HYDROLOGICAL MODELLING OF ARKUN DAM BASIN IN CORUH RIVER BY USING GR4J-CEMANEIGE MODEL

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ABSTRACT

HYDROLOGICAL MODELLING OF ARKUN DAM BASIN IN CORUH RIVER BY USING GR4J-CEMANEIGE MODEL

In this study, the hydrological modelling of Arkun dam basin is made by using GR4J runoff-precipitation model and CemaNeige snow accounting routine. Arkun dam located in Çoruh River is chosen as an outlet and its basin determined by using Geographical Information Systems. The area is chosen due to its characteristics. The basin is largely fed by melting snow during spring and early summer seasons. In the working area, the highest mountains of Turkey are located. The altitude of Arkun dam is 870 m and the highest altitude of the basin is 3705 m. The elevation fluctuates throughout the basin. Due to these characteristics, the hydrology of the basin is mostly affected by the altitude differences, snow melting and its delayed effect. In this study, model parameters of GR4J and CemaNeige are tried to be determined for Arkun dam basin in order to be used in streamflow calculations. Besides, GR4J model is also presented alone without any snow accounting routine. The necessity of a snow accounting routine, in this case CemaNeige, is clearly shown.

ÖZET

ÇORUH NEHRİ ÜZERİNDE BULUNAN ARKUN BARAJI HAVZASININ GR4J-CEMANEIGE MODELLERİ KULLANILARAK HİDROLOJİK MODELLEMESİ

Bu çalışmada, Arkun barajı havzasının hidrolojik modellemesi GR4J yağış akım modeli ve CemaNeige kar hesaplama modülü ile yapılmıştır. Çoruh nehrinde bulunan Arkun barajı boşalım noktası olarak düşünülmüş ve havzası Coğrafi Bilgiler Sistemleri aracılığı ile tespit edilmiştir. Alanın seçilmesinde karakteristik özellikleri etkili olmuştur. Havza çoğunlukla bahar ve yaz aylarında oluşan kar erimeleri ile beslenir. Çalışılan havzada, Türkiye?nin en yüksek dağ sıraları bulunmaktadır. Arkun barajının rakımı 870 m iken, havzadaki en yüksek nokta 3705 m rakımdadır. Arazi yükseltisi bu iki değer arasında havza boyunca değişmektedir. Bu özelliklerinden dolayı, havzanın hidrolojik modellemesi çoğunlukla yükselti farklılıklarından, kar erimelerinde ve kar erimelerinin gecikmeli etkisinden etkilenir. Bu çalışmada GR4J ve CemaNeige model parametreleri havza için akım hesaplamalarında kullanılmak üzere belirlenmeye çalışılmıştır. Ayrıca, GR4J yağış akım modeli herhangi kar hesaplama modülü olmadan hesaplanmıştır. Sonuçlar, kar hesaplama modülü gereksinimini açıkça göstermektedir.

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LIST OF SYMBOLS

$BETA$	Relative Contribution to the Runoff
C	Runoff Coefficients
C_{MELT}	Degree-day factor
eT_G	Snowpack Cold Content
FC	Soil Moisture Storage
LP	The Shape of the Reduction Curve for Potential Evapotranspiration
NS_rQ	Efficiency Objective Function
PE_A	Adjusted Potential Evapotranspiration
R^2	Regression Analysis
Q_cd	Calculated Discharge
Q_obs	Observed Discharge
Q_sim	Simulated Discharge
TT	Threshold Temperature
θ_G1	Snowmelt Factor
θ_G2	Cold Content Factor
η	Efficiency
γ	Temperature Lapse Rate
ξ	Value at Risk

LIST OF ACRONYMS/ABBREVIATIONS

GIS	Geographical Information System
GR3J	Modelá du génie rural á 3 paramétres
GR4J	Modelé du gï¿$\frac{1}{2}$nie rural á 4 paramï¿$\frac{1}{2}$tres
GRG	Generalized Reduced Gradient
HBV	Hydrologiska Byr$\dot{a}$ns Vattenbalansavdelning
SAR	Snow Accounting Routine
SRM	Snowmelt Runoff Model
SRTM	Shuttle Radar Topography Mission
WHO	World Meteorological Organization

1. INTRODUCTION

The existence of water from past to present has been one of the fundamental elements in the life of living things. Nowadays, however, climate change and rapid growth with global warming developing world population adversely affects water resources in many aspects. With the aim of reducing these influences, the importance of the protection and effective use of water resources gradually increases. In this context, the necessity of the science of hydrology is revealed day by day. Hydrological modeling studies especially focusing snow-related topics contributes to the flow forecasts as well as having impact on the efficiency increase of natural water resources usage. The optimistic operation of the dams and the flood protection workings to be made largely depend on these forecasts.

The geography Turkey, with its 1.130 m of mean elevation and the increasing altitude from west to east, is suitable for the flow forecast workings. This topography constitutes 45% of the country. The collection of hydro-meteorological data on area having tough topographical condition becomes difficult. This situation also clears the necessity and the importance of a hydrological modelling for one of those fields.

In this study, the hydrological modelling and flow forecast workings are aimed for the Coruh river basin by using GR4J precipitation runoff model and CemaNeige snow accounting routine. Coruh river rises from the west hillsides of Mescit Mountains whose elevation is 3225 m and flows firstly to the west in the eastern Turkey. Afterwards, it advances to the east through the Bayburt plain. Coruh river unites with Tortum and Oltu creeks by passing through one of the deepest valleys in Turkey, Coruh Valley. Coruh river flows into the Black Sea within the border of Georgia by passing the cities of Bayburt, Erzurum and Artvin in Turkey. The modelling is made by using the data gathered by Peterek Streamgage Gauge Station which is very close to Arkun Dam constructed on Coruh river. Therefore, the model is limited for the Arkun Dam part of the basin which is fed by largely snow-melting runoff. The Arkun dam basin is first analyzed in Geographical Information System in order to determine basin characteristics with the map. At the end, the model performance for the Arkun Dam Basin is tested and the proper model parameters for this basin are determined.

2. LITERATURE REVIEW

Real-world systems like surface water, groundwater etc. can be simplified by mathematical tools and software which enables to understand and the predict of its behavior. The hydrological modelling has taken the advantage of mathematical tools and software much more as time passes. Thanks to this advantage, the models become more complex, more representative of the basins. Besides, they set light to a lot of problems and questions related hydrology and water resources by either extrapolating the available hydrological knowledge or attempting to model the effects of the changes in the environment by human being. The ability to answer more question in the hydrological or water resource literature causes the drastic increase in the number of the models where each model focuses on the specific field. The model types and the way they work have also changed by this development. Therefore, the interdisciplinary study is much more requested in this area. The literature review of this study includes; the essential of hydrological modelling along with the classification of the hydrological models, the principals that need to be taken into consideration for hydrological modelling and lastly, the simple explanation of HBV and SRM models which are widely used in the literature.

2.1. Hydrological Modelling of a Watershed

Air, water and soil who maintain the life on earth are the most essential elements of the environmental continuum. These three elements have a complex relationship in between. Due to this complexity, one small deviation on one of these elements of environmental continuum has a great effect on the others which are neither known nor measurable. This interrelatedness requires us to approach to the environmental management systems by being integrated and interdisciplinary. In order to accomplish an integrated water management, the determined area has to be divided to the watersheds which are the spatial units and the modelling should be implemented on those spatial units called watersheds.

The integrated water management may have more than two dimensions, namely; water necessity, the policy to reply this necessity and the implementation of the policy. The first dimension can be the all facets of water quality and quantity which can be called water elements. Water uses such as water supply, agriculture, recreation, energy production etc. follow the water elements as a second dimension. Lastly, the balance between water elements and the demand for water uses requires a well-defined policy. Thus, the implementation of this policy is the third dimension. The fourth dimension can be defined according to the changing demands from one society to the other or from one time to the another.

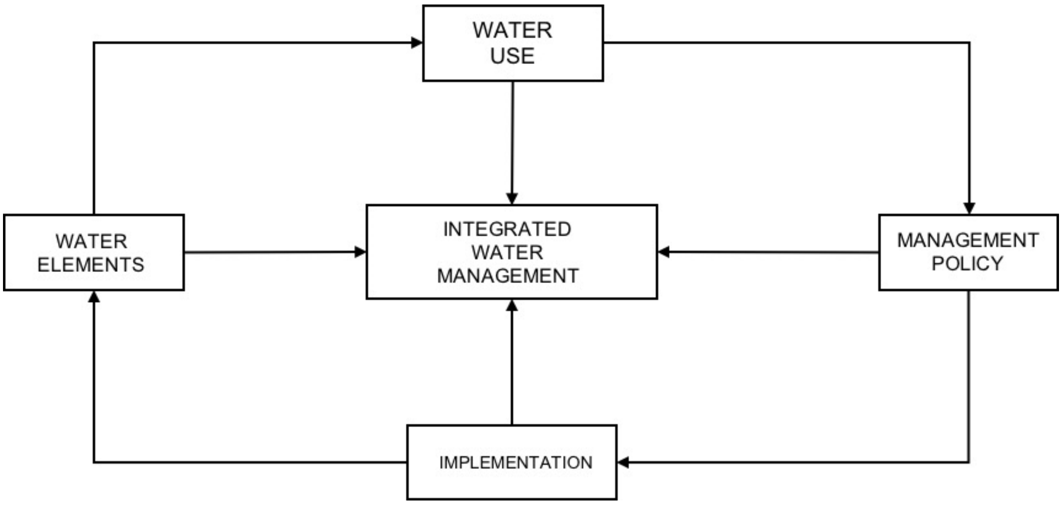


Figure 2.1. Integrated water management (Singh, 1995).

2.1.1. The Classification of Watershed Models

The watershed modelling is the keystone of the integrated water management and there are plenty of the hydrologic watershed models in the literature. Therefore, it requires a classification of the watershed models so that the user can choose one according to the characteristics of the watershed or his/her study area. Three main criteria can be used for the classification of the watershed models, namely; process description, scale and the solution technique.

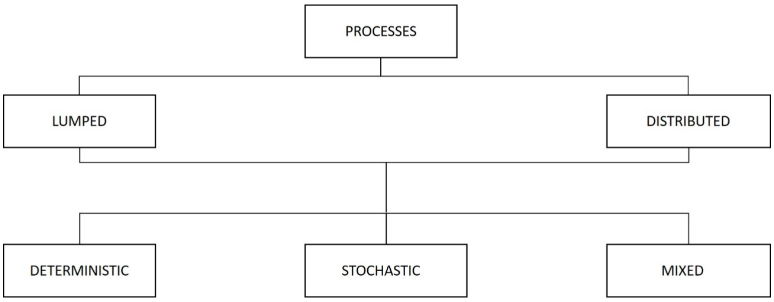


Figure 2.2. Classification of models based on process description (Singh, 1995).

2.1.1.1. Process-Based Classification. The five components encompassing watershed characteristics, the input, governing equations, initial and boundary conditions and the output constitute a model. There are several combinations of these components.

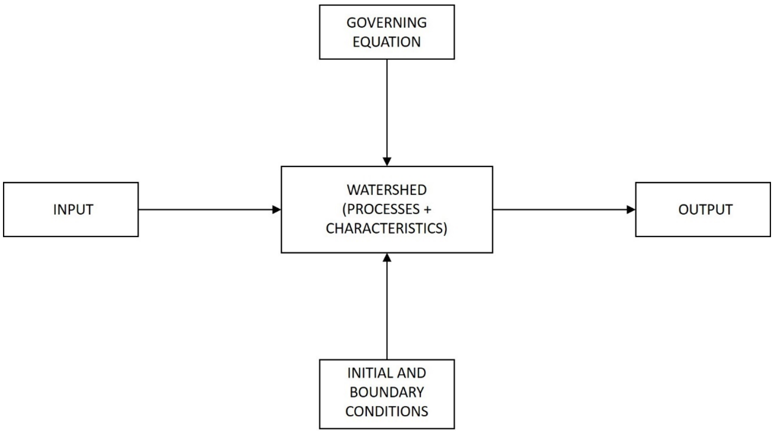


Figure 2.3. Model Components (Singh, 1995).

According to description of the hydrologic processes together with the watershed characteristics, the model might be lumped or distributed, deterministic or stochastic or mixed.

A lumped model is generally stated by ordinary differential equations. The lumped model does not include the spatial variability of processes. Most of the processes are defined by differential equations which are the simplified versions of hydraulic laws; and the rest is described by empirical algebraic equations. On the other hand, distributed models include an explicit account of spatial variability of hydrologic processes. In the Table 2.1, the process-based classifications of the model components are shown.

Table 2.1. Lumped and distributed models (Singh, 1995).

Input	System Characteristics	Component Processes	Governing Equation	Output	Model Type
Lumped	Lumped	Lumped	ODE	Lumped	Lumped
Lumped	Lumped	Distributed	PDE	Distributed	Distributed
Distributed	Distributed	Distributed	PDE	Distributed	Distributed
Distributed	Lumped	Distributed	PDE	Distributed	Distributed

Time-Scale Based Classification: The time scale can be defined as a combination of two time-intervals (Diskin and Simon, 1979). Two different time intervals can be used in the model. The one is for the input and the computation. The other is for the output. Based on this, the models are separated as; continuous-time or event based, daily, monthly and yearly models.

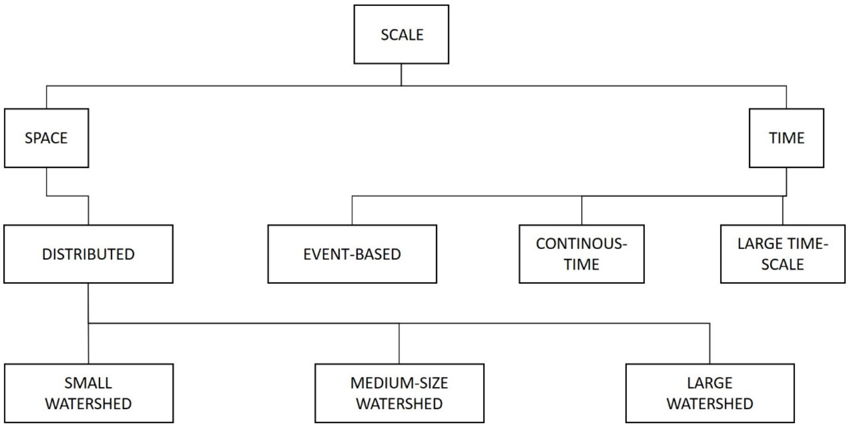


Figure 2.4. Classification of models based on space and time scales (Singh, 1995).

Space-Scale Based Classification: The models can be classified according to the size of a watershed which it covers. The watersheds having less than 100 km^2 are defined as small-watersheds. Those watersheds whose area is between 100 km^2 and 1.000 km^2 are medium-size watersheds. Further, the watersheds having more than 1.000 km^2 are large watershed models. It needs to be noted that this classification is experimental not conceptual.

Land-Use Based Classification: Based on land use, the watersheds may be classified as agricultural, urban, forest and range land, desert, mountainous, coastal, wetlands and mixed (Singh, 1995).

There are also further classification categories used on purpose. For instance, the models can also be classified according to their solution technics.

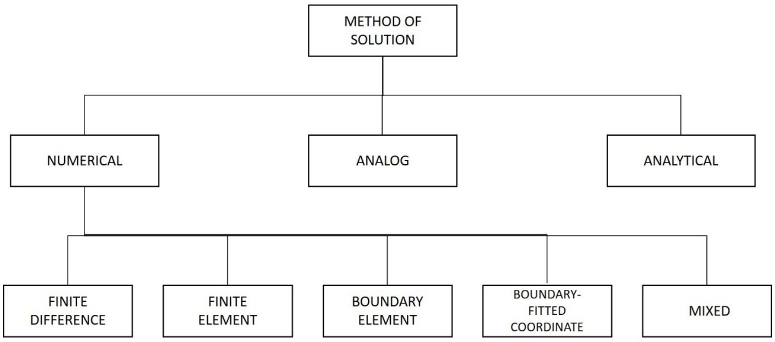


Figure 2.5. Classification of models based on solution technic (Singh, 1995).

2.2. Principals of Hydrological Modelling

As the models become more complex and start to answer more questions by merging scientific findings from different areas, it is needed to define some principals that needs to be followed while developing a model.

2.2.1. Model Structure Selection Process

In this process, the modeler should first select the type of the model weather it is going to be conceptual or physically based model. The two types are formed for different purposes. Physically based models perform better under the conditions where physical parameters are known well and the variability is not high. However, conceptual models which are proper for process studies require much more data than the conceptual ones require.

The conceptual models are adjusted for the basins unlike the physical based models. The approach is that the variability of the physical processes is almost unknown which leads to simple statistics methods. The parameters in a conceptual model are adjusted to represent the average of the large area and try to combine different models and their variabilities. Meaning that, the results of the conceptual models should be taken as a reference index instead of true values. From this point of view, the results of conceptual models can be considered as less confident. On the other hand, the advantage of a conceptual model is that they require much less data which creates high level of applicability in the areas such as hydrology. They are widely used in runoff recording, flood forecast and reservoir operations (Bergstrï¿½m, 1991)

It can be said that physical models rank high against the conceptual ones since they require less calibration of the parameters. Nevertheless, it is more important to have the input data being more accurate and representing the basin. It is very well known that fields like hydrology, geology, land use or topography have extremely high level of variability even for the distributed models (Beven, 1989). All these conditions may force a modeler to use conceptual models.

Nowadays, the conceptual and physical approaches are tried to be integrated while developing a model. The model used in this study (GR4J) is also one of the models having both approaches.

2.2.2. Complexity

The level of complexity in the model is one of the most important decisions taken while developing a model. It has effects on the level of the need for data and the computer capacity. Therefore, the applicability of a model is direct result of the complexity selection. It is known that some complex models do not have significant difference in the solution of the problem (WMO, 1986). At some point, the complexity may become redundant. The complexity of the structure does not have an effect on the accuracy of the simulation results. The high complexity may also cause overparameterization for the basin. In complex nitrogen turnover model, it is seen that the same level of performance could have been obtained by a much more simpler runoff model (Brandt, 1990a).

