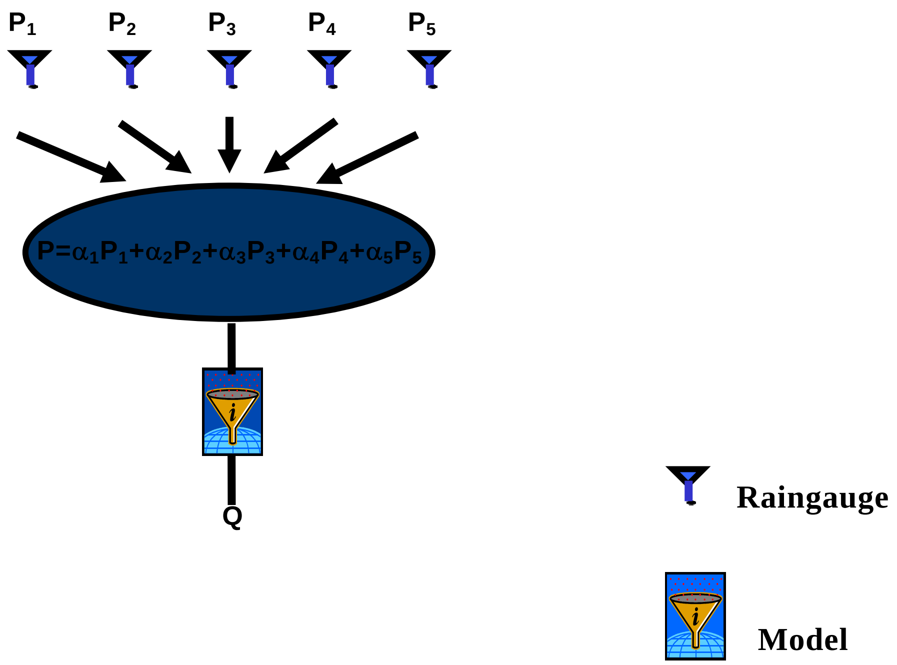


Figure 9a: Approach 1,where P is monthly rainfall input to the model, α_1, α_2, α_3, α_4, α_5 are weighted factors and P_1, P_2, P_3, P_4, P_5 are rainfall from the 5 stations.

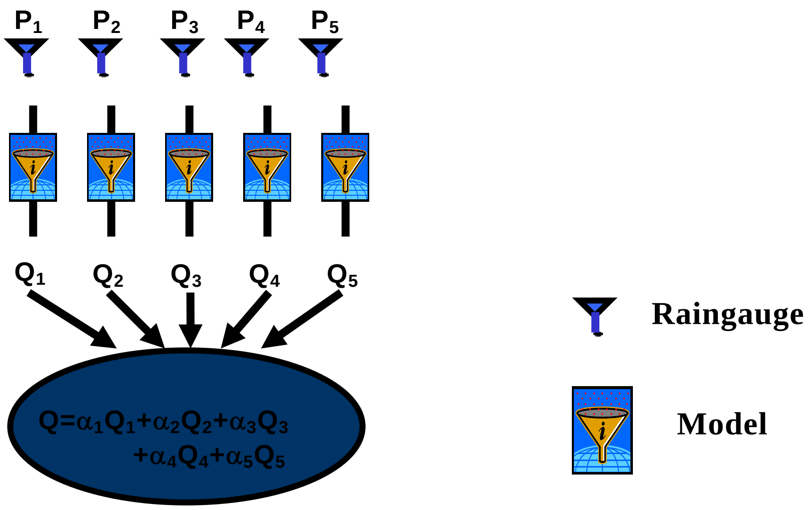


Figure 9b: Approach 2, where Q is the final discharge obtained from the optimized parameters α_1, α_2, α_3, α_4, α_5 and Q1, Q2, Q3, Q4, Q5 are the discharges got from the model.

4.2 Monthly time scale

From the simulations of the approach 1 and approach 2, we can see that all the models are able to simulate the global pattern of the measured discharge, with few artifacts (*Fig 10 and Fig 11*). The baseflow is also captured well. It should be noted that none of the models seem to be able to simulate the highest peak of the year 1998; HAAN and SDIO show the best simulation. With exception of the year 1996, none of the models are able to simulate the maximum discharge for other years.

When we observe each compartment of the simulated discharge, the signature of each model is different and also the change in the approach influences the simulation. In the model ABCD, with approach 1, we see that the main contribution to the discharge comes from base-flow (98%) and only 2% contribution from surface runoff. On the contrary, with approach 2, 76% comes from surface runoff and the rest from baseflow. Though both the approaches have almost the same Nash coefficient, the signatures of each are different. For the CATP model, the first approach produces zero baseflow and the discharge comes mainly from surface flow, while the second approach produces 40% baseflow and 60% surface runoff. Here even though both the approaches have the same Nash coefficient, the signals are different. The only exception being the HAAN model, which is simulating the discharge better with approach 2,

the Nash coefficient being 81%. In both the approaches the surface runoff and baseflow compartments are reacting similarly with 85% surface runoff and 15 % of baseflow.