On the other hand, the situation might be opposition for some cases. The model performance may increase as the level of complexity raises, especially in the case that the model focuses on the total hydrological system instead of a single reservoir basin. As a result, the challenge is to decide necessary complexity of the model. While doing that, it may become difficult to ignore any concept or theory for the implication. At that point, a strategy to develop a model by going more complex from the simple should be used (Nash and Sutcliffe, 1970). The aim is to take one more complexity if it contributes to the model performance. Going from simple to the complex model is extremely useful, especially for the basin-oriented models, as it happened in the development of GR4J from GR3J.

2.2.3. Confidence of the Model

In order to have a confidence to the model, the results should be controlled properly by comparing them with the observation values. Even if the model performs well, it does not ensure that the system used in the model is defined properly. The performance of the model should rely upon the related reasons (Klemes, 1986). The complete available data should not be used and some part should be left aside for the verification and validation. This part may be used as warm-up of the model.

The confidence is milestone of a hydrological modelling and it can only be achieved by testing the model under the variety of different hydrological, geological, climatological and geographical circumstances.

2.2.4. Calibration

Calibration is the process of the adjustment of some coefficients in the model. The process is repeated several times until the results and the observation values come closer. The explained variance, R^2, is described as a statistical criterion to match the simulation and observation values (Nash and Sutcliffe, 1970). This statistical approach is a raw estimate of the model performance and it is time-specific for a defined time interval. Furthermore, the best way to illustrate the model result is to compare them with the observation data in the same graph.

The problems of overparameterization should be avoided. Sometimes, there might be too much degrees of freedom according to the information defined in the observed data.

2.2.5. Extremes and Peaks

For some cases, the model cannot be controlled due to the lack of available data and the high level of uncertainties. These cases can be named as extreme floods and long-term environmental effects.

If a hydrological model tries to calculate of extreme floods, it faces a lot of uncertainties which need to be taken into consideration. In order to have better performance for such an extreme flood, the hydrological conditions described in the model should represent the extreme circumstances as well. Moreover, the model should be tested with the data outside the range of calibration data. This is also the reason why most of the models have low performance on the peak values.

The hydrological models can also be used for the estimation of environmental effects like the contamination or acid precipitation etc. In this kind of estimations, the uncertainties increase in the model and the verification of the model becomes a challenge. Much more detailed data is required in that case. For instance, the determination of flood risks is most likely related to timing of extreme precipitation and the soil moisture rather than general increase. It can be seen from Figure 2.6 that the accuracy mostly depends on the timing of the hydrological processes for flood generation.

2.2.6. Sensitivity Analysis

Sensitivity analysis is a crucial point of the model development. The results of the sensitivity analysis show the insignificant effect of some parameters. Therefore, it provides model simplicity by creating a possibility to exclude some parameters. The sensitivity analysis helps defining the stability of the results according the uncertainties which the model has.

Sensitivity analysis can be made in two ways. First one is to compare visually the different results of the different assumptions in the graph. The second is the mapping of the error function of the topography relying on the criterion measuring the variance between simulation and observation (Bergstrï¿½m, 1991).

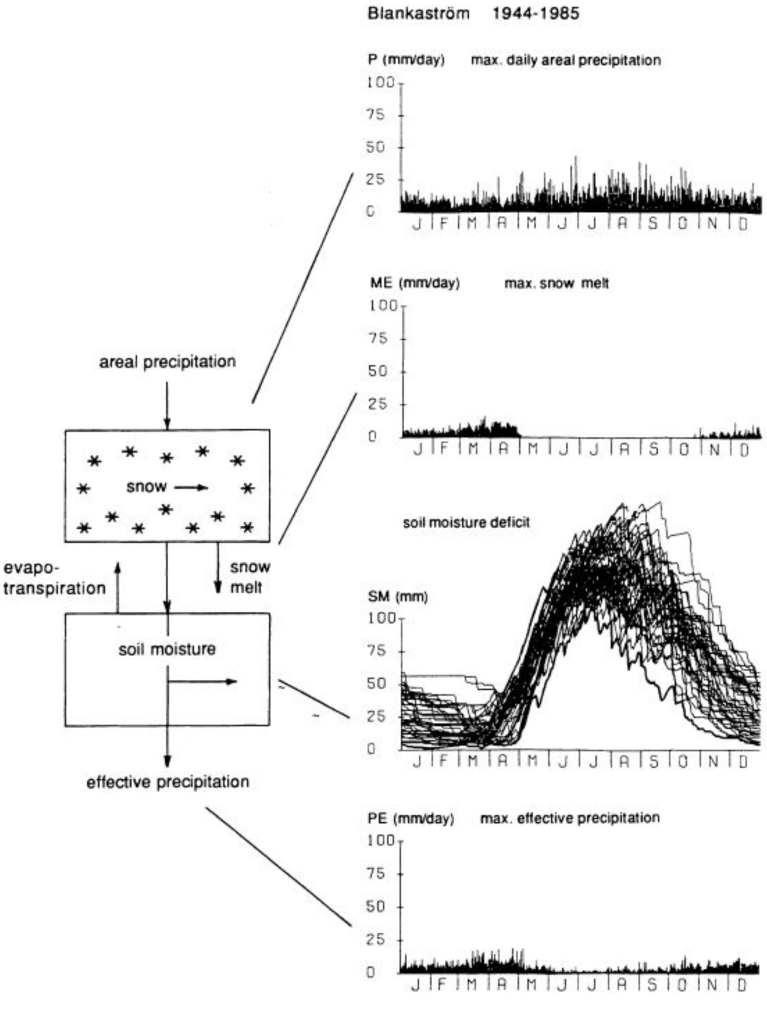


Figure 2.6. Maximum daily areal precipitation and model simulation of maximum snow melt, soil moisture deficit and maximum effective precipitation for Blankastrï¿½m river in southeast Sweden (Bergstrï¿½m, 1991).

2.3. The Model HBV

The HBV model which is a semi-distributed conceptual model is one of the second generation of models. It tries to contain the most significant runoff producing processes. The HBV model takes these processes as their simplest and most robust forms. The model includes subbasins, an area-elevation and a few types of the land use. The subbasins are the basic hydrological units that the model uses. There are three different components which form the model. These are snow accumulation and melt, soil moisture accounting and river routing.

The model consists of several free parameters. These free parameters are calculated by calibration. The model has also other parameters like coefficients trying to represent the features of the basin and its climatology. These parameters should remain same when free parameters are calibrated. In order to avoid having very large number of free parameters from each subbasins, same group of free parameters can be used due to the limited variability of the parameters. The general structure of the HBV model can be seen in Figure 2.7.

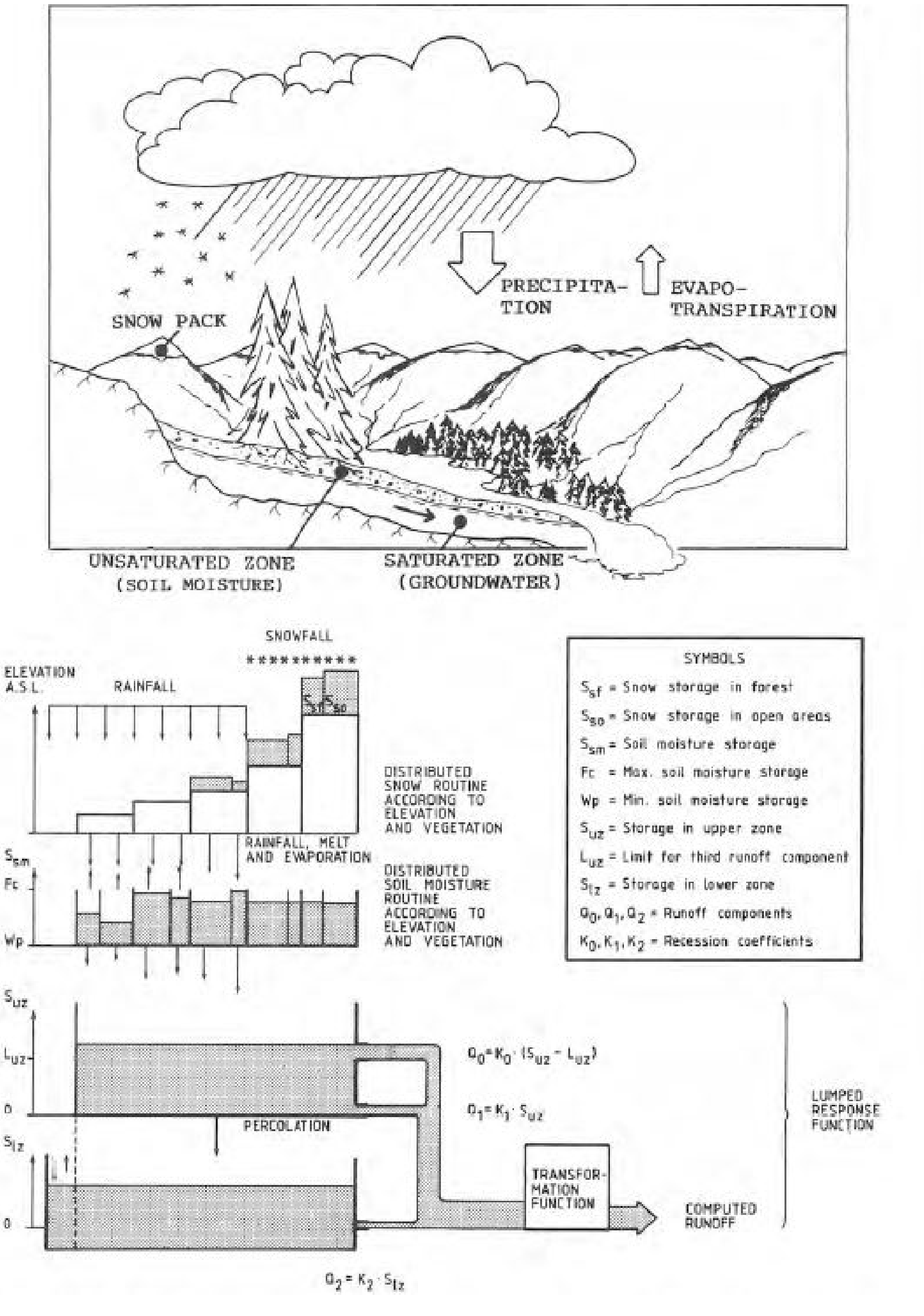


Figure 2.7. The general structure of the SMHI version of the HBV when applied to one subbasin (Bergstrï¿½m, 1992).

2.3.1. Data and Structure of HBV Model

The HBV model runs with the daily time steps unless there is more detailed data. Precipitation and the air temperature are the input data of the model. Air temperature is needed to distinguish the areas covered by snow. Moreover, the potential evapotranspiration is demanded for the soil moisture accounting routine. Monthly standard values can be used for this purpose. The data of potential evapotranspiration can be calculated by Penman formula or measured by existing stations in the field. In the case that potential evapotranspiration is measured by evaporimeters, the data should be corrected to avoid any systematic errors. The climatological and topographical data must be averaged spatially for each subbasins. Simple weighing procedure is made either by climatological and topographical consideration or Thiessen polygon method. Following, the averaged data should be corrected for the different altitudes by constant lapse rate which is defined as -0.6C per 100 meters.

For the snow routine of the model, a threshold value is defined and precipitation is taken granted as snow accumulation when the air temperature is under the threshold value. Snow accumulation is tuned by a free parameter, CSF, the snowfall correction factor to include snow precipitation and winter evaporation. The simple degree-day approach is used for the estimation of the snow melt when the air temperature goes above the threshold value.

$$MELT = C_{MELT}(T - TT) \tag{2.1}$$

where $MELT$ is the snowmelt expressed in mm/d, C_{MELT} is degree-day factor and TT is the threshold temperature.

Even the snowmelt occurs, it needs to exceed the liquid water which holds the snow capacity in order to generate any runoff. Th liquid water holding capacity of snow is generally predefined as 10%. The model also includes the refreezing coefficient if the snowmelt cannot continue. Therefore, there are three free parameters needs to be calibrated inside the snow routine of the model. These are C_{SF}, C_{MELT} and the threshold value. If the basin modelled is divided to more than one vegetation zones, the number of free parameters is multiplied (Singh, 1995). The snow routine of the HBV model has been modified for the further version of the model to be used in the located-oriented purposes (Killingtveit and Aam, 1978).

For the soil moisture accounting routine, the HBV model calculates the moisture of the whole basin as an index. The model further merges the interception and soil moisture storage. The soil moisture routine is tuned by three free parameters. These are FC (soil moisture storage in the basin), BETA (relative contribution to the runoff) and LP (the shape of the reduction curve for potential evapotranspiration) which are illustrates in Figure 2.8.

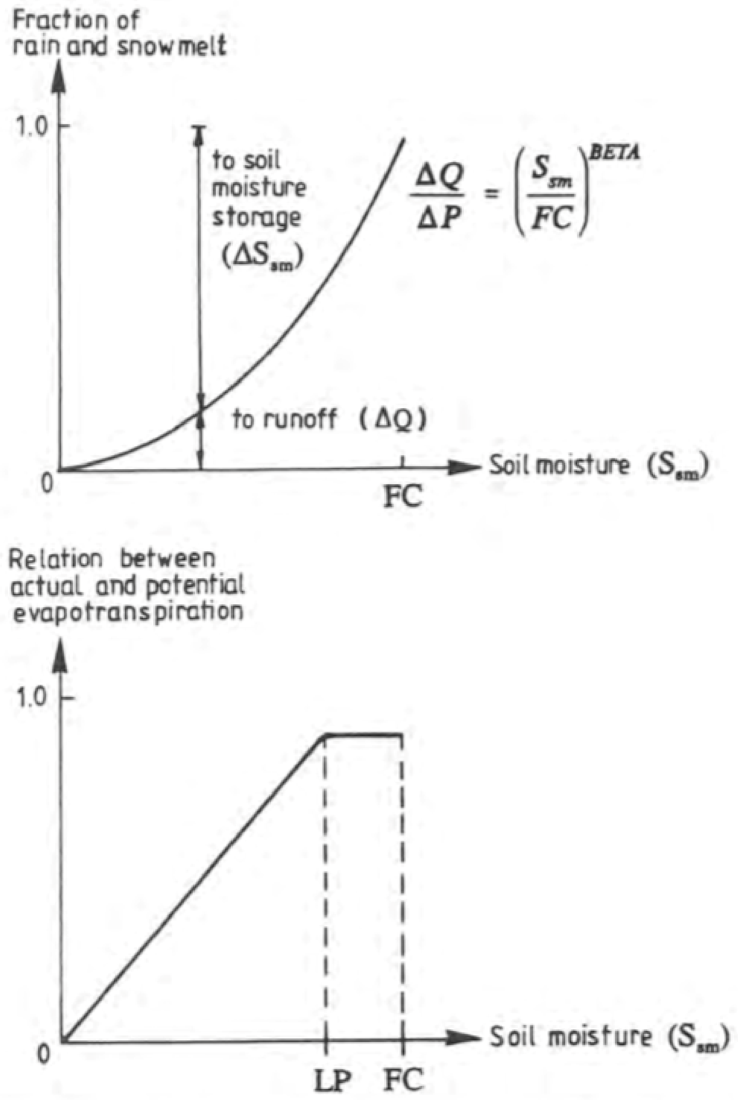


Figure 2.8. Soil moisture accounting routine of HBV model; FC, LP and BETA are empirical parameters (Bergstrï¿$\frac{1}{2}$m, 1992).

In addition, the evapotranspiration routine of the model has been modified in order to have better model performance especially when the observed data is extreme.

For instance, the spring and summer might be much colder or much hotter than the data range. This routine corrects the temperature deviations with the help of mean daily temperatures and long terms averages (Lindstrï¿½m and Bergstrï¿½m, 1992).

$$PE_A = (1 + C(T - T_M))PE_M \tag{2.2}$$

where PE_A is the adjusted potential evapotranspiration, C is the empirical model parameter, T is the daily mean air temperature, T_M is the monthly average temperature and PE_M is the monthly long-term average potential evapotranspiration.

As a last step of the model calculation for the simulation, runoff response routine of the model calculates excess water and distribute it to each subbasins. This runoff response routine has two reservoirs and five free parameters. These are there recession coefficients; K_0, K_1, K_2; a threshold (UZL) and the infiltration rate (PERC). Then, the generated flow needs to be filtered for smoothing by triangular weighting function which has one free parameter, MAXBAS. The procedure can be seen in Figure 2.9.

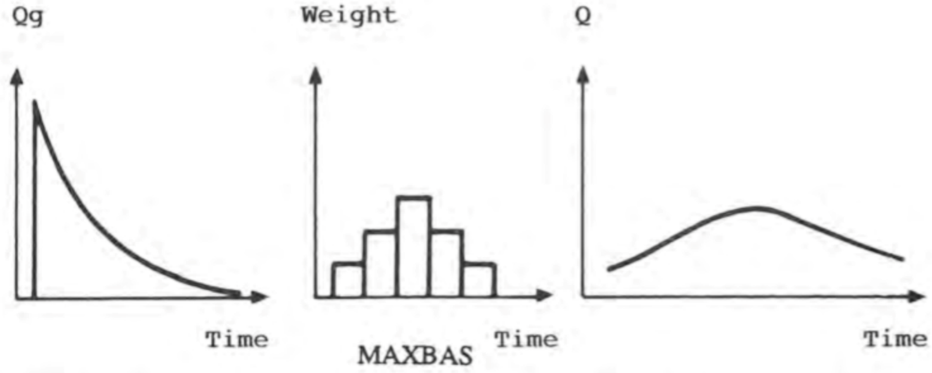


Figure 2.9. Generated runoff is smoothed by model parameter MAXBAS (Bergstrï¿½m, 1992).

Further routines can be included in the model, for case-specific purposes. The lower model reservoir might include the lakes in the subbasins which can easily be modelled explicitly with the help of storage-discharge relationship. The representation of this further routine can be seen below.

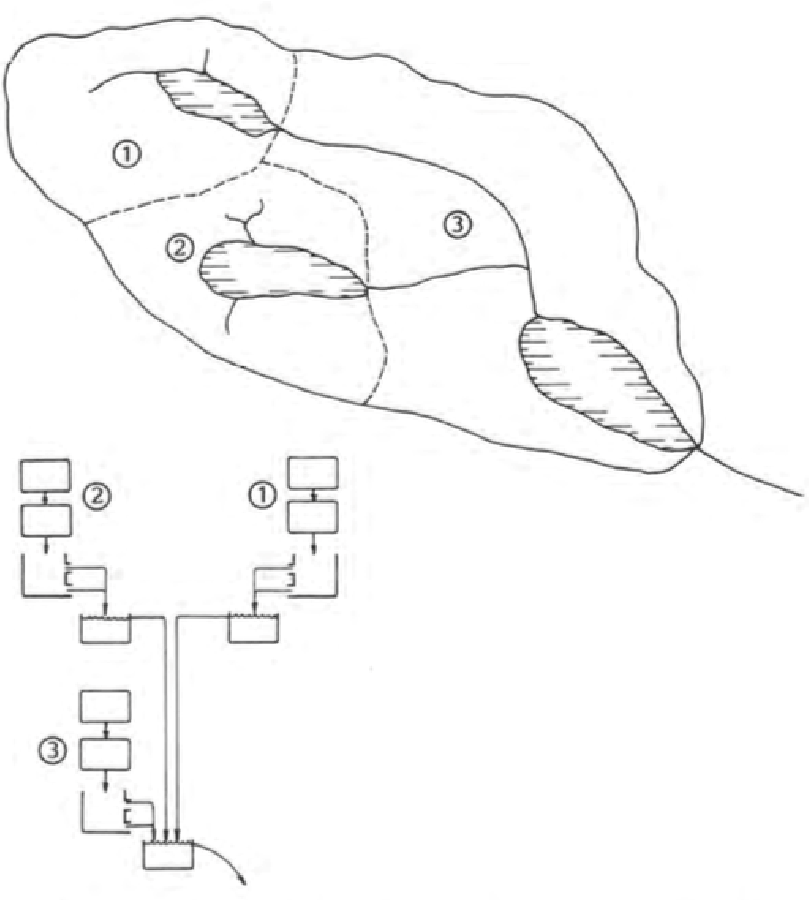


Figure 2.10. The subdivisions of the model into submodels when an explicit lake routing routine is used (Bergstrï¿½m, 1992).

2.3.2. Calibration of HBV Model

There are 12 free parameters with its routines in the HBV model having only one basin and one vegetation zone. In fact, there is a risk of overparameterization for the HBV model. The calibration of the model parameters can be made with trial and error technic and the performance can be evaluated according to the statistical criterion (Nash and Sutcliffe, 1970):

$$R^2 = \frac{\sum\left(\overline{Q_o} - Q_o\right)^2 - \sum\left(Q_c - Q_o\right)^2}{\sum\left(\overline{Q_o} - Q_o\right)^2} \tag{2.3}$$

R^2 value is calculated as 1 in the case that the observation values and simulation values are matched. If R^2 value is 0, this means that the parameters do not perform better than the average values. Negative value means even worse performance of the model.

At the end, the model output is illustrated on the graph and can easily be compared with the observation values. It is also important to present input data so that the effects of the change input can be seen visually. Further, the forecasts of the simulation can be presented. One example of the HBV graph presentation can be examined in Figure 2.11.

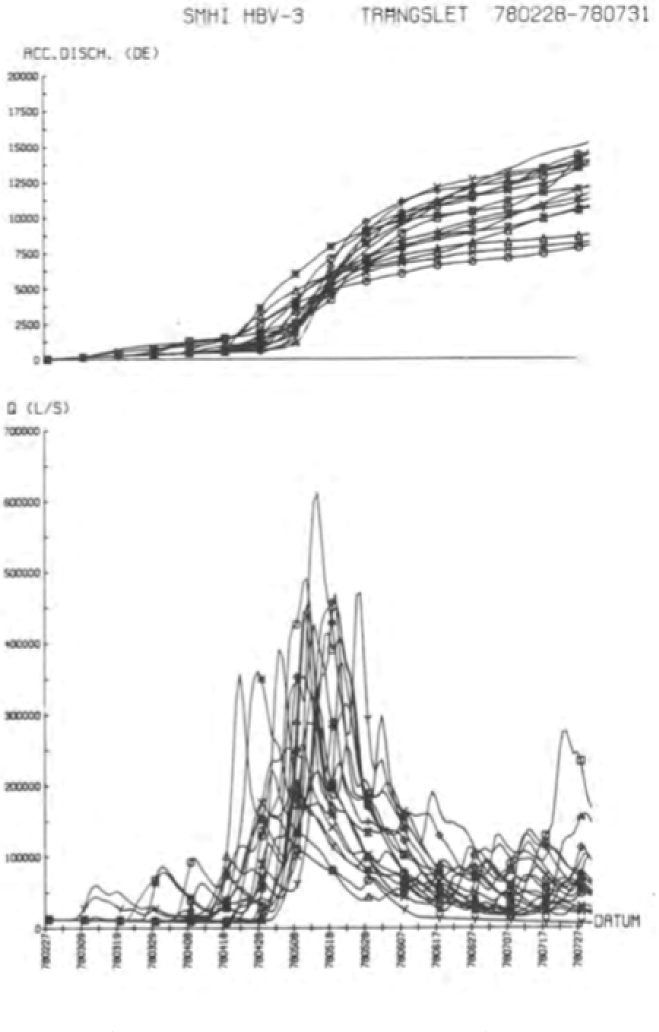


Figure 2.11. Example of a long-range hydrological forecast by HBV (Bergstrï¿½m, 1992).

2.4. The Model SRM

The Snowmelt Accounting Runoff Model (SRM) is used in order to simulate and make a forecast streamflow of a basin in terms of daily parameters. SRM is largely used in mountainous basins where the snow accumulation dominates the streamflow calculation. SRM which was first designed for small European basins demands remote sensing input (Martinec, 1975). As the development of satellite remote sensing of snow-covered areas, SRM has started to be used for larger basins. Currently, the model has become one of the most used hydrological models globally. SRM is indicated successful in terms of the real time runoff forecasts (WMO, 1992).

2.4.1. Model Structure

The amount of water generated due to the snowmelt and direct rainfall is calculated daily. Later, it is added to the calculated recession flow and converted to the daily discharge from the basin. The equation can be seen below.

$$Q_{n+1} = [c_{Sn} \times a_n(T_n + \Delta T_n)S_n + c_{Rn} \times P_n] \frac{A_A \times 10000}{86400}(1 - k_{n+1}) + Q_n \times k_{n+1} \quad (2.4)$$

where Q is the average daily discharge, c is the runoff coefficient representing the losses in terms of runoff divided by precipitation; c_S is for snowmelt and c_R is for rain, a is the degree-day factor referring to snowmelt depth, T is the number of degree-days, S is the ratio of snow covered area to the total area, P is the precipitation which contributes to runoff, A is the area of the basin and k is the recession coefficient which represents the decline in the discharge when there is no snowmelt or rainfall.

P, S and T are the variables which need to be measured or determined at the beginning of the model. cR, cS, ΔT and k are the parameters which change from basin to another. In case that the elevation of the basin is bigger than 500 m, the basin should be subdivided into elevation zones for each 500 m. Therefore, Q is calculated for each zone.

2.4.2. Data for Running SRM

2.4.2.1. Variables. Temperature and degree-days (T), precipitation (P), and snow-covered area (S) are the variables of the model.

Firstly, it is needed to calculate daily snowmelt depth and the numbers of degree-days can be determined from the measurement. The model has two options; using the mean value of temperature and using both max and min values of the temperatures. The temperature values are then extrapolated for different elevation zones by using the temperature lapse rate and the altitudes. In case that the degree-day numbers become negative, the model set this variable to zero so that the model prevents any negative snowmelt.

Secondly, precipitation values should be set to the model. However, it is difficult to have realistic representative of the areal precipitation especially for the mountainous basins. SRM is modified in the way that the snowmelt as an input dominates the model much more than the direct runoff from precipitation. This may lead to miscalculation in the model when heavy rainfall and consequently strong peaks occur in the basin. This point of the model should be taken into consideration. Furthermore, a critical temperature value (T_CRIT) is defined in the model in order to determine if the precipitation is rainfall or snowfall. When the precipitation is determined as snowfall, its effect on the runoff is delayed in the model and it is added to snowpack.

Snow-covered area which is the third variable of the model declines gradually throughout the melting season. The curves of snow-packed area can be examined and the daily values which are the important inputs of SRM can be derived by interpolation. The snow cover is determined by remote sensing. It can be terrestrial observation, aircraft photography and satellite. Thanks to the improvement of satellite systems, SRM has become a model widely used.

2.4.2.2. Parameters. Different from other hydrological models, the calibration or optimization processes of the historical data are not made in the SRM. The parameters can be measured or estimated from the basin characteristics or empirical regression analysis. There are seven parameters in the SRM model, namely; runoff coefficient, degree-day factor, temperature lapse rate, critical temperature, rainfall contributing area, recession coefficient and time lag.

Runoff coefficient (c) measures the difference between total water volume of snowmelt as well as rainfall and the outflow of the basin. Degree-day factor (a) transforms the number of degree-days into the daily snowmelt depth. Degree-day values and the daily decline of the snow water equivalent are compared and hence, the degree-day ratio can be assessed. Temperature lapse rate (γ) is used when the temperature is defined for a specific altitude. It can be biased from the historical data. In SRM, 0.65^{o}C per 100 meter is accepted as temperature lapse rate. Critical temperature (T_CRIT) is used whether the precipitation is snowfall or rainfall. It is needed in SRM during snowmelt season. Rainfall contributing area (RCA) is determined according to whether the snowmelt season is just started or about to be end. Either rainfall is fell on snowpack or when rainfall occurs, same amount of water is also released from the snowpack. Recession coefficient (k) is one of the most important parameters of the SRM. $(1 - k)$ is the proportion of the daily meltwater production. k can also be determined by using the historical data. Time lag (L) is the representation of the daily fluctuations of snowmelt runoff. The time lag can be obtained from existing hydrographs.

2.5. Conclusion of the Literature Review

As time passes, the understanding and analyzing of real-world components by human being is increased. Thanks to the modelling technics, this process is drastically triggered as the real-world components are simplified. In order to that, it is first needed to categorize the different way of modelling technics. Each of them is formed on purpose. Moreover, the principals that need to be taken into consideration while modelling a real-world hydrologic component are presented in this literature review.

In hydrological modelling literature, HBV and SRM models are most common used models. Both models have been improved by the continuous efforts as computer systems also develop. As mentioned above, both models have several parameters which are calibrated by existing data. In addition to their usefulness and their successful history, they have a possibility of overparameterization that needs to be paid attention by the users.

3. THE MODEL COMPOUND OF GR4J-CEMANEIGE

3.1. Methodology

The model compound of GR4J and CemaNeige snow accounting routine (SAR) is based on mostly empirical lines. During the choice of a modelling approach, model structure assessment and the complexity of the model are assumed fundamentally. For the model and SAR, the empirical approach defined by Nash and Sutcliffe (1970) is chased. The approach simply starts from the basic one and tries to improve the efficiency after testing model modification one by one. Later, it suggests that the model needs to be improved by keeping the most satisfactory modification. In this approach, the additional parts are embedded to the model only in case of an increased versatility which causes a better fit between observed and computed output values. This modelling process has also a same direction with the system identification approach which suggests to start with simple assumption and calculate the modifications as reaching the observed values (Jakeman et al. 1994).When there is no any additional information, the improvement of an empirical model by trial and error approach has most likely low benefit/cost ratio as the modification is applied (Klemes, 1982). However, it is useful in order to control the relevance of model developments by the additional information provided by the large spectrum of the catchments which forces to test the model with several catchments. This approach is also used in HBV model configurations. (Bergstrï¿½m, 1991 and Lindstrï¿½m *et al.*, 1997). The methodological developments of the model GR4J and snow accounting routine CemaNeige are explained separately below.

3.1.1. The Methodology of GR4J

The quantitative evaluation of a model may become difficult. Instead, it is better to evaluate its performances in a comparative method. Therefore, the model GR4J is evaluated according to comparative approach. 429 catchments from different climatic and geographical conditions with their time interval which ranges between one and eight are taken. Following, the dataset is halved and 3204 simulation tests are held in a comparative way. The results are evaluated according to five criteria.

CR1 is the classical Nash-Sutcliffe criterion and given by:

$$CR1(\%) = 100\left(1 - \frac{\sum\limits_{i=1}^{n}\left(Q_{obs,i} - Q_{cal,i}\right)^2}{\sum\limits_{i=1}^{n}(Q_{obs,i} - \overline{Q_{obs}})^2}\right) \tag{3.1}$$

where $Q_{obs,i}$ and $Q_{cal,i}$ are the observed and calculated streamflow values respectively at a time step i, Q_{obs} is the mean observed streamflow value over n number of time steps.

CR2 is the Nash-Sutcliffe criterion calculated on square root transformed streamflow (Chiew and McMahon, 1994).

$$CR2(\%) = 100\left(1 - \frac{\sum\limits_{i=1}^{n}\left(\sqrt{Q_{obs,i}} - \sqrt{Q_{cal,i}}\right)^2}{\sum\limits_{i=1}^{n}(\sqrt{Q_{obs,i}} - \overline{\sqrt{Q_{obs}}})^2}\right) \tag{3.2}$$

CR3 is the Nash-Sutcliffe criterion calculated on the logarithm transformed streamflow. This criterion is beneficial for the model trying to make forecasts (Ye *et al.*, 1997).

$$CR3(\%) = 100\left(1 - \frac{\sum\limits_{i=1}^{n}\left|Q_{obs,i} - Q_{cal,i}\right|}{\sum\limits_{i=1}^{n}\left|Q_{obs,i} - \overline{Q_{obs}}\right|}\right) \tag{3.3}$$

CR4 is a criterion of absolute error. It quantifies the capability of the model if it can simulate streamflow values over the designated period.

$$CR4(\%) = 100\left[1 - \left|\sqrt{\frac{\sum\limits_{i=1}^{n} Q_{cal,i}}{\sum\limits_{i=1}^{n} Q_{obs,i}}} - \sqrt{\frac{\sum\limits_{i=1}^{n} Q_{obs,i}}{\sum\limits_{i=1}^{n} Q_{cal,i}}}\right|\right] \tag{3.4}$$

Lastly, CR5 is a water balance criterion. The values of all criteria change between $]-\infty, 1]$ for the model. The value of 1 means the perfect agreement. The performances of different GR4J models are compared to 19 lumped rainfall-runoff model tested. A hypothetic model is also defined to indicate the upper bound of the performance (Perrin *et al.*, 2001a). Figure 3.1 illustrates the distribution of the results gathered for all models for CR2.

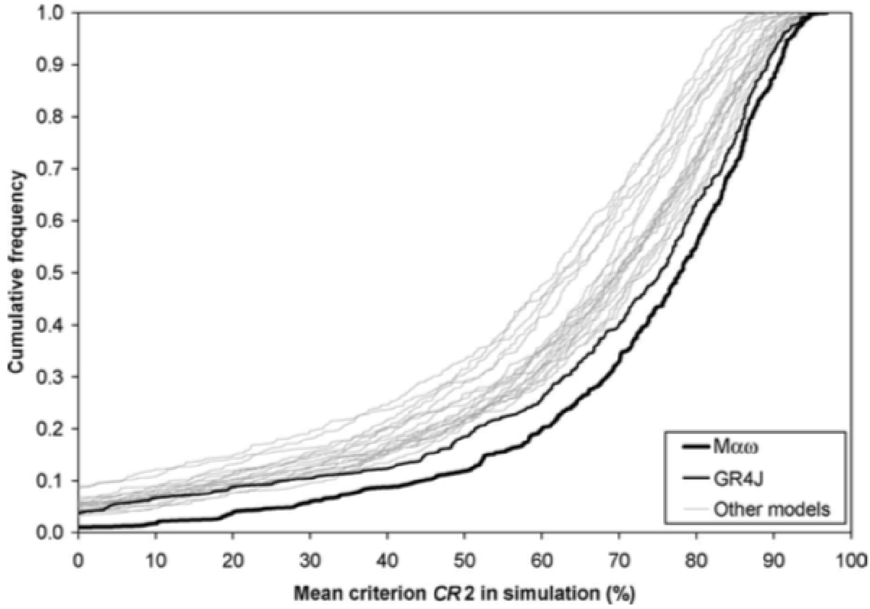


Figure 3.1. Distribution of mean performances per catchment obtained in simulation with criterion CR2 (Perrin *et al.*, 2003).

As the distribution of a model gets closer to the hypothetic model, the performance of that model is better. Hence, the graph shows that GR4J performs better than other 19 model versions (Perrin *et al.*, 2003). Table 3.1 shows the mean performances of GR3J and GR4J models in terms of five criteria by testing them on 429 catchments. To quantify the development, statistic approach is used (Senbeta *et al.*, 1999).

$$r^2 = \frac{R_2 - R_1}{1 - R_1} \tag{3.5}$$

where R_1 and R_2 are the efficiencies of GR3J and modified version which GR4J at the end accordingly. r^2 which is bigger than 0.10 indicates important development of the model performance. It is seen that the model performances are improved for each criterion. The improvement of the model is the greatest in case of CR3. Meaning that, GR4J performs better for the simulation of low flows thanks to the definition of the percolation function. Table 3.1 is sufficient itself to show the validation of the GR3J modification which is GR4J.