The same can be observed for the models GEOR and SDIO, with the first approach simulating the discharge better. In GEOR, the first approach produces the discharge only with surface runoff, while in the second approach 40% comes from surface runoff, 60 % from baseflow.

While for SDIO, the first approach yields 70% surface runoff, with 30% baseflow and with second approach there is nearly no baseflow at all.

Discussion

In general approach 2 is preferable, even though Nash coefficient is better for approach 1(table 3), because we feel that the second approach is more representative of reality. It is able to simulate a reasonable baseflow, which is not the case in approach 1, with the exception of SDIO model. Among the 5 models in approach 2, HAAN can be considered the most appropriate model and representative of the watershed charatctersitic, as it is producing a constant baseflow and simulating the closest measured surface runoff. In approach 1, SDIO *with a Nash coefficient 78% is capturing the baseflow and surface runoff. Unlike HAAN in approach 2, the baseflow is not constant here.*

Model	Approach 1	Approach 2
ABCD	**77**	**74**
CATP	**74**	**74**
GEOR	**74**	**64**
HAAN	**77**	**81**
SDIO	**78**	**61**

Table 3: Nash coefficient expressed in percentage for monthly time scale: 1996 – 2000

4.3 Weekly time scale

Weekly time scale trial was done to achieve better simulation. Weekly time scale simulation for 4 consecutive years (1996-1999) were carried out, which did not produce promising results, the Nash coefficient for all the models being more or less around 50%, shown in table 4. An example for one of the simulation (TOPMODEL) is shown in figure 12.

To further improve the simulations, we tried to capture the pattern with individual years. The data for which are show in the figure 7. The results of which are contrasting (*Fig 13*). While some of the models performed well for one particular year, it failed to produce the same consistency for others. The models in general seem to average the flow, without capturing the short storm events.

The simulation for the years 1998 and 1999 are not very good when compared to 1996 and 1997. This could be a seasonal change in the rainfall and the inability of the models to capture this variation. Similar to monthly time scale, none of the model was able to simulate the peak. The baseflows are simulated with artifacts. The artifacts generated here are because of the predefined conditions in the models like the humidity, saturation of the soil reservoir which produces the runoff, while in reality it is not invoked.

In model GR5J, baseflow is neglected and the discharge is produced by surface runoff basically (80%). GR and GRHUM on the contrary with similar Nash coefficients for all the years, produces discharge dominated by baseflow (80%). Thus showing how two different models react to the same input, producing different hydrological process.

TOPMODEL is also dominated by baseflow (96%) for the years 1996 and 1999, having a Nash coefficient of 73% and 59% respectively. But for the year 1997 and 1998, the contribution by the surface runoff is comparatively higher, with 50%. This shows the interpretation of the model, for different hydrological years.

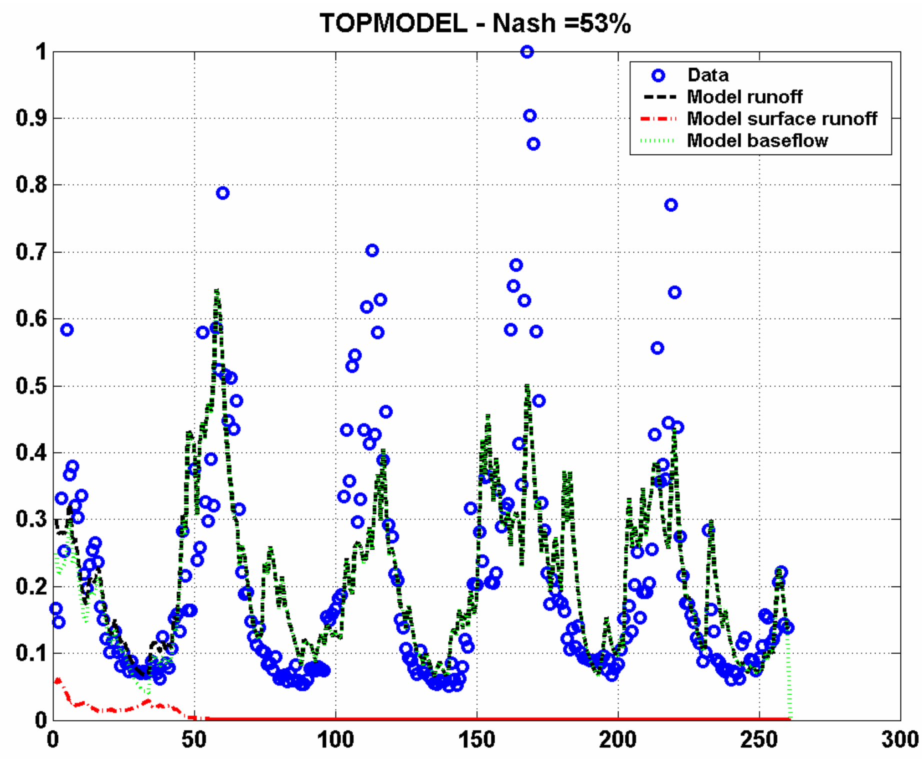


Figure 12: Weekly time scale simulation by TOPMODEL from 1996-1999

Discussion

The highest Nash coefficient being for TOPMODEL with 80% with 48% baseflow and 52% surface runoff, i.e both surface and baseflow contribute equally to the discharge. Thus being the most efficient among the weekly time scale model (Table 5).