Table 3.1. Mean performances of the GR3J and GR4J models and estimation of performance improvement (Perrin *et al.*, 2003).

	GR3J	GR4J	r2
CR1 (%)	47.0	51.0	ï¿½7.5
CR2 (%)	58.6	61.9	ï¿½7.8
CR3 (%)	52.6	57.5	ï¿½10.3
CR4 (%)	50.0	52.2	ï¿½4.4
CR5 (%)	78.4	79.0	ï¿½2.9

Parallel to its previous versions in the GR4J model, mathematical operators are combined in order to obtain the best forecast of the actual runoff transformation output by comparing the observed values. The first task is to prevent any misconceptions caused by the application of the known hydraulic theories with unknown boundary conditions. The model GR4J basically tries to imitate and represent catchment behavior using a single reservoir (Michel, 1983). For this purpose, 235 modified versions of the model GR3J which is the predecessor of the GR4J were tested in total (Perrin *et al.*, 2003) to imitate the catchment reality along with testing of a large number of very simple formulations.

As an example of empirical model modification, the water exchange function described in the model GR3J assumes that ideally few catchments are segregated bodies, instead they are underlaid by impervious substratum. The water exchange function is eventually developed to form a satisfactory water balance on all types of the catchment (Nascimento and Michel, 1992).

The model validation can only be achieved according to its performance in different conditions and it is quite tricky to include every condition of the catchments. For this purpose, while developing GR4J, a wide range of hydrological data set has been used in order to form the empirical approach. The data set includes a few hundred catchments located in different climatic and geographical conditions. Further, the extreme weather conditions can change the behavior of the catchment which act likely a catchment from completely different conditions. Hence, the model performance should be high in various conditions. This is either explicitly or implicitly accepted by several hydrological works dealing with the models in different conditions (Chiew *et al.*, 2002).

Further point of the model developing is to take the influence of complexity into consideration on the efficiency of the model. The complexity of the model can be seen as the number of parameters that needs to be optimized (Kokkonen and Jakeman, 2001). Too much model parameters may cause in the overparameterization and ill-conditioned problems during optimization. The number of parameters from three to five is found to be sufficient to obtain acceptable results of streamflow simulations at a daily time step (Perrin *et al.*, 2001a). Since GR4J is the modification of GR3J model, the ultimate complexity is decided according to the success of the simulation mode by testing several versions having different parameters. 235 different model structure are first derived from GR3J and later all of them are tested with 429 catchments gathered from different conditions. The complexity levels of these versions are compared and it ranges between zero and six optimized parameters (Perrin *et al.*, 2003). Figure 3.2 illustrates that the simulation mode tested for criteria CR1, CR3 and CR5 and; their performances in these criteria.

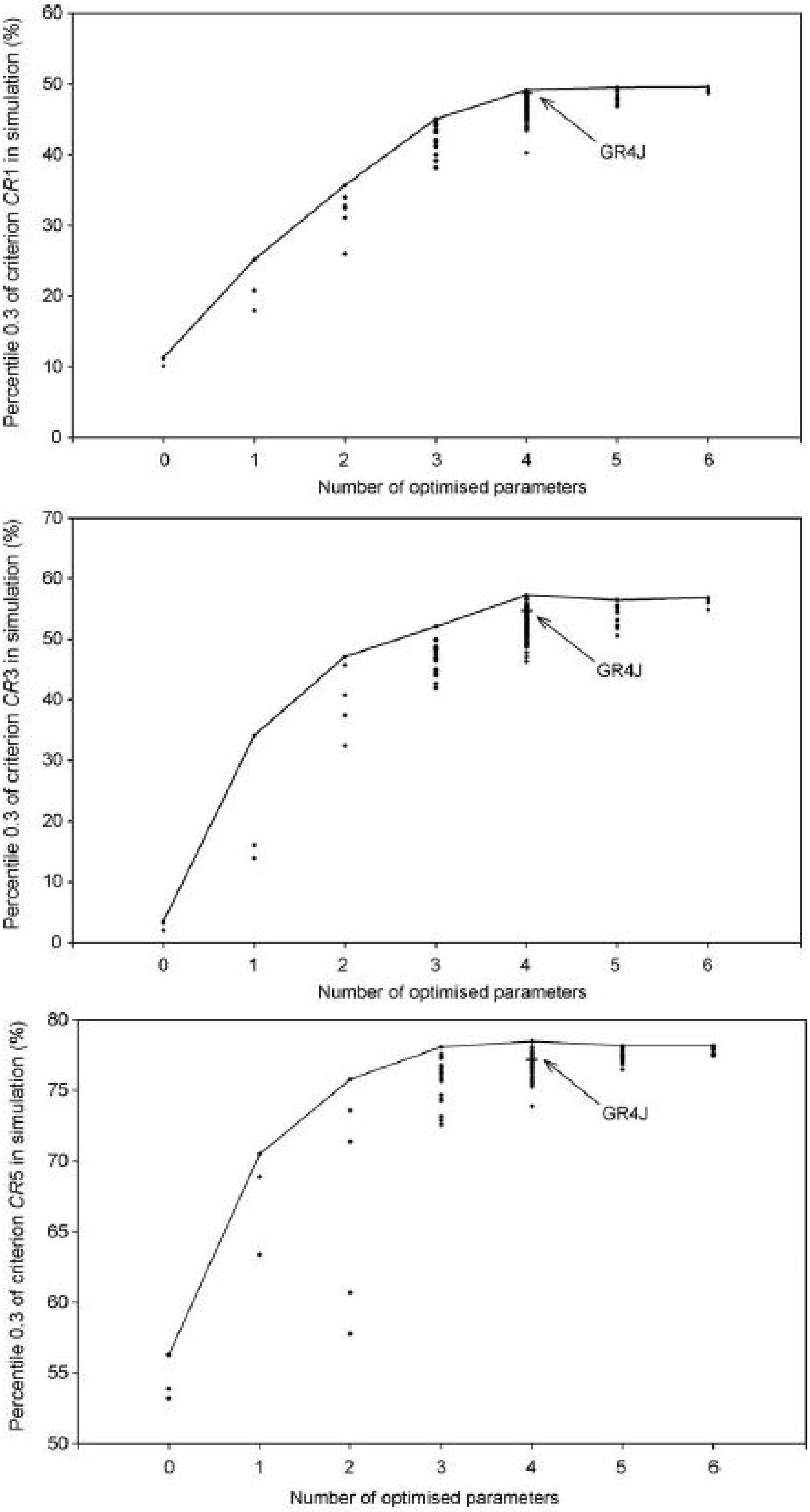


Figure 3.2. Percentiles 0.3 of criteria CR1, CR3, CR5 for the optimization of parameters (Perrin *et al.*, 2003).

In the comparison, the percentiles of 0.3 of the distribution of results are used. Mean performances are avoided to be used since they are less illustrative as the model decreases because of negative efficiency values. As it can be seen easily, the performance increases rapidly from zero parameters to four. However, it doesn't tend to increase by fifth and sixth parameters and even decreases for CR3 and CR5 criteria. Therefore, four parameters are decided to be the most reliable of complexity (Perrin *et al.*, 2003). It also approves that the parsimonious model is satisfactory to model the catchment behavior (Kokkonen and Jakeman, 2002).

3.1.2. Methodology of CemaNeige Snow Accounting Routine

There are two classification of the methods to calculate snow accumulation and melt, namely; temperature index and energy budget. The temperature index method integrates indirect measurements of energy fluxes. On the other hand, energy budget method details the components of complete energy budget (Braun and Lang, 1986). Later, a hybrid approach which combines a radiation term with degree-day relation is presented (Hock, 2003). Although it is widely accepted that the degree-day method is sufficient approach to forecast at catchment scale and greater time steps, the temperature-based methods are mostly used in the hydrology thanks to the availability of the input data. CemaNeige makes the analysis by using temperature-index methods since the purely physically-based energy balance methods cannot be held. CemaNeige tries to compute the snow-melt at a local scale and the snow-melt on the entire snow-covered area (Anderson, 1973; Martinec and Rango, 1981).

During the development of CemaNeige, the comparative assessment is made by using 380 catchments from four countries, namely; France, Canada, Sweden and Switzerland. The data gathered for these catchments is used in two hydrological models with six different SARs. The hydrological models are GR4J (Perrin *et al.*, 2003) and HBV (Bergstrï¿½m, 1995).

The catchments included in this dataset display different features which increase the versatility of the comparative assessment. For the most of the catchments included from France, few of the precipitation is snow while 30 catchments from Switzerland show strong mountainous features. 94 catchments from Sweden are in high latitude and they show Nordic characteristics. The area is covered by snow during the most of the season. 36 catchments are included from Canada where very cold winter and hot summer conditions are experienced. During catchment selection period, the possible interaction and combination with non-snow related processes which may have an effect on streamflow are avoided (A. Valéry *et al.*, 2014).

After the dataset, a classical calibration/validation approach and the split sample test procedure is followed (Klemes, 1986). The data for each catchment is halved in terms of time period for calibration and validation. Meaning that, calibration and validation tests are performed twice for each catchment. The parameters of SAR and rainfall-runoff models (GR4J, HBV) are optimized at same time by using the local search algorithm (Edijatno *et al.*, 1999).

In order to evaluate the efficiency, the objective function is used (Nash and Sutcliffe, 1970). The criterion is calculated on root-square transformed streamflow because high and low flows should be computed and the results of the root-square transformed streamflow are acknowledged in both cases (Oudin *et al.*, 2006).

$$NS_{rQ} = 1 - \frac{\sum_{j=1}^{N} \left(\sqrt{Q_{obs}(j)} - \sqrt{Q_{sim}(j)}\right)^2}{\sum_{j=1}^{N} \left(\sqrt{Q_{obs}(j)} - \overline{\sqrt{Q_{obs}}}\right)^2} \tag{3.6}$$

where Q_{obs} is the observed daily runoff and Q_{sim} is the simulated daily runoff for the day j. Since large dataset is used, bounded version of the NS-type criteria is used. The transformed values change between -1 and 1 while it was previously $-\infty$ and 1. This transformation makes possible to analyze mean values over the catchment by ignoring highly negative values for the catchments (Mathevet *et al.*, 2006).

$$C = \frac{NS}{2 - NS} \tag{3.7}$$

The classical Nash-Sutcliffe criterion is used in order to evaluate the efficiency. It is computed for all time steps of the date period and the root-square transformed streamflow (NS_{year}) is considered. By doing this generalization, the evaluation of SAR might not be reflected very well because the snow influence on streamflow is remarkable during only specific time period of a year. Therefore, it is decided to separate two sub-periods of calculation and to take two additional snow specific criteria; NS_{snow} and NS_{melt} (A. Valéry *et al.*, 2014).

NS_{snow} is calculated on the half year affected by snow. The goal is to include performance assessment throughout snow accumulation and snowmelt periods. Since all catchments are in the northern hemisphere. The criterion can be computed over first half of the year. NS_{snow} is computed from 1^{st} of December to 31^{st} of May (A. Valéry *et al.*, 2014).

NS_{melt}, the second snow-specific criterion, is computed over the period of the year when snow melts. Since the melting is an input to the model from the point of view of operation, this period is the most critical one. Moreover, melting period is much shorter than the snow accumulation period. Snowmelt period basically depends on air temperature variability. This dependence causes that snowmelt period changes from one year to another and for one basin to another. Two months sub-periods are described for each catchment. For the catchments from France the criterion is calculate from 1st of February to 31st of March whereas NS_{melt} is calculated from 1^{st} of April to 31^{st} of May for the other catchments (A. Valéry *et al.*, 2014).

Table 3.2. Mean performances over 380 catchments by models without any snow routine and with one of snow routines (A. Valery *et al.*, 2014).

Hydrological models	Assessment Criteria	SAR option (number of optimized parameters)						
		No snow	MOHYSE	CEQUeau	HBV	NAM	MORD4	MSNE
		routine (-)	-1	-3	-3	-3	-4	-7
GR4J	C_year	0.415	0.640	0.657	0.671	0.668	0.692	0.681
	C_snow	0.285	0.580	0.606	0.615	0.633	0.652	0.634
	C_melt	0.157	0.481	0.504	0.535	0.576	0.576	0.547
HBV	C_year	0.348	0.560	0.590	0.600	0.543	0.607	0.598
	C_snow	0.221	0.504	0.545	0.561	0.516	0.567	0.549
	C_melt	0.122	0.425	0.470	0.493	0.462	0.500	0.485

In Table 3.2, it can be seen that the introduction of a SAR for both hydrological models increase the efficiency drastically by evaluating with different periods. MORD4 snow accounting routine performs the best with the model GR4J. This increase in the efficiency shows the necessity of a snow accounting routine integrated to the hydrological model.

3.2. Model Structure

3.2.1. The Structure of Model GR4J

The GR4J model (modéle du Génie Rural a 4 paramétres Journalier) is a daily lumped four-parameter rainfall-runoff model (Perrin *et al.*, 2003). It is the continuation of soil moisture accounting models. The GR4J model which was successfully modified by Perrin (2003) is the revised version of the GR3J model presented by Edijatno and Michel (1989) and later developed by Nascimento (1995) and Edijatno *et al.*, (1999).

The structure model of the model is formed according to lumped approach in terms of spatial resolution. The main reason to choose lumped version is that the significant subsoil processes such as vegetation canopy or the infiltration conditions are still not known very well in the catchment scale. Therefore, it is needed to know how catchments work as a whole system. Additionally, each part of the distributed or semi-distributed model is actually lumped rainfall-runoff model. Figure 3.3 shows the diagram of the rainfall-runoff model.

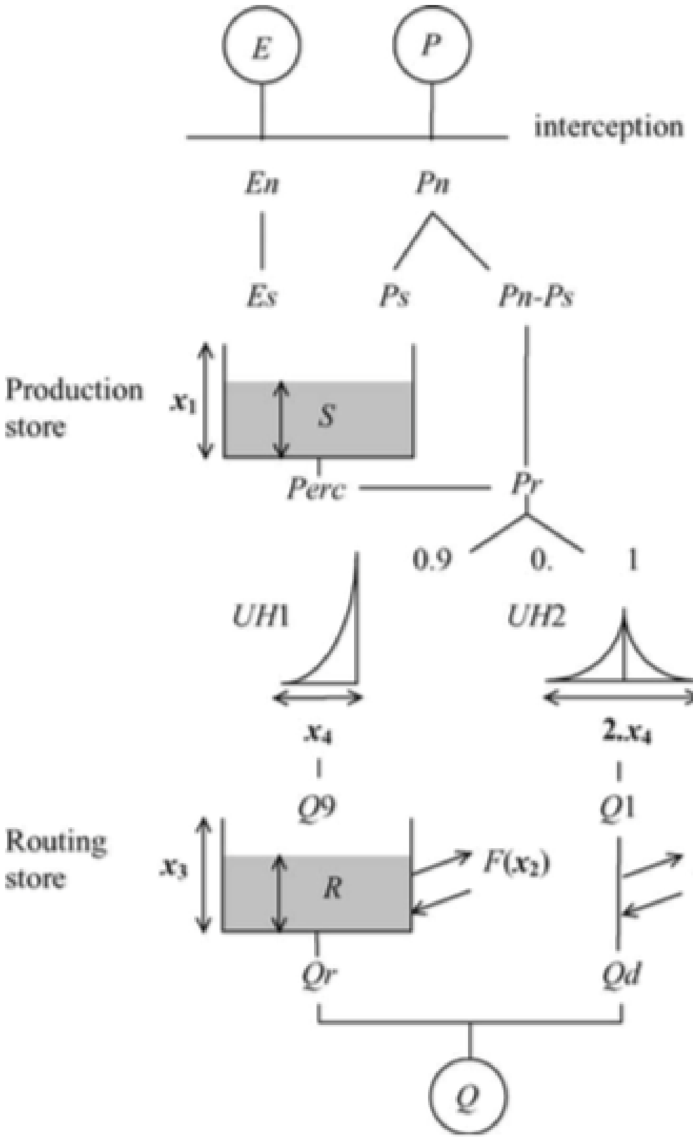


Figure 3.3. Diagram of GR4J rainfall-runoff precipitation model (Perrin *et al.*, 2003).

The inputs of the model are rainfall depth indicated here as P and the potential evapotranspiration (PE) indicated here as E. Rainfall depth (P) is an estimation of areal catchment rainfall. It can be calculated by the interpolation method from the existing raingauge values. For E value, the long-term average of evapotranspiration values can be used. This assumes the repetition of PE every year. The units of water quantities in the model are stated in mm which can be found by using the catchment area. The formulation explained below is based on the discrete model formulation.

First of all, it is needed to obtain the net rainfall or evapotranspiration by subtracting E from P value. If P is the bigger one, then the model works positively if not the model works negatively.

$$If P \geq E,\ then\ P_n = P - E\ and\ E_n = 0\ otherwise\ \mathrm{P}_n\text{= } 0\ and\ \mathrm{E}_n = E - P \tag{3.8}$$

When the model works positively, some part (P_s) of the net rainfall (P_n) starts to fill the production store. P_s is a function of the level of production store (S)

$$P_s = \frac{x_1\left(1 - \left(\frac{S}{x_1}\right)^2\right)\tanh\left(\frac{P_n}{x_1}\right)}{1 + \frac{S}{x_1}\tanh\left(\frac{P_n}{x_1}\right)} \tag{3.9}$$

In this expressions where x_1 is the maximum capacity of the production store and the first parameter of the model needed to be calibrated. It was a fixed value in the model GR3J as 330 mm.

In the opposition, the model works negatively and some part of the net evapotranspiration should be calculated as a function of the level of production store (S).

$$E_s = \frac{S\left(2 - \frac{S}{x_1}\right)\tanh\left(\frac{E_n}{x_1}\right)}{1 + \left(1 - \frac{S}{x_1}\right)\tanh\left(\frac{E_n}{x_1}\right)} \tag{3.10}$$

Therefore, the water amount in the production store can be found by:

$$S = S - E_s + P_s \tag{3.11}$$

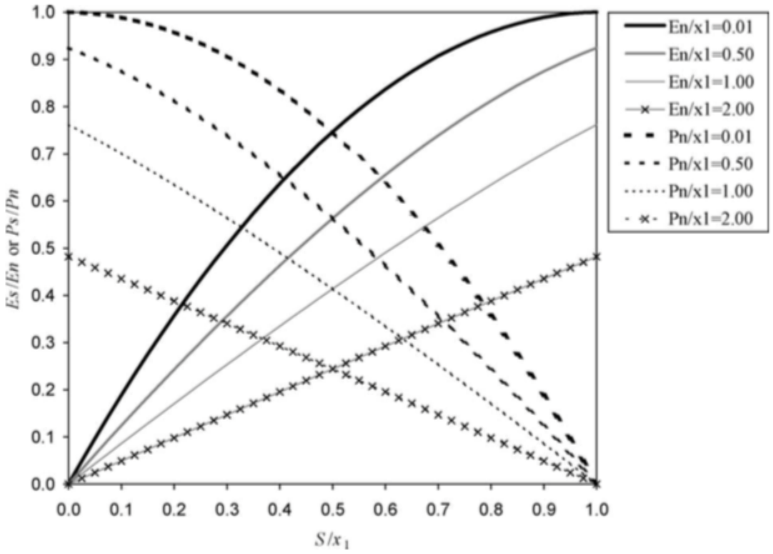


Figure 3.4. Illustration of the behavior of the production functions (Perrin *et al.*, 2003).

The infiltration (percolation) from the production store can be calculated as seen below. It is a power function of the level S.

$$Perc = S\left\{1 - \left[1 + \left(\frac{4}{9}\frac{S}{x_1}\right)^4\right]^{-1/4}\right\} \tag{3.12}$$

Therefore, the water amount in the production store can now be found by:

$$S = S - Perc \tag{3.13}$$

The definition of the percolation formula is one of the model developments when comparing GR3J and GR4J. The total amount of the water contributing the route (P_r) can be found by the formula below:

$$P_r = Perc + (P_n - P_s) \tag{3.14}$$

P_r contains two flow components; a unit hydrograph (UH1) routes 90% of P_r and a single unit hydrograph (UH2) routes the rest, 10% of P_r. Thanks to UH1 and UH2, the time delay between rainfall event and the peak in the streamflow can be included in the simulation. The time parameter of the both hydrographs is x_4 which is the fourth parameter of the model. The ordinated of the unit hydrographs are expressed as SH1 and SH2 respectively. They are derived from the corresponding S-curves. The values of unit hydrographs can be calculated iteratively in discrete form as the formulation is explained below:

$$For \ \ \text{t} \leq 0, SH1(t) = 0 \tag{3.15}$$

$$For\ 0 < t < x_4,\ SH1(t) = \left(\frac{t}{x_4}\right)^{5/2} \tag{3.16}$$

$$For\ t \geq x_4,\ SH1(t) = 1 \tag{3.17}$$

$$For\ t \leq\ 0,\ SH2(t) = 0 \tag{3.18}$$

$$For\ 0\ <\ t\ \leq\ x_4, SH2(t) = \frac{1}{2}\left(\frac{t}{x_4}\right)^{5/2} \tag{3.19}$$

$$For\ x_4 < t < 2x_4,\ SH2(t) = 1 - \frac{1}{2}\left(2 - \frac{t}{x_4}\right)^{5/2} \tag{3.20}$$

$$For\ t \geq 2x_4,\ SH2(t) = 1 \tag{3.21}$$

$$UH1(j) = SH1(j) - SH1(j-1) \tag{3.22}$$

$$UH2(j) = SH2(j) - SH2(j-1) \tag{3.23}$$

Figure 3.5 illustrates UH ordinates for is equal to 3.8 days which is the parameter calibrated for all dataset.

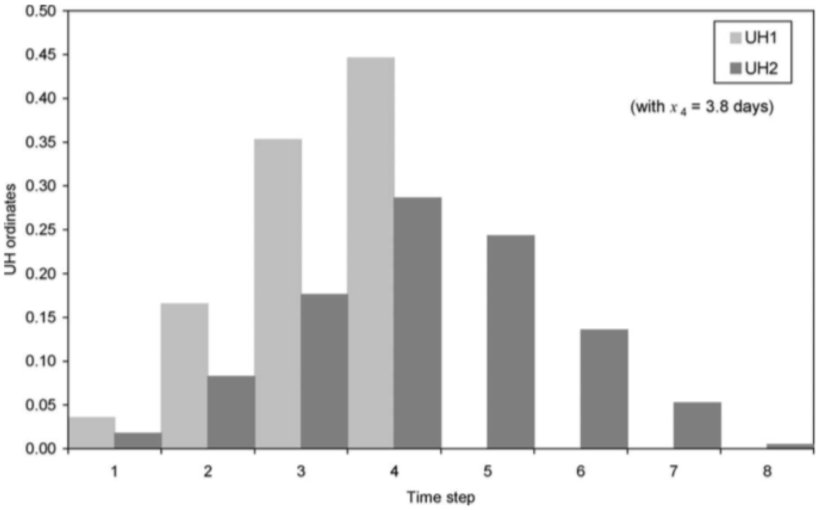


Figure 3.5. Example of ordinates of unit hydrographs (Perrin *et al.*, 2003).

Moreover, catchment water exchange can be calculated. The groundwater exchange term F affects two flow components, UH1 and UH2. Its formulation is:

$$F = x_2\left(\frac{R}{x_3}\right)^{7/2} \tag{3.24}$$

where R is the level of routing store and Rx_3 is the capacity of the routing store and is the water exchange coefficient. Rx_2 and Rx_3 are the second and third parameters of the model.

Now, we can recalculate the level of the routing store (R) by adding Q9 of UH1 and F:

$$R = \max(0; R + Q9 + F) \tag{3.25}$$

Note that R cannot be lower than zero. Besides, the outflow of Q_r can be computed by the formula below:

$$Q_r = R\left\{1 - \left[1 + \left(\frac{R}{x_3}\right)^4\right]^{-1/4}\right\} \tag{3.26}$$

The updated level of the routing reservoir is:

$$R = R - Q_r \tag{3.27}$$

The capacity x_3 can also be considered as "one day ahead maximum capacity".

Further, the output of UH2 which is $Q1$ is affected by the same water exchange F and the related flow component can be calculated as below:

$$Q_d = \max(0; Q1 + F) \tag{3.28}$$

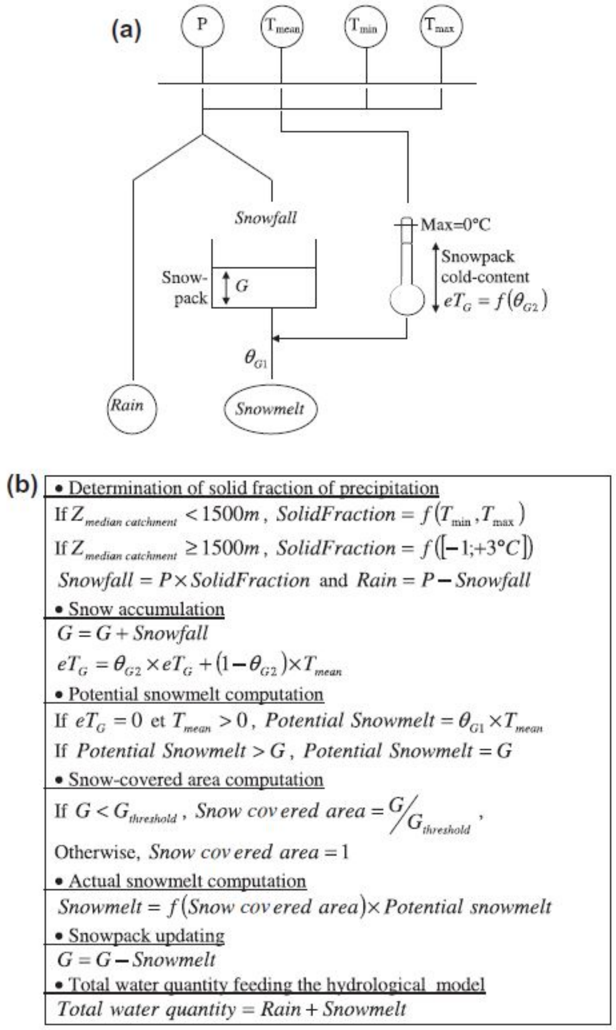
Finally, the total streamflow Q is computed as below (Perrin *et al.*, 2003):

$$Q = Q_r + Q_d \tag{3.29}$$

3.2.2. CemaNeige SRM Model Structure

CemaNeige is a semi-distributed snow accounting routine which has two parameters working with the daily time steps. The mechanism of CemaNeige is illustrated in Figure 3.6. The inputs of CemaNeige are water depth of total precipitation in the form of the daily liquid equivalent and the daily air temperature which might be T_mean, T_min or T_max. In order to adapt the model to the catchment scale, the catchment needs to be divided into five elevation zones having same areas.

CemaNeige has five functions presented below Figure 3.6 where the model diagram is also illustrated. There are two internal states, namely; snowpack quantity (G) and its cold content (eT_G). These two internal states are dependent of the input data. However, they are independent for each elevation zone. The accounting routine calculates two outputs for each elevation zone, namely; rain and snowmelt. The results of each elevation zone are averaged. It can be averaged because it is divided into equal areas. At the end, they are summed and the output of CemaNeige is the input of the model GR4J.



- Determination of solid fraction of precipitation

If $Z_{median\ catchment} < 1500m$, $SolidFraction = f(T_{\min}, T_{\max})$

If $Z_{median\ catchment} \geq 1500m$, $SolidFraction = f([-1;+3°C])$

$Snowfall = P \times SolidFraction$ and $Rain = P - Snowfall$

- Snow accumulation

$G = G + Snowfall$

$eT_G = \theta_{G2} \times eT_G + (1 - \theta_{G2}) \times T_{mean}$

- Potential snowmelt computation

If $eT_G = 0$ et $T_{mean} > 0$, $Potential\ Snowmelt = \theta_{G1} \times T_{mean}$

If $Potential\ Snowmelt > G$, $Potential\ Snowmelt = G$

- Snow-covered area computation

If $G < G_{threshold}$, $Snow\ covered\ area = {}^{G}\!/_{G_{threshold}}$,

Otherwise, $Snow\ covered\ area = 1$

- Actual snowmelt computation

$Snowmelt = f(Snow\ covered\ area) \times Potential\ snowmelt$

- Snowpack updating

$G = G - Snowmelt$

- Total water quantity feeding the hydrological model

$Total\ water\ quantity = Rain + Snowmelt$

Figure 3.6. Conceptual scheme and the equations of CemaNeige snow accounting routine (A. Valéry *et al.*, 2014).

CemaNeige has also five main features:

- It determines the solid fraction of the precipitation. If the mean altitude of the catchment is below 1500 m, T_min and T_max values can be used. If not, the fixed temperature interval [-1;3] can be used (L'Hote *et al.*, 2005).
- It can calculate the snow accumulation. The snow can be detected according to the temperature of the precipitation and can be added to the existing snowpack. G is the snowpack water equivalent.
- The calculated snowpack is updated by using the free parameter which is cold content factor. This procedure is derived from the daily mean temperatures and previous time-steps.
- A free parameter of snowmelt factor is formed according to the degree-day approach. Therefore, the potential snowmelt is computed.
- According to the decrease of the snow quantity in the snowpack, actual snowmelt is computed. It is assumed that the catchment is covered by 90% of mean annual snowfall.

On the other hand, it is tested that melting factor is either dependent on seasons or not. The efficiency of CemaNeige does not change when melting factor is defined as depending on the seasons. As a result, the melting factor in the model is excluded from season effects. Furthermore, water retention capacity in the snowpack is not considered since it does not increase the efficiency of the model.

4. GEOGRAPHY INFORMATION SYSTEM (GIS) ANALYSIS OF THE BASIN

Coruh river rises from the west hillsides of Mescit Mountains whose elevation is 3225 m and flows firstly to the west in east Turkey. Afterwards, it advances to the east through the Bayburt plain. Coruh river unites Tortum and Oltu creeks by passing through one of the deepest valleys in Turkey, Coruh Valley. Coruh river flows into the Black Sea within the border of Georgia by passing the cities of Bayburt, Erzurum and Artvin in Turkey.

Coruh basin which is one of the 25 hydrological basins of Turkey, has an area of 221 km^2 in total. Coruh river which is the most fast-flowing stream in Turkey, carries 6.3 billion m3 of the water and 5.8 million m3 of sediments annually (Sucu and Dinc, 2008). The river has 431 km long and its 411 km long is within the borders of Turkey while only its 20 km is within the borders of Georgia. From this perspective, Coruh river and its basin are in the category of transboundary waters and liable to the international laws. On the other hand, it has an importance for Turkey in terms of water management systems with its hydraulic systems and dams, namely; Laleli, ï¿½spir, Gï¿½llï¿½bag, Aksu, Arkun, Yusufeli, Artvin, Deriner, Muratli and Borcka Dams.

Figure 4.1. Illustration of the borders of Coruh River Basin in the geographical map.

4.1. GIS Analysis of Arkun Dam Basin

In this study, the basin of Arkun Dam is analyzed since the conceptual studies of hydrological modelling in this area is quite rare. The basin of Arkun Dam in Coruh river is mainly fed by the melting snow of high altitude of the mountains.

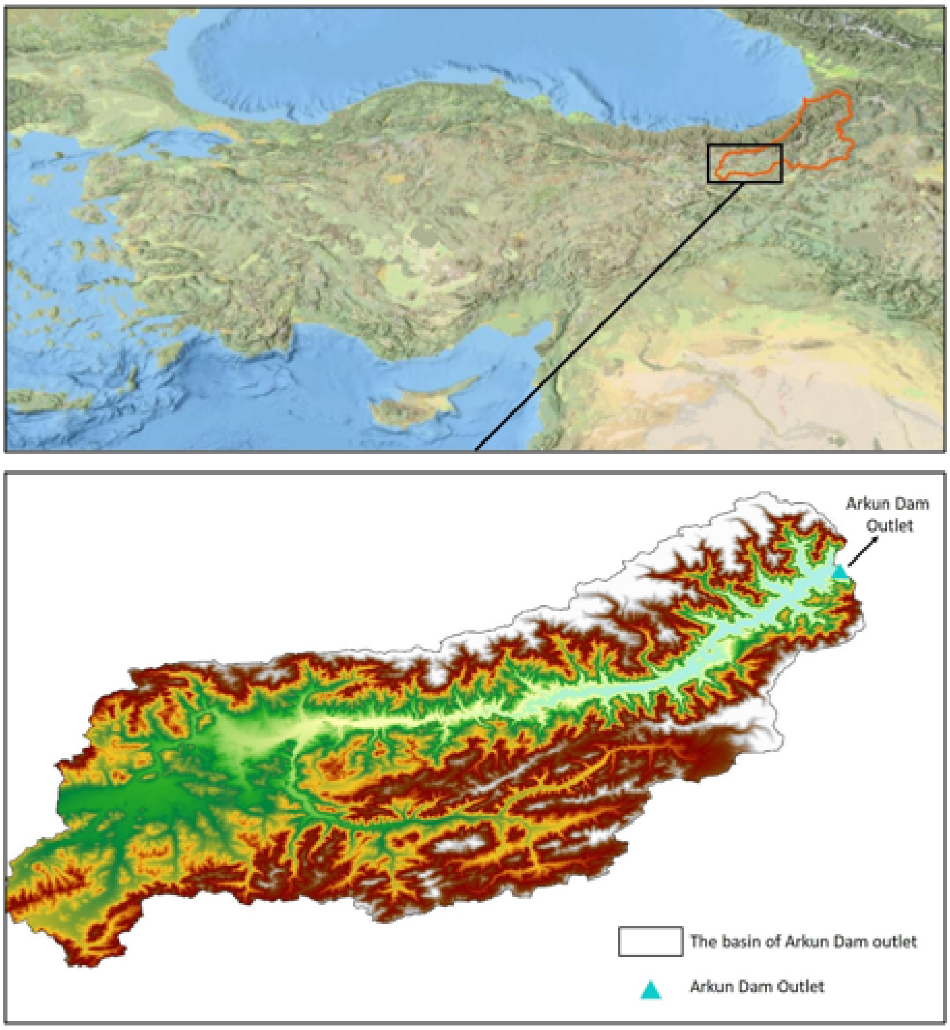


Figure 4.2. Arkun dam outlet and its basin.

The topographical properties of the basin of Arkun dam outlet is analyzed via GIS software (ESRI ArcGIS). First, Coruh river basin is determined in ArcGIS by using Shuttle Radar Topography Mission (SRTM) geographical data. After determining flow accumulation pixel by pixel in the software, the location of Arkun Dam is also determined as an outlet with the help of coordinates. Later, the basin is drawn by the command of watershed.

As seen below Figure 4.3, the aspect of the basin is illustrated for eight direction and for the flat areas. The aspect is the compass direction that a slope faces. It defines the angles of sunlight over the basin which affects snow potential, evapotranspiration and snow melting. The slopes having north-northwest aspect are majority in the basin.