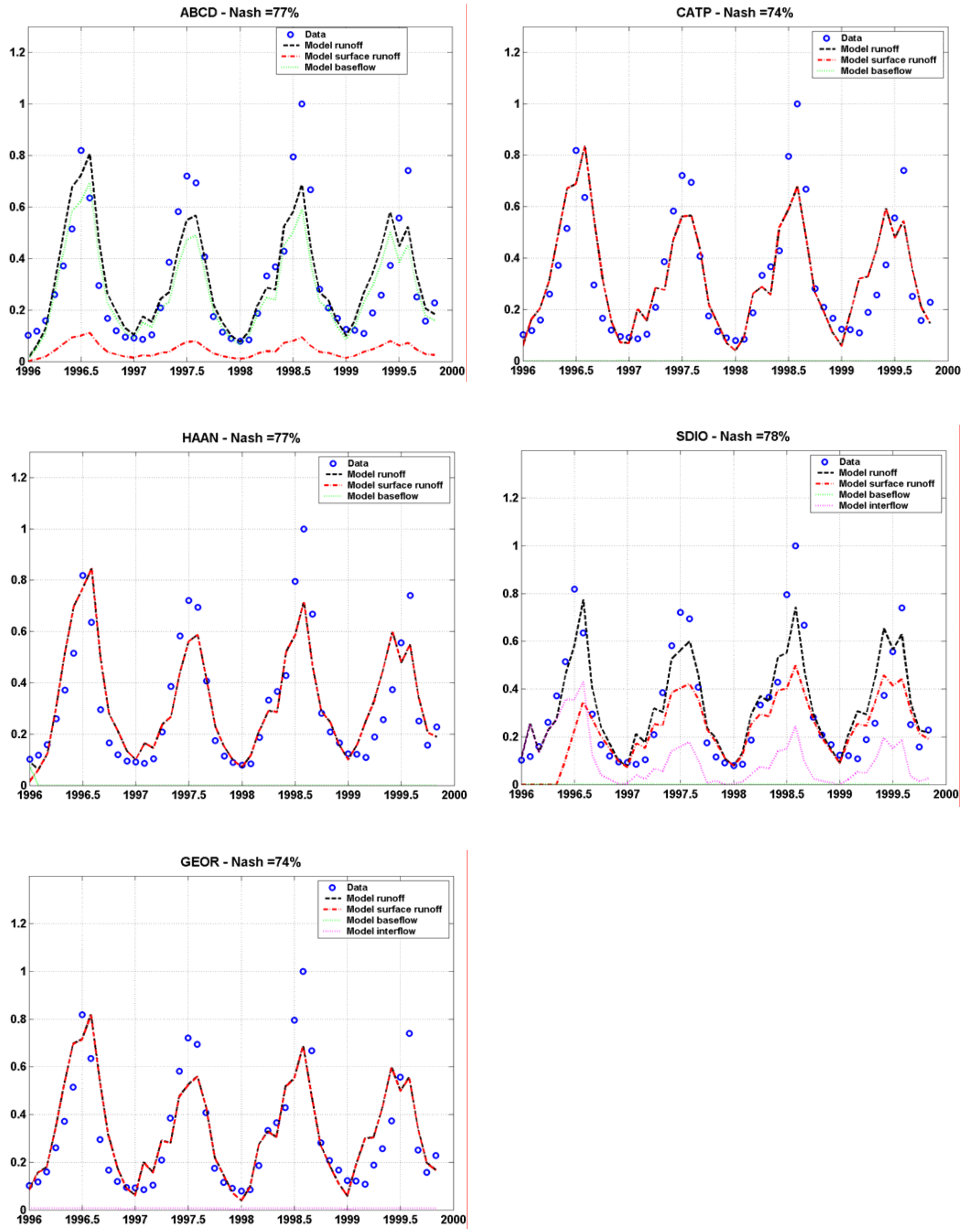


Figure 10: Simulations of monthly time scale by approach 1

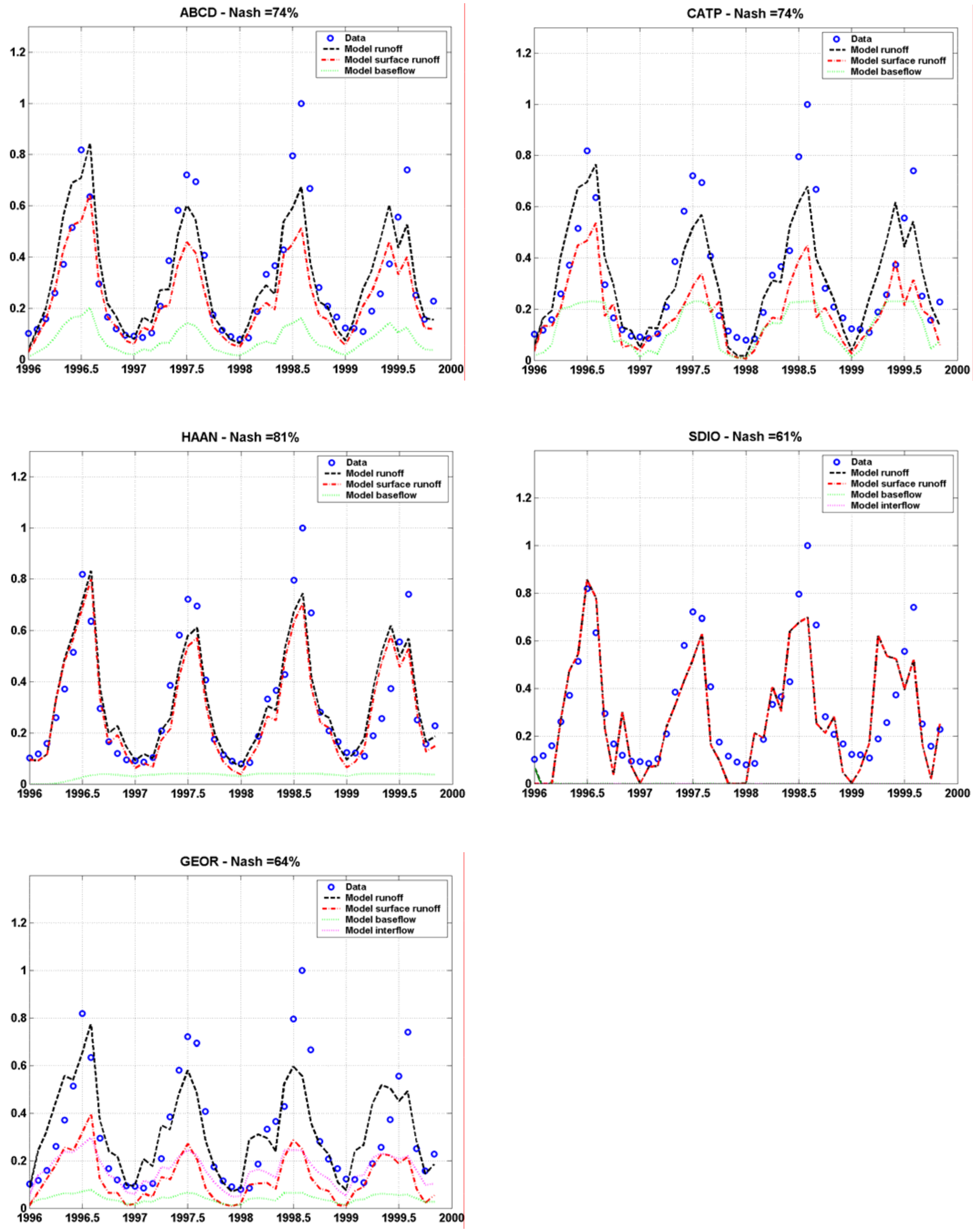


Figure 11: Simulations of monthly time scale by approach 2

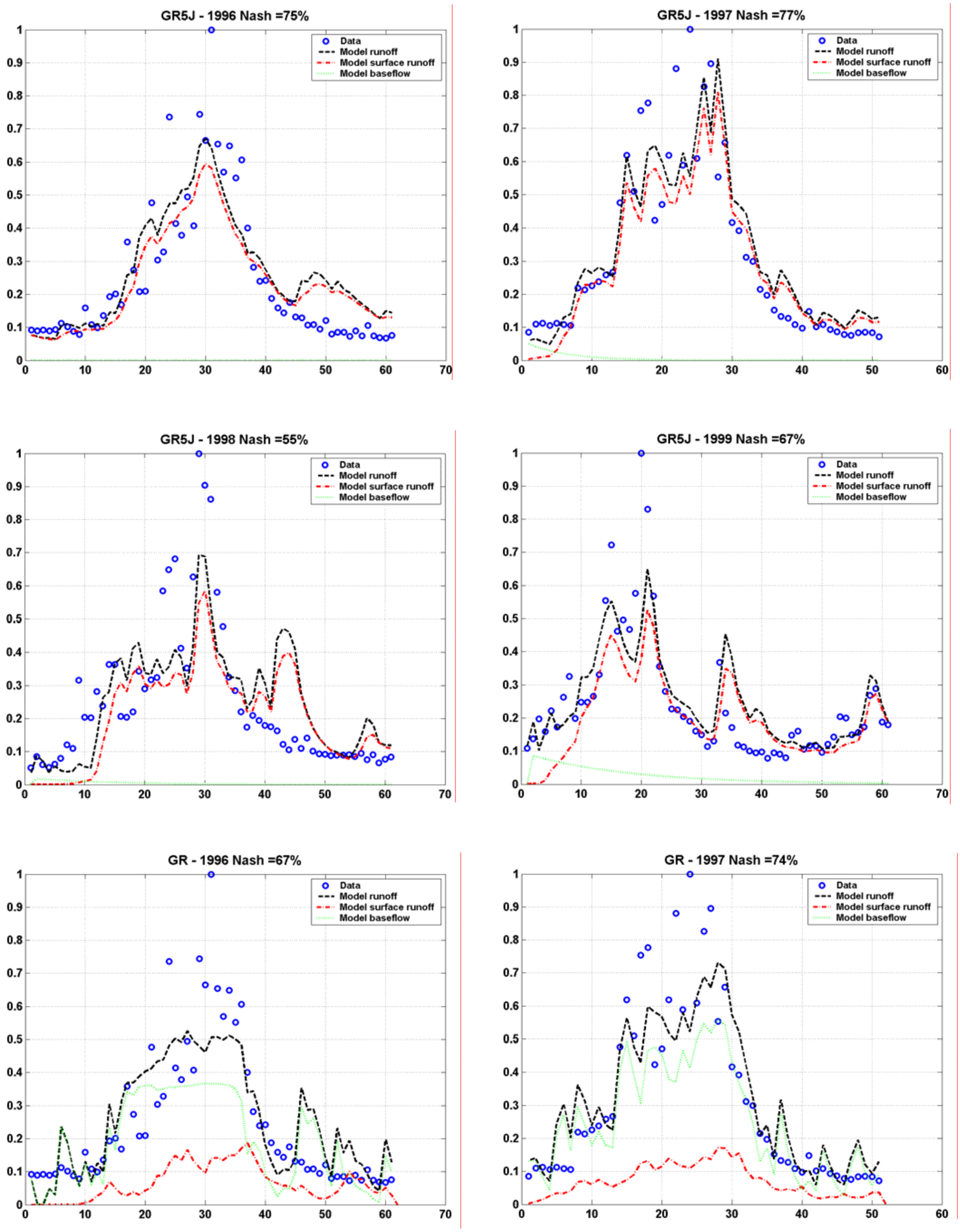


Figure 13a: Simulation of weekly time scale for individual years

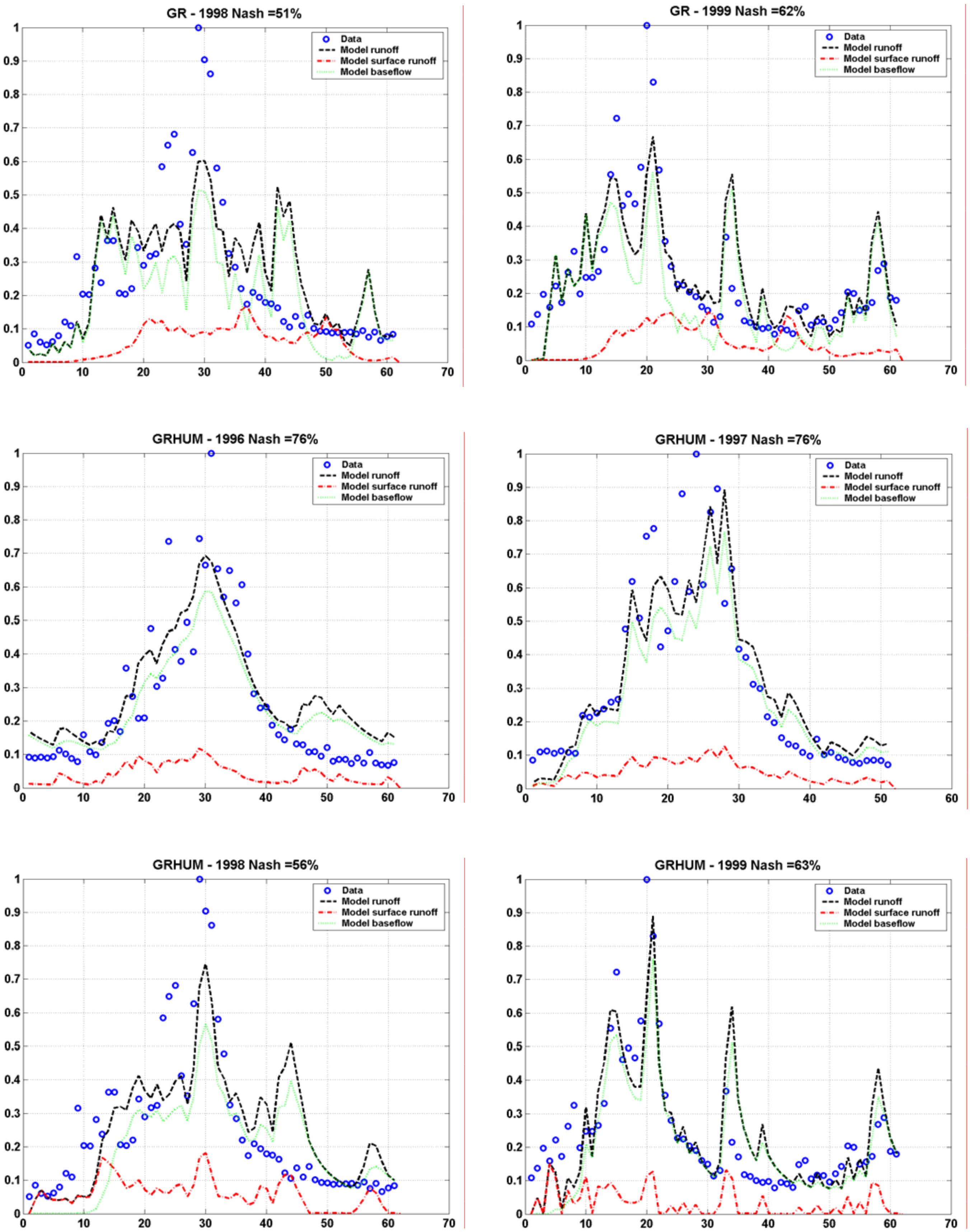


Figure 13b: Simulations of weekly time scale for individual years

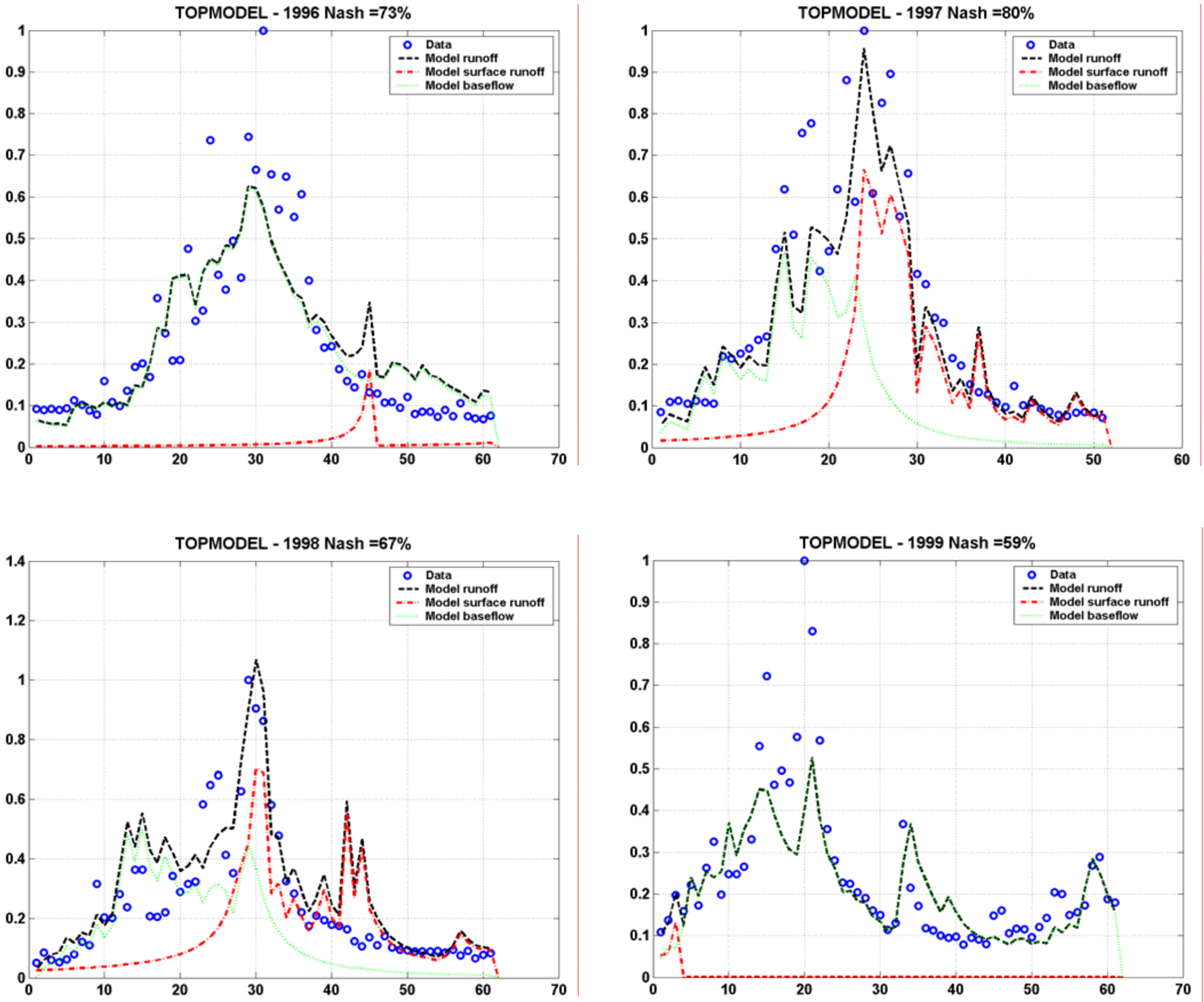


Figure 13c: Simulations for weekly time scale for individual years

Model	1996 – 1999
ABCD	52
GR5J	51
GR	47
GRHUM	55
TOPMODEL	53

Table 4: Nash coefficient expressed in percentage for weekly time scale: 1996 – 1999

Model	1996	1997	1998	1999
GR5J	75	77	55	67
GR	67	74	51	62
GRHUM	76	76	56	63
TOPMODEL	73	80	67	59

Table 5: Nash coefficient expressed in percentage for weekly time scale: individual years

5 CONCLUSION

The models performed well, particularly in the monthly case, where often more than 90% of the variance of observed streamflow was explained in simulation on independent periods. However, while the simple conceptual model is adequate for monthly periods, the weekly simulations results indicate that a slightly more complex model is required for short term periods. Thus suggesting that the models used at short time scales and developed at larger ones may not be as efficient as they could be, because of inadequate structure and level of complexity.