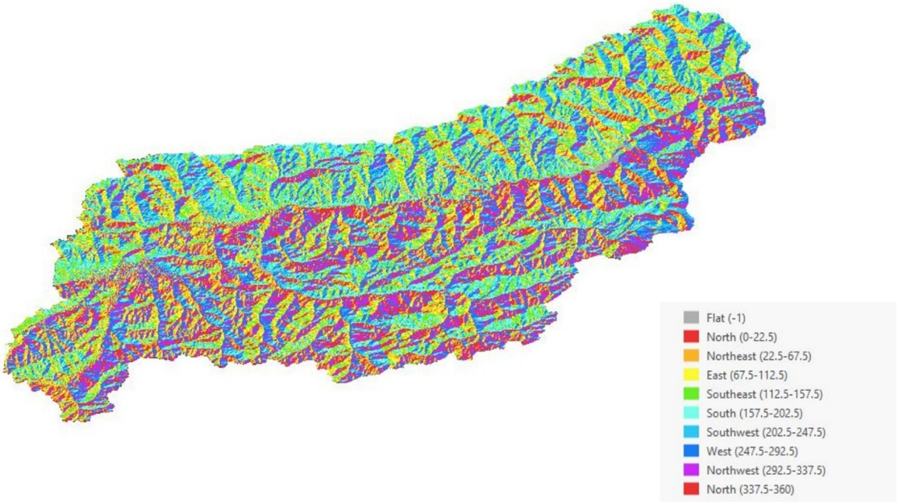


Figure 4.3. Aspect of the Arkun Dam Basin.

Further property of the basin is slope which is illustrated in Figure 4.4. The slopes of the area are categorized and the slope values are indicated as percentage. In Figure 4.4, as the color shading goes from the light tone to the darker, the slope increases. As seen below, the area of the basin is steep which affect the distribution of the elevation all over the basin.

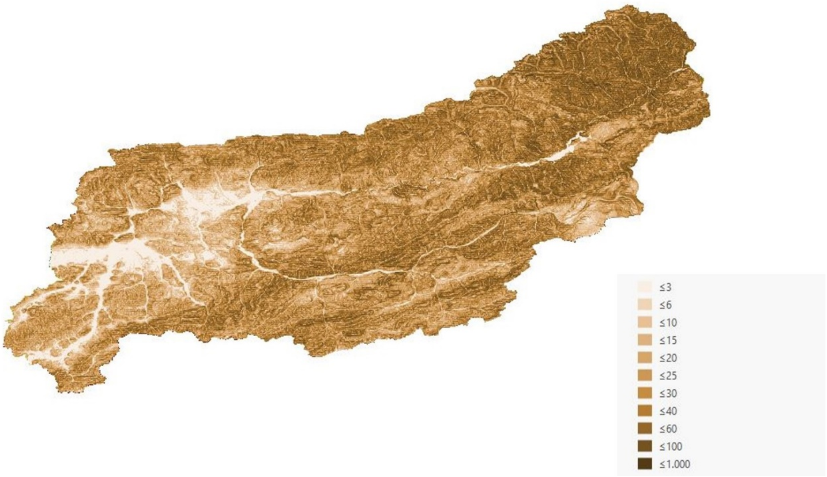


Figure 4.4. Slope values of the areas in the Arkun dam basin.

As mentioned in the model description, the area where hydrological modelling is made should be divided at least 5 equivalent areas divided according to their elevation. In order to make hydrological modelling of the Arkun dam basin, 10 equivalent areas are created in ArcGIS software. Having 10 equivalent areas instead of 5 would most likely provide more accurate model results since the Arkun dam basin is extremely mountainous and snow-melting plays crucial role in the hydrology of the basin. In Figure 4.5, the slice of the Arkun dam basin to 10 equivalent zones are shown.

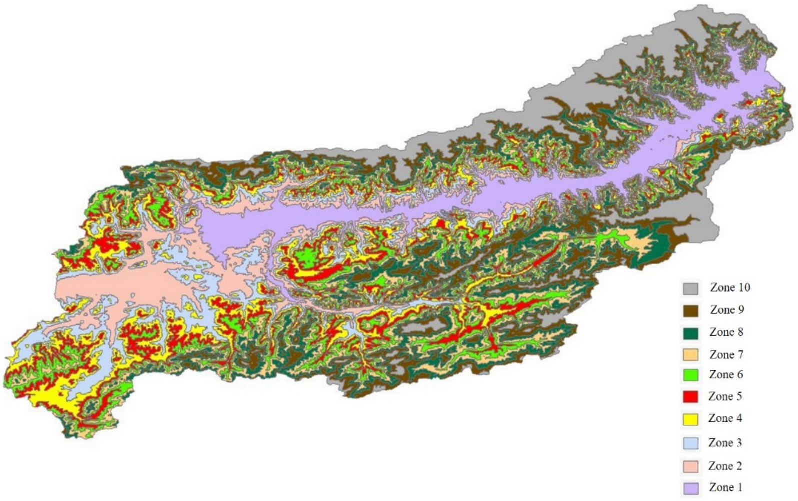


Figure 4.5. 10 equivalent zones of Arkun dam basin.

The area of Arkun dam basin is calculated as 6886 km^2 via ArcGIS software. The lowest elevation of the basin is 870 m and the highest elevation of the basin is 3705 m. According to data gathered via ArcGIS software, the hypsometry of the Arkun dam basin is drawn below.

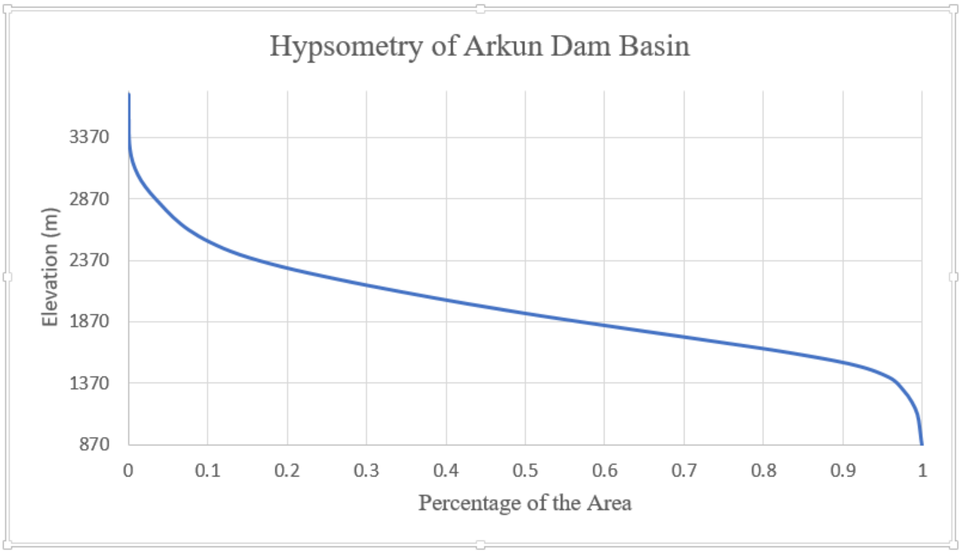


Figure 4.6. The hypsometric graph of Arkun dam basin.

All 10 equivalent zones of Arkun dam basin are presented below separately. As it can be monitored, the valley which has the stream bed has the lowest elevation and the first zone starts from this valley.

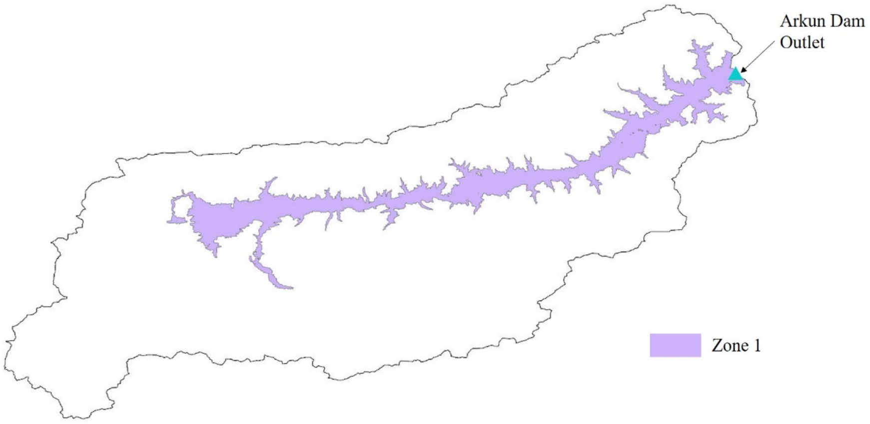


Figure 4.7. Illustration of Zone 1 within Arkun dam basin.

The area of Zone 1 is 690 km^2 and its elevation range is between 870 m and 1595 m. The mean elevation of this zone is 1447 m. Since this elevation is lower than 1500 m, max and min temperature values are also included in the snowpack and snow melting calculation, instead of using threshold numbers. For the rest of equivalent zones, threshold numbers are used for the snowpack and snow melting calculations.

Figure 4.8. Illustration of Zone 2 within Arkun dam basin.

The area of Zone 2 is 690 km^2 and its elevation range is between 1596 m and 1702 m. The area starts to expand through the hill shades of surrounding mountains. The mean elevation is 1654 m.

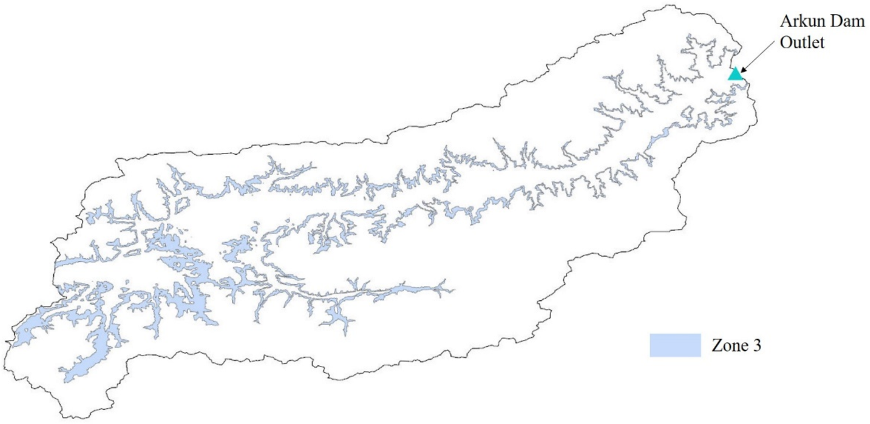


Figure 4.9. Illustration of Zone 3 within Arkun dam basin.

The area of Zone 3 is 686 km^2 and its elevation range is between 1703 m and 1798 m. The mean elevation is 1751 m.

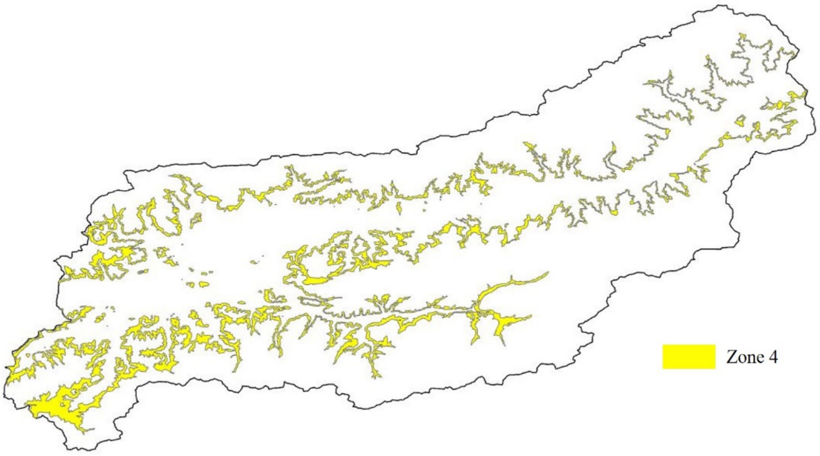


Figure 4.10. Illustration of Zone 4 within Arkun dam basin.

The area of Zone 4 is 693 km^2 and its elevation range is between 1799 m and 1892 m. The mean elevation is 1845 m. The area expands through the south of the basin where high altitude mountains exist.

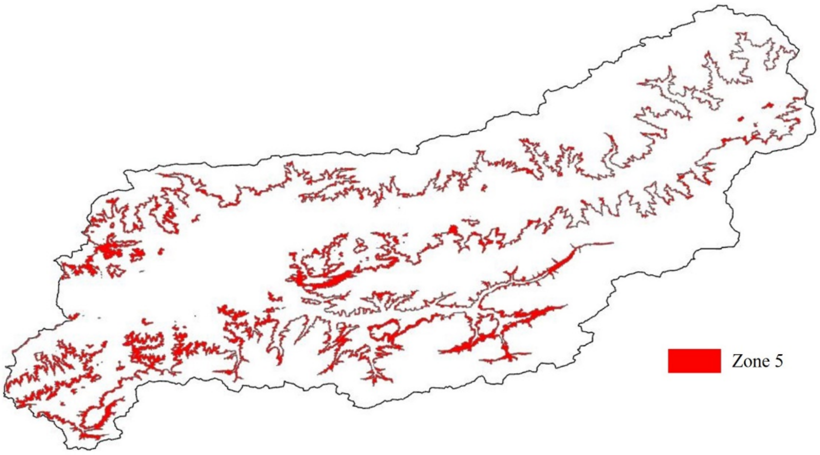


Figure 4.11. Illustration of Zone 5 within Arkun dam basin.

The area of Zone 5 is 688 km^2 and its elevation range is between 1893 m and 1990 m. The mean elevation is 1941 m.

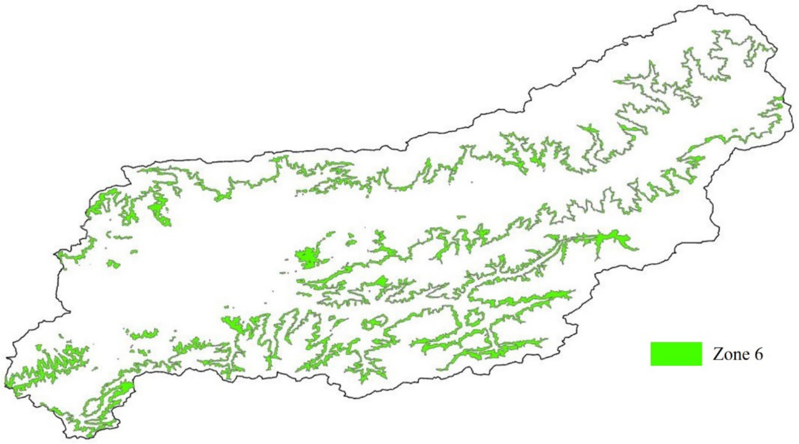


Figure 4.12. Illustration of Zone 6 within Arkun dam basin.

The area of Zone 6 is 688 km^2 and its elevation range is between 1991 m and 2099 m. The mean elevation is 2043 m.

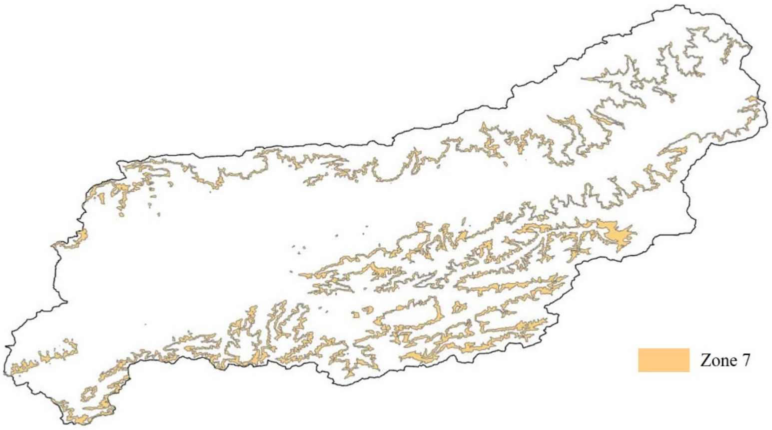


Figure 4.13. Illustration of Zone 7 within Arkun dam basin.

The area of Zone 7 is 688 km^2 and its elevation range is between 2100 m and 2220 m. The mean elevation is 2159 m.

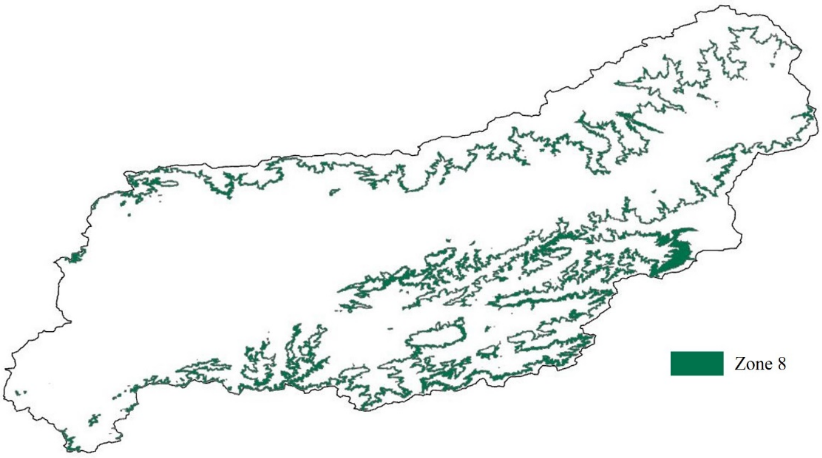


Figure 4.14. Illustration of Zone 8 within Arkun dam basin.

The area of Zone 8 is 686 km^2 and its elevation range is between 2221 m and 2358 m. The mean elevation is 2287 m.

Figure 4.15. Illustration of Zone 9 within Arkun dam basin.

The area of Zone 9 is 690 km^2 and its elevation range is between 2360 m and 2577 m. The mean elevation is 2453 m. Besides, the area of Zone 10 is 687 km^2 and its elevation range is between 2578 m and 3705 m. The mean elevation is 2850 m.