Even if the conceptual models may be much more simplified and lumped, they offer the potential for development based on process understanding of key zones or reservoirs of catchment response. A major obstacle in moving forward with conceptual modeling approaches is how to fully utilize experimental data for internal calibration and validation. Currently, the use of this field data for model calibration is often limited beyond simple streamflow information despite the general acceptance that internal state information is necessary for ensuring model consistency. The usefulness of having various criteria for assessment of model performance is widely accepted [4]. When multi-criteria are used for calibration or validation, this has often meant only the use of two or three criteria (e.g. runoff and groundwater levels) as compared to only one criterion (i.e. runoff). Clearly, more criteria are desirable but in most cases there is no suitable data available.

The dilemma in conceptual modeling of catchment hydrology is that parsimonious models, which may allow identification of parameter values through calibration against runoff, in general are too simple to allow a realistic representation of the main hydrological processes and, thus, provide only limited possibilities for internal model testing.

6 PERSPECTIVE

The conceptual models are very usefull in water management like forecasting and predition. On the other hand, the internal working of the model is complicated and is not necessarily representative of the physical process. Thus causing a hinderance to the understanding of the hydrological process. Distributed models, though requires more information gives an insight into the different processes involved in the catchment hydrology and a initial trial was carried out to simulate the catchment runoff (description in annex).

Soil texture, temperature, dimensions of drainage; information are required to complete the hydrological budget and to simulate reasonable catchement runoff. Because of the lack of data, we were unable to produce good simulations. But with more information about the basin characteristic; hydrometeorological variables, unbroken and concurrent time series of rainfall and streamflow that are consistent through time there is scope for improvement.

The data available and attainable to run a distributed hydrological model was collected (*Figures 1 to 5*). This is generally a painstaking task because either the datas are not available for the study area in question or the available data sets are not consistent, which further complicates the study. Especially if the study area is very large, as in this case. It becomes difficult to model a large heterogenous watershed with sparsity of data. For example the DEM for a large scale watershed in particualar should be as refined as possible, otherwise the flow direction and flow accumulation processess are difficult to determine. This information being vital for modelling the discharge. Next, to incorporate the losses in the modelling process; evapotranspiration, interception and percolation the texture of soil and landuse information are needed. With this information an initial estimation can be carried out, thus helping us to understand the role of different hydrological process.

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Internet sites and other sources

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8 ANNEX

Proposal of a large scale watershed model:

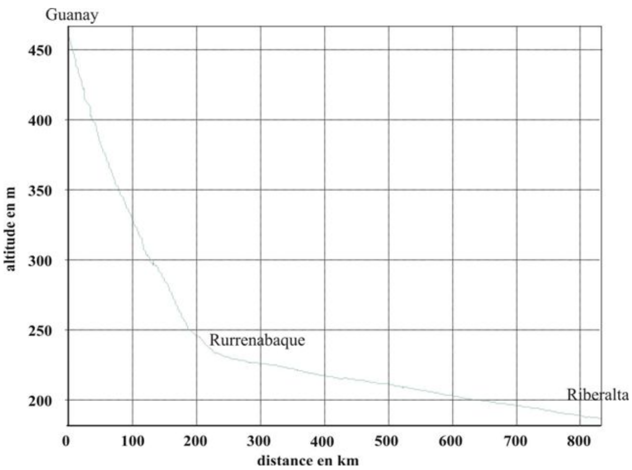
The distributed model used in this study is MARINE Large Watershed developed between IMFT and LMTG. It is a physical based distributed model. The model MARINE LW simulates hydrograph at the outlet of the watershed. To model the different hydrological process, an integration of the information such as the DEM (Digital Elevation Model), the soil occupation and its nature and the morphological information of the river is needed. It also calculates the lateral inflow to the river in time, along the watercourse. It is coupled with St Venant 1D equation for the flux in the river. MARINE-LW permits to calculate a hydrogram at the outlet of the watershed, with a spatially distributed rainfall. The runoff is generated form excess infiltration. The infiltration capacity is determined at every time step using Green-Ampt method (1911), which is a simplified form of Richards's equations. Flow to the river uses an eulerian approach. There are two types of data necessary for the simulation: data invariable with time (DEM, landcover, delineation of the watershed) and variable data (rainfall events). For the calculation of transfer of runoff into the river, it is necessary to treat the raw data supplied, particularly the DEM. The pretreatment is done once, which then permits to simulate the runoff.

Calculation of the slope

The DEM evaluates the slope of each pixel with respect to its direction. The calculation of slope of each pixel is based on the largest difference in altitude between the pixel in question and the 4 surrounding pixel. It is thus possible to determine the direction of runoff i.e the direction with highest slope.

Accumulation treatment

There exist some cases, where it is difficult to determine the direction of flow, because the altitude is not very precise: for example if a pixel is surrounded by 4 pixels at higher elevation. In such a case, the pre-processor searches a nearest pixel with the lowest altitude, considering it to be the outlet and modifies the slope, such a way that the water flows along the direction of the outlet. We use the algorithm of Bresenham which helps to identify the pixels situated below the highest slope. With the following graphs, we were able to get information about the terrain.



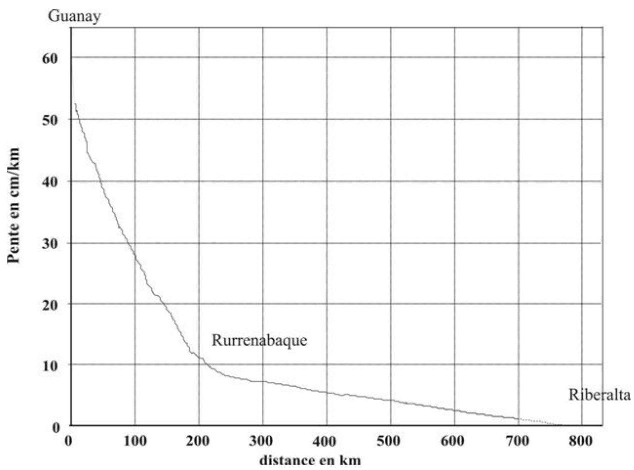


Figure 14: Profile of the altitude and slope of watershed

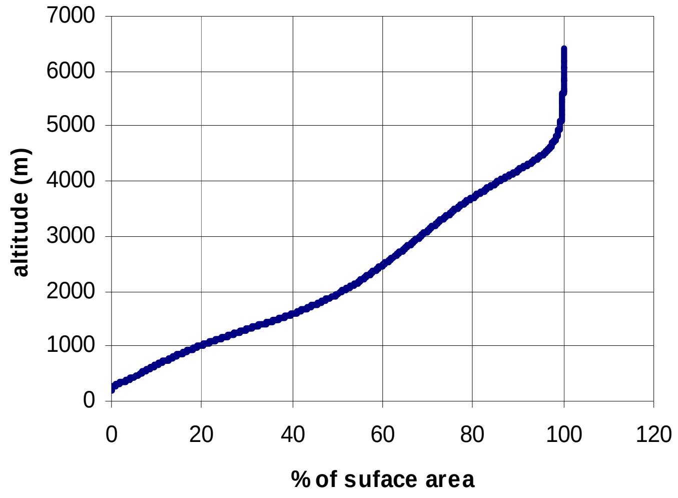


Figure 15: Hypsometric curve

Simulation for one year (1996) was carried out with the physically distributed model (*Fig 16*). The simulation obtained was not very consistent, but could be improved with data adapted to a distributed model.

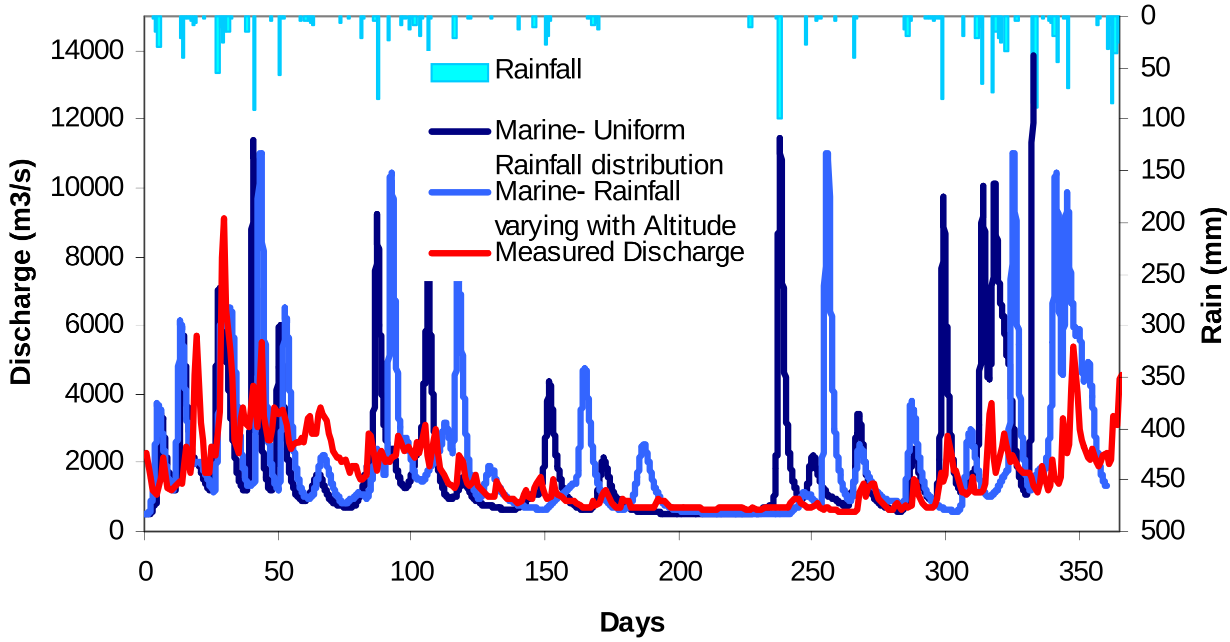


Figure 16: Preliminary simulation of the model MARINE for the year 1996