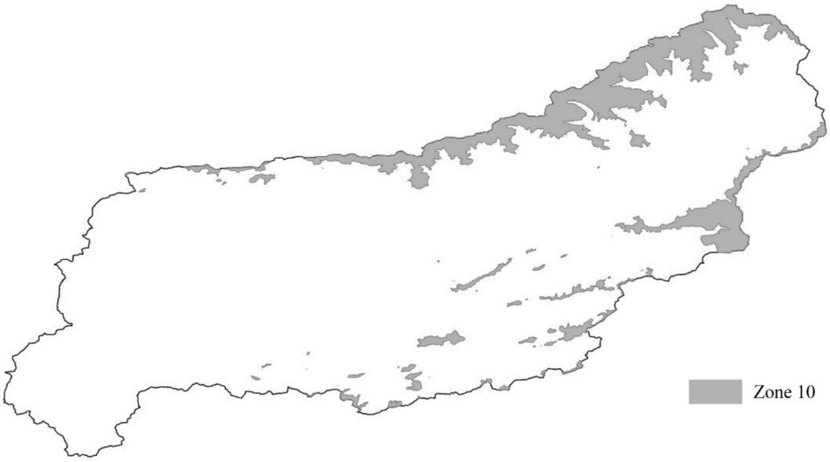


Figure 4.16. Illustration of Zone 10 within Arkun dam basin.

As it is presented, as going from Zone 1 to Zone 10, the area goes to the edge of Arkun dam basin since the other hill shades of those points exists in the other basins. The snow in Zone 10 is melted lastly and the runoff effect of this zone is the one which is the most delayed. Even, there are perennial snow-covered areas in Zone 9 and Zone 10. The data presented in Table 4.1 is used in the model calculation.

Table 4.1. Areas and max, min and min elevation of each equivalent zone.

Elevation Range	Zones	Area (km^2)	Hmean
870-1595	1	690.23	1447.14
1596-1702	2	690.33	1653.51
1703-1798	3	685.55	1750.87
1799-1892	4	692.68	1845.43
1893-1990	5	688.76	1940.77
1991-2099	6	687.51	2043.78
2100-2220	7	688.33	2158.69
2221-2358	8	685.75	2286.99
2359-2577	9	689.56	2453.35
2578-3705	10	686.77	2846.38

5. RESULTS

In this part, the model calculation and the results are presented. First, the data of minimum, maximum and mean temperature values of the catchment are needed as well as the daily precipitation values. Later, the observed discharge values are used for the calibration of the model. The data of Peterek Streamgage Gauging Station is used in this model. The elevation of Peterek Station is 880 m which is very close to the elevation of Arkun Dam Basin. Therefore, the data gathered by Peterek Station is extremely confidence for the Arkun Dam Basin. The data between 1979 and 2009 are used in the model.

Firstly, the model of GR4J runoff-precipitation model is presented without any snow accounting routine or CemaNeige. The aim is to show how model performance is poor without snow accounting routine especially for mountainous basins like Arkun Dam. Following, the results of model compound of GR4J and CemaNeige is presented.

5.1. The Results of GR4J without CemaNeige

Although the four parameters of the model are calibrated with the 30-year daily data, the Nash-Sutcliffe criteria of the model are extremely low. The values can be seen below:

$$\begin{aligned} CR1 &= 1.3 \\ CR2 &= 4.2 \\ CR3 &= 22.2 \end{aligned} \tag{5.1}$$

With these Nash-Sutcliffe criteria, it can be said that the model actually does not work. The graph of observed and calculated steam flow values is illustrated in Figure 5.1. Unfortunately, the model cannot catch the changes in the streamflow. Instead, the calculated value tends to continue either constant or with small changes.

The model calculates the precipitation as an input regardless if it is snow or not. The temperature is only included in the potential evapotranspiration calculation. While considering the catchment is 6885 km^2 and the elevation of area varies between 870 m and 3750 m, the failure of a model which does not take the snow accounting into consideration is likely expected.

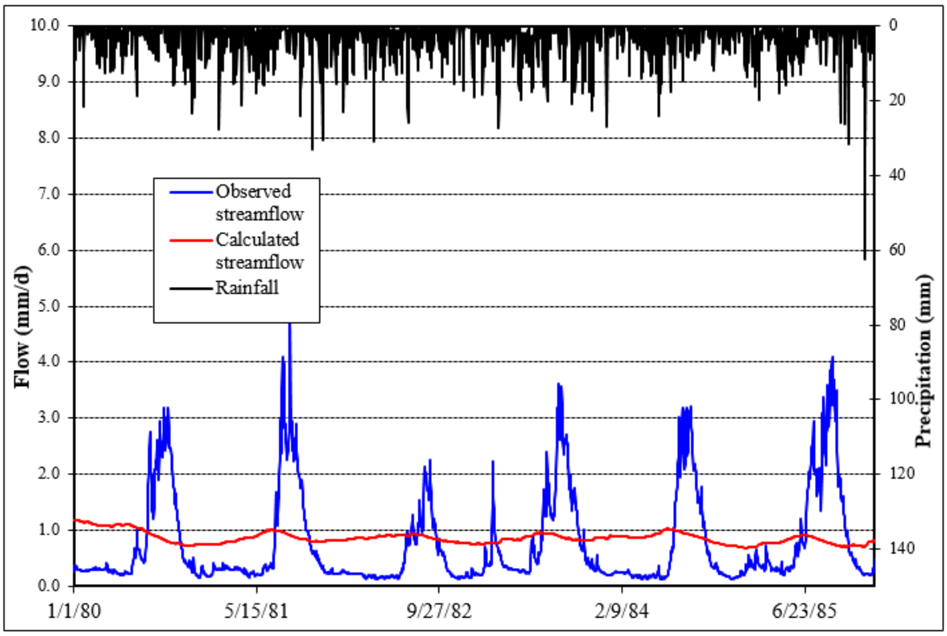


Figure 5.1. The illustration of observed streamflow, calculated streamflow and rainfall between 01.01.1980 and 31.12.1985.

In the Figure 5.1, the line of calculated streamflow clearly shows the model failure. The values of the model parameters are as follows:

$$\begin{aligned} x_1 &= 7.33 \\ x_2 &= 5.91 \\ x_3 &= 8.89 \\ x_4 &= 2.25 \end{aligned} \tag{5.2}$$

The model parameters are initially set as suggested by Perrin (2003) as:

$$\begin{aligned} x_1 &= 5.9 \\ x_2 &= 0 \\ x_3 &= 4.5 \\ x_4 &= 0.2 \end{aligned} \tag{5.3}$$

The above model parameters are calibrated as maximizing the Nash-Sutcliffe criteria by GRG nonlinear solving method. The suggested constraint is set as below (Perrin *et al.*, 2003):

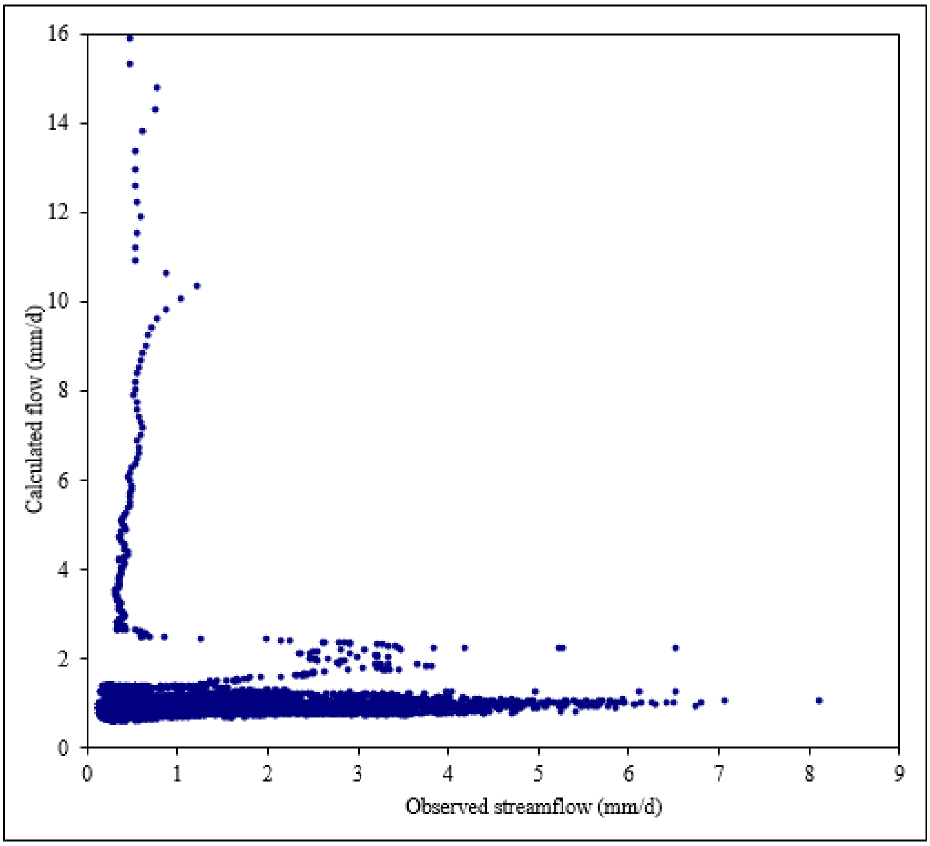


Figure 5.2. The graph of calculated streamflow values with respect to observed streamflow values.

For the high level of the model performance, the dots on the graph illustrated in Figure 5.2 should be converge to the line of the equation $x = y$. The model failure can also be recognized from the Figure 5.2.

5.2. The Results of GR4J-CemaNeige Model Compound

In this section, the data are tested on the GR4J-CemaNeige model compound. As mentioned, the data gathered from Peterek Streamgage Gauging Station is used in the model. Snow accounting routine is included in the model and the precipitation is first evaluated whether it is rainfall or snowfall. If it is rainfall, the model takes it as an input. If it is snowfall, the model calculates the snowpack which will be melting when the temperature raises. Since Arkun dam basin is mountainous and the elevation range is expanded, the snowpack and snow-melting calculation are crucial points of the model calculation.

At this time, the model calculation requires both T_{min}, T_{max} as well as T_{mean} values due to the snow fraction calculation of CemaNeige snow accounting routine. It is suggested to divide the catchment area to five zones in order to have better model results. As explained in Section 3.1, the Arkun dam basin is divided to ten zones in order to include the elevation effects inside the model. Furthermore, for the zones whose elevation is below 1500 m, in this case only Zone 1, the snow fraction is calculated by T_{min} and T_{max} values. On the other side, for the zones from 2 to 10, the temperature threshold is determined as [-1,3] for the completely snowfall and completely rainfall. In between threshold numbers, the snow fraction is calculated by T_{mean} values between 0 and 1.

The potential evapotranspiration is calculated from the global radiation values according to the catchment latitude. Later, the other variables of the model are defined. Temperature lapse rate is defined as 0.0065^{o}C/m. Meaning that, as the elevation raises by 100 m, the temperature decreases by 0.65^{o}C. The temperature values of the elevation zones are extrapolated by making this temperature spatialization.

The data between 01.10.1979 and 31.12.2010 including the precipitation, temperature and discharge values are used. Since the model works daily, the number of 11.415

daily data are used.

The model parameters are initially set as below parallel to the suggestion (Perrin *et al.*, 2003). Following, the four parameters are calibrated accordingly by maximizing the Nash-Sutcliffe criteria. The two parameters (and) of CemaNeige are also calibrated together with the parameters of GR4J. After the calibration, the parameters can be set for the Arkun dam basin by using 30-year data. The calibrated parameters are:

$$\begin{aligned}
x_1 &= 726.86\ mm \\
x_2 &= 19.21\ mm \\
x_3 &= 243.86\ mm \\
x_4 &= 1.33\ days \\
x_5 &= 12.58 \\
x_6 &= 0.25
\end{aligned} \tag{5.4}$$

The calibration of the model parameters is done by the GRG nonlinear solving method. After the calibration, the below Nash-Sutcliffe efficiency criteria are defined.

$$\begin{aligned}
CR1 &= 82.4 \\
CR2 &= 83.6 \\
CR3 &= 78.2
\end{aligned} \tag{5.5}$$

The value of 100 for the criteria means perfect modelling and it can be said that the model works sufficiently in Arkun dam case, it grasps the general trend and the peaks of the observed streamflow. In the Figure 5.3 (1980-1984), Figure 5.4 (1990,1994) and Figure 5.5 (2000,2004); observed and calculated streamflow values are shown with the time series of four years. Illustrations of all figures and python code of the model compound can be found in Appendix.

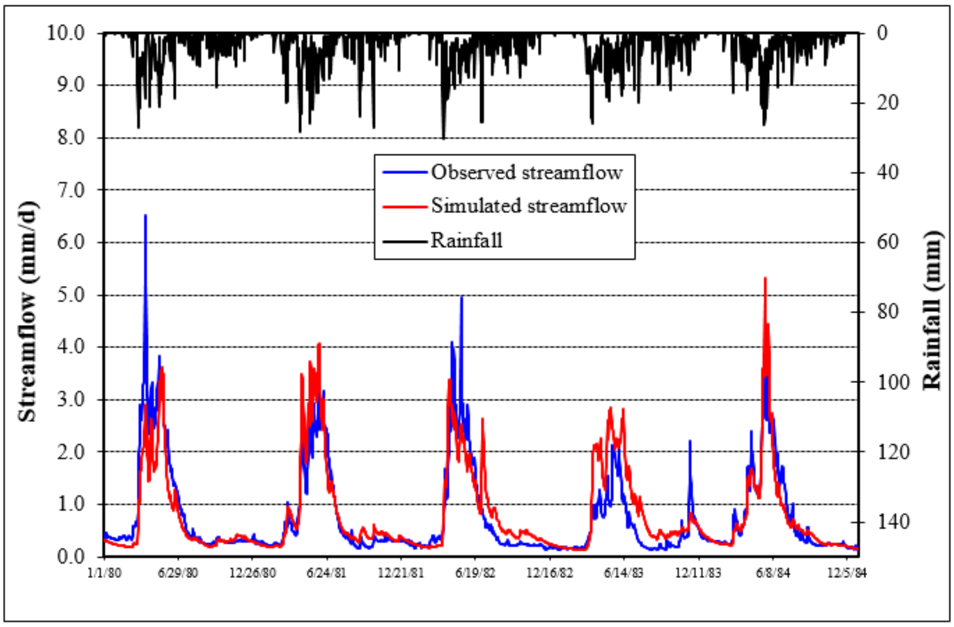


Figure 5.3. Rainfall, observed streamflow and calculated streamflow values for Arkun Dam Basin between 1980-1984.

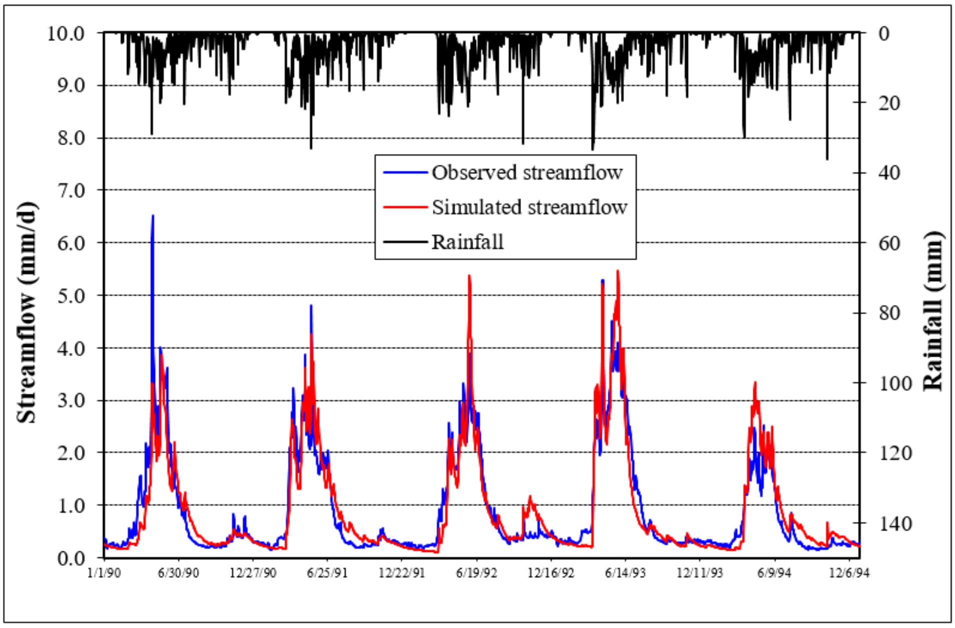


Figure 5.4. Rainfall, observed streamflow and calculated streamflow values for Arkun Dam Basin between 1990-1994.

As it can be seen, the model represents the general trend of the observed streamflow values very well. The model could even perform well while extreme peaks happen. The observed streamflow rises gradually after the winter season ends and the snow melting starts. From the spring to the summer, the streamflow is fed by the snowmelts. Since the Arkun dam basin is surrounded by high mountains, snow melting continues until the summer season.

In the low season, the observed streamflow is around 0.2 and 1.0 mm/d. On the other, it fluctuates between 1.0 and 4.0 during high season. The values above 4.0 mm/d are rare and can be considered as extreme peaks.

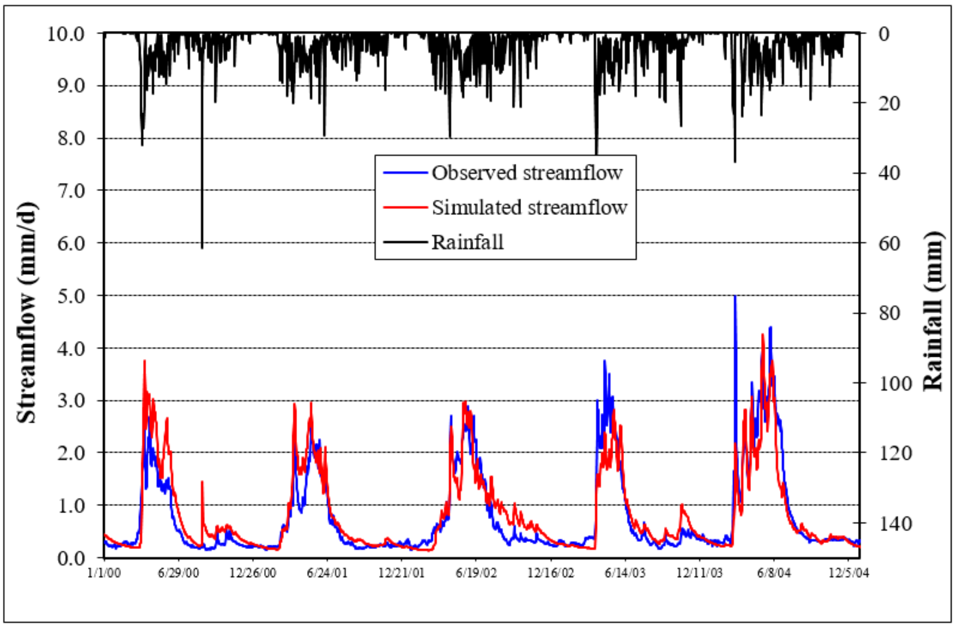


Figure 5.5. Rainfall, observed streamflow and calculated streamflow values for Arkun Dam Basin between 2000-2004.

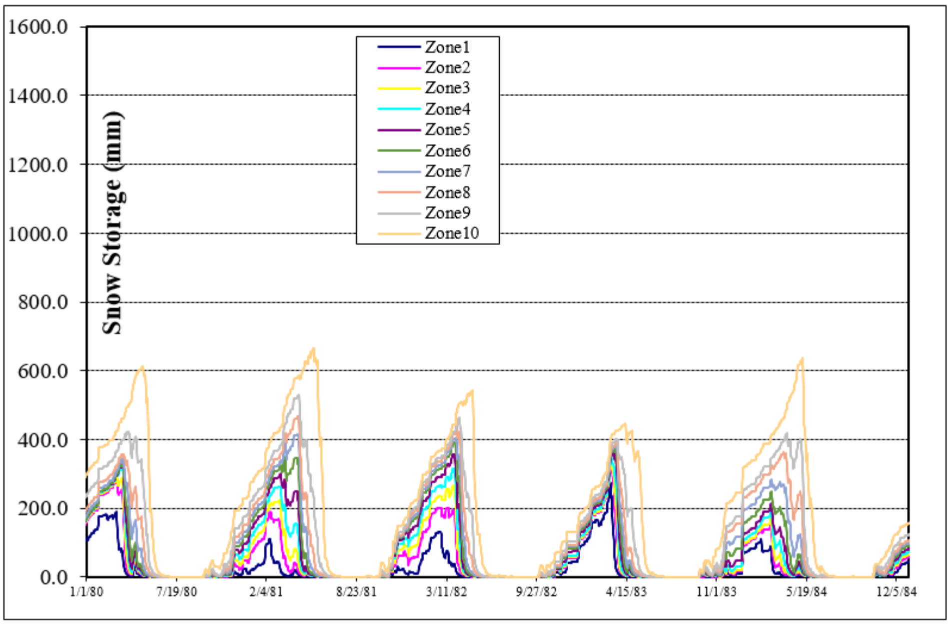


Figure 5.6. The amount of snowpack over the all ten zones between 1980-1984.

In Figure 5.6, the snow packs calculated for all zones are illustrated. As going from Zone 1 to Zone 10, the amount in the snow pack increases. Accordingly, the time requested for snow melting is also increases. Further snow packs of the zones for different time period is shown in Figure 5.7.

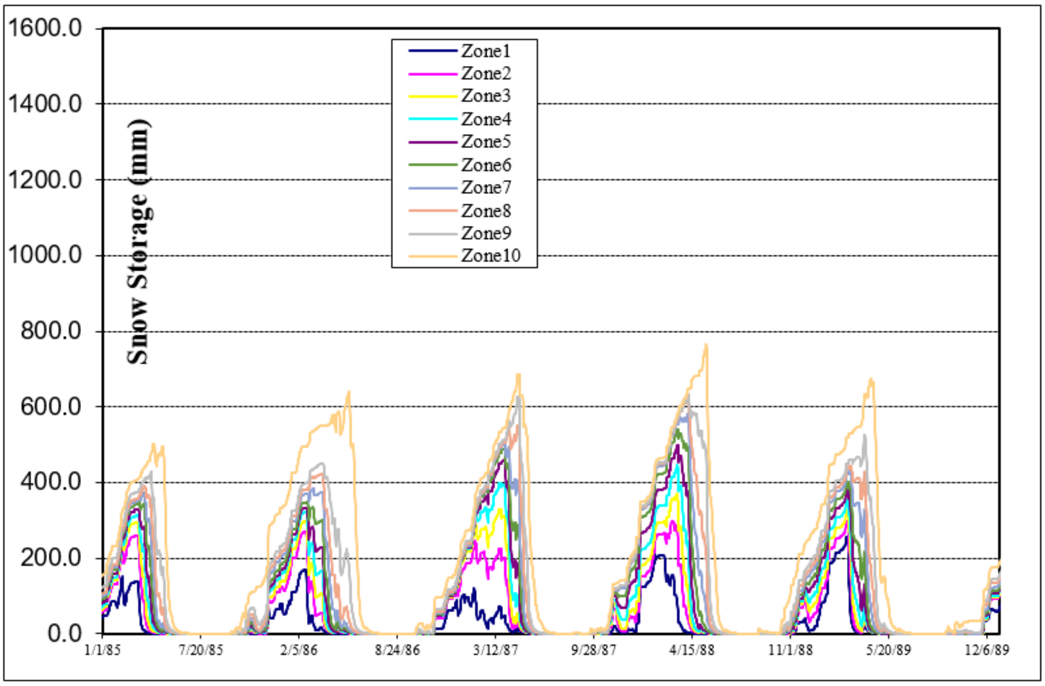


Figure 5.7. The amount of snowpack over the all ten zones between 1985-1989.

The snowpack over the zones is highly depended on the temperature distribution. Therefore, it affects the snow-covered area and the runoff during the spring season due to snow-melting. There is a peak in both observed streamflow and the snowpack of year 1988.

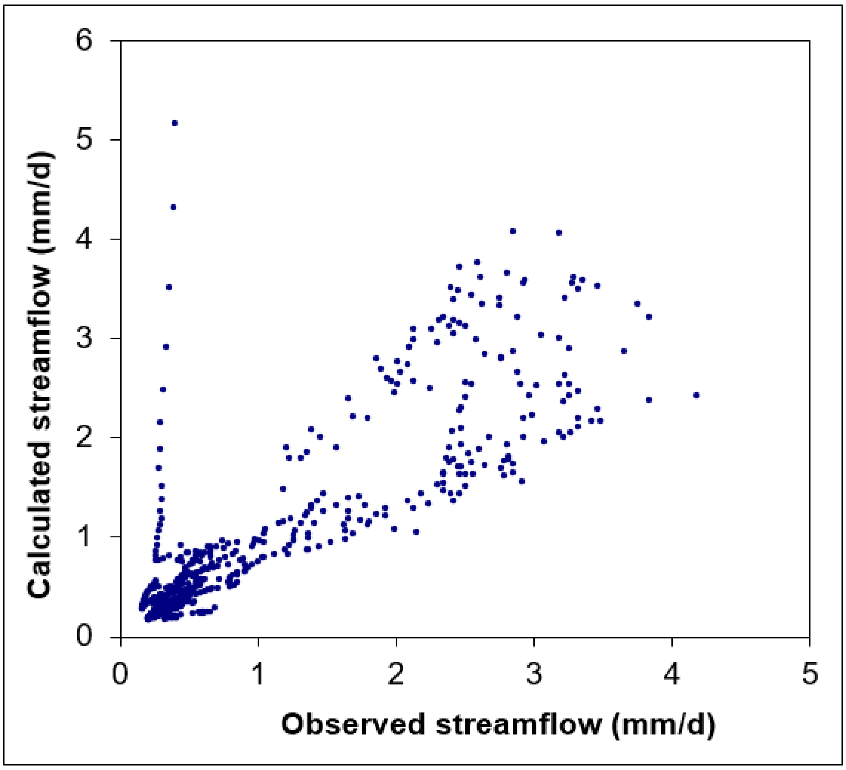


Figure 5.8. Calculated streamflow values with respect to observed streamflow values.

In Figure 5.8, the graph of calculated and observed streamflows are presented. As it is mentioned, the line of x=y represents the perfect model results. Here in this model, the results lower than 1 mm/days are able to be calculated precisely. On the other hand, as the streamflow values get larger, the model performance starts to decrease until the extreme peaks. Most of the points are concentrated on the area representing the lower streamflow.

With the different graphs provided above, the results of the modelling of Arkun Dam Basin can be seen a sufficient representation of the real-life system of the basin which is actually the main aim of the modelling. Therefore, the Arkun Dam Basin is now ready for the simulation of the streamflow for the forecast with its calibrated parameters by using GR4J- CemaNeige model compound.

Lastly, it is now possible to present the streamflow forecast for the Arkun dam basin with the inputs of temperature and precipitation. The total data for Arkun dam basin is available from 01.10.1979 to 31.12.2010. This whole data was already used for calibration and validation for modelling purposes. From this date, while the data can be used as an input is available, the daily observed streamflow values are missing. Therefore, since the model parameters are available for the basin, the streamflow forecast can be made for next years. In Figure 5.1 below, the simulated streamflow for the years 2011-2012 can be seen below. The characteristics of the Arkun dam basin can be clearly observed in the forecast.

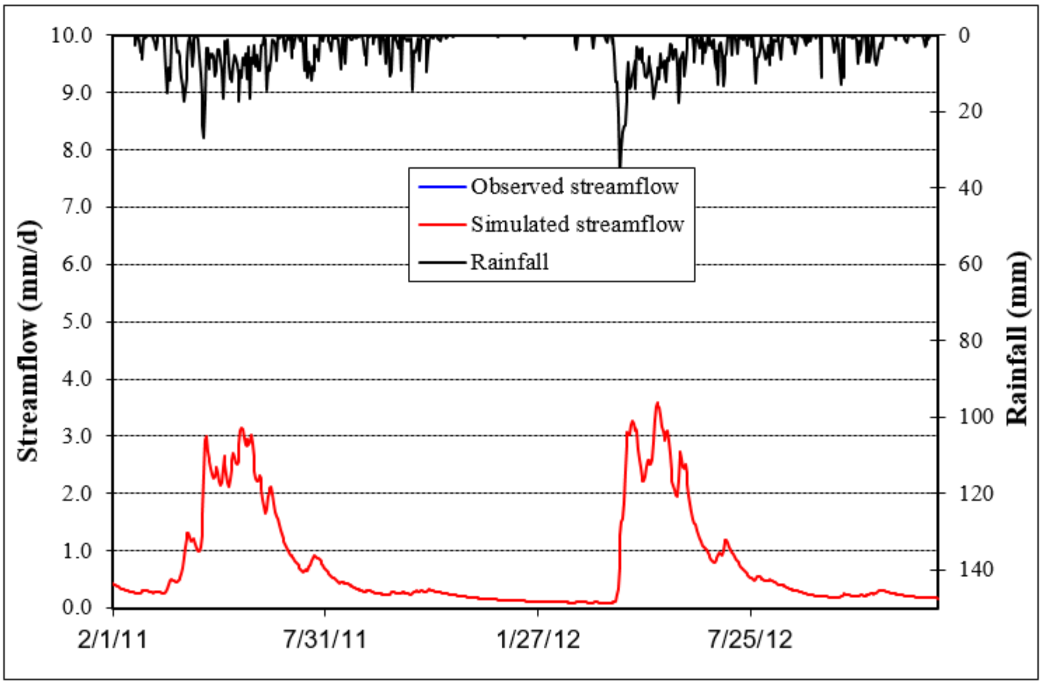


Figure 5.9. Forecasted streamflow values for the years of 2011 and 2012.

The characteristics of the Arkun dam basin can be clearly observed in the forecasts. The streamflow is extremely high due to snow melting occurred in spring and early summer. On the other hand, the streamflow is low during the winter due to the snowpack. This also presents the vital importance of the snow accounting routine in the hydrological modelling.

6. FURTHER STUDIES ON OPTIMAL OPERATION OF A HYDROPOWER SYSTEM

The existing methodological studies in the examination of the hydro-systems of water resources are generally focused on a long-term aggregate system which is crushed and consequently, the economics of a hydrological schemes stimulates the short and medium-term market planning. The stochastic approach of hydrological and price forecasts are combined with maintenance planning and economic influences for the medium-term operation policy. The optimization of an operation of a hydroelectric system requires an evaluation of the mid-term operation policy conducted for the water amount that needs to be discharged. There are two main factors that mid-term operation policy relies on. These are the market price of a coming day while the runoff to the hydro system continues and the company targets for the electricity sales. Therefore, optimization of a water discharge from a hydropower system can be made by the current level of the system, inflow forecasts and the market price.

First of all, the water to be discharged and the power generated need to be correlated for the day-ahead operation. Thanks to the forecasts of the runoff to the system and the market price, a company that operates a hydropower system is able to take appropriate actions about its bids in the electricity market pool. Hence, the forecast analysis is then deepened for the advanced analysis of market economics by using the physical situation of a hydropower system. This requires either medium or short-term planning which may have several numbers of ambiguities. As the operation of a hydropower system tried to be optimized, these ambiguities should be reduced step by step.

The variables that affect the head calculations for a reservoir or hydropower system need to be evaluated in terms of hydro units in order to build a technical efficiency calculation. This is one of the most crucial components in the optimization. This helps to take actions while bidding in the market and self-scheduling for the economic signals. The results can be used in the formulation of the short-term strategies which will increase the technical and economic performances.

There are several techniques and approaches which have been used for the problems raised from the hydroelectric power, such as; linear approximation and functions, standard linear algorithms and network flow. In the optimization modelling, the mathematical representation of a hydro system needs to be away from nonlinearities and non-concavities for the sake of the problem simplicity. However, it is known that the functions of a hydroelectric generation are mostly nonlinear and nonconvex. As the models become more complex and sophisticated, the representation for the optimization becomes more realistic. On the other hand, apportion of all existing variable to the calculation could create a decrease of 15% of efficiency in a plant (Siu *et al.*, 2001). Therefore, the representation of the continuous nonlinear functions of hydropower generating units by defining performance curves can be chosen for the optimal operation of the Arkun Dam in Coruh river. Mixed-integer nonlinear programming can be enhanced for the operation of the dam. In that way, Arkun dam could get a better forecast to make decision for the questions of when the water should be held or what should be the quantity of the water discharged from the dam.

6.1. General

The mathematical of the power output can be represented as a function of the water discharge, net head in the reservoir and the unit efficiency. The equation can be presented as below:

$$p(i,t) = 9.81 \times 10^{-3} efi(i,t)h(i,t)\ q(i,t)\ \forall i \in I,\ \forall t \in T \tag{6.1}$$

Determining the performance of a hydroelectricity generation may be found complex. There three variables affecting the generation unit. Those are the water discharge, the net head and the technical efficiency. These variables have also other variables. For instance, the net head is a function of the gross head, water discharge and the water level in the reservoir of a hydropower system. The efficiency of a hydroelectric generating unit can be expressed as:

$$\eta = \beta_0 + \beta_1 h + \beta_2 + \beta_3 h^2 + \beta_4 q^2 + \beta_5 hq \tag{6.2}$$

where n represents the efficiency of the unit of hydroelectricity generation, h is the net head, the q is the water discharged to the turbines of a dam and B are the regression model parameters. (Diaz and Contreraz, 2012). The efficiency changing by different level of the net head and the water discharge can be illustrated in Hill diagrams (Diaz, 2009). Hill diagram enables to read the efficiency of a turbine at any level of net head and water discharge.

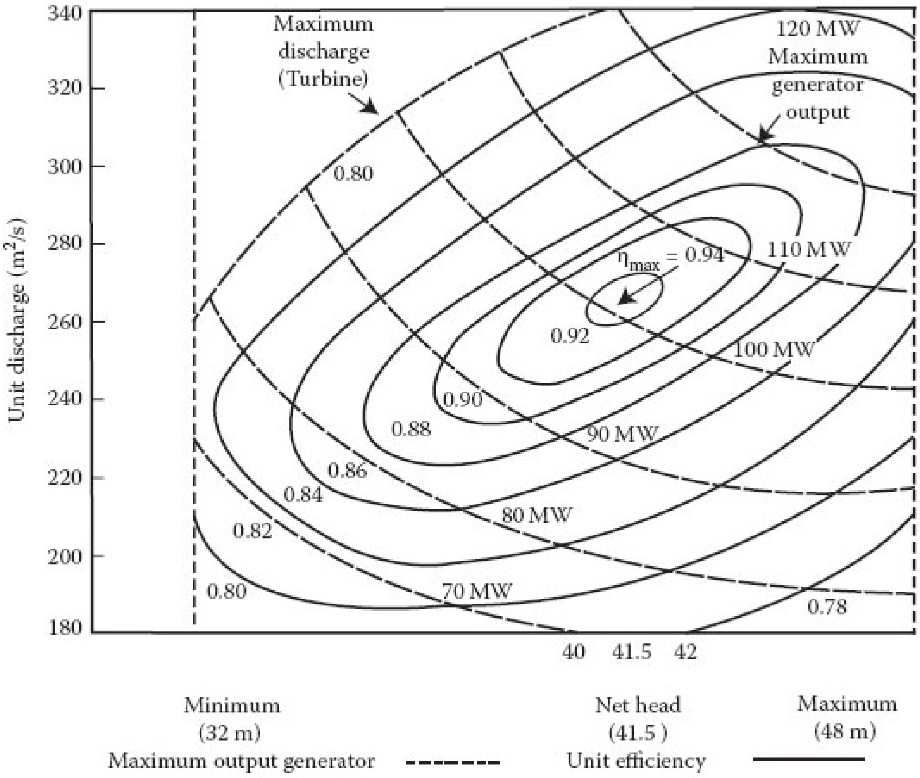


Figure 6.1. Hill Diagram (Finardi, 2003).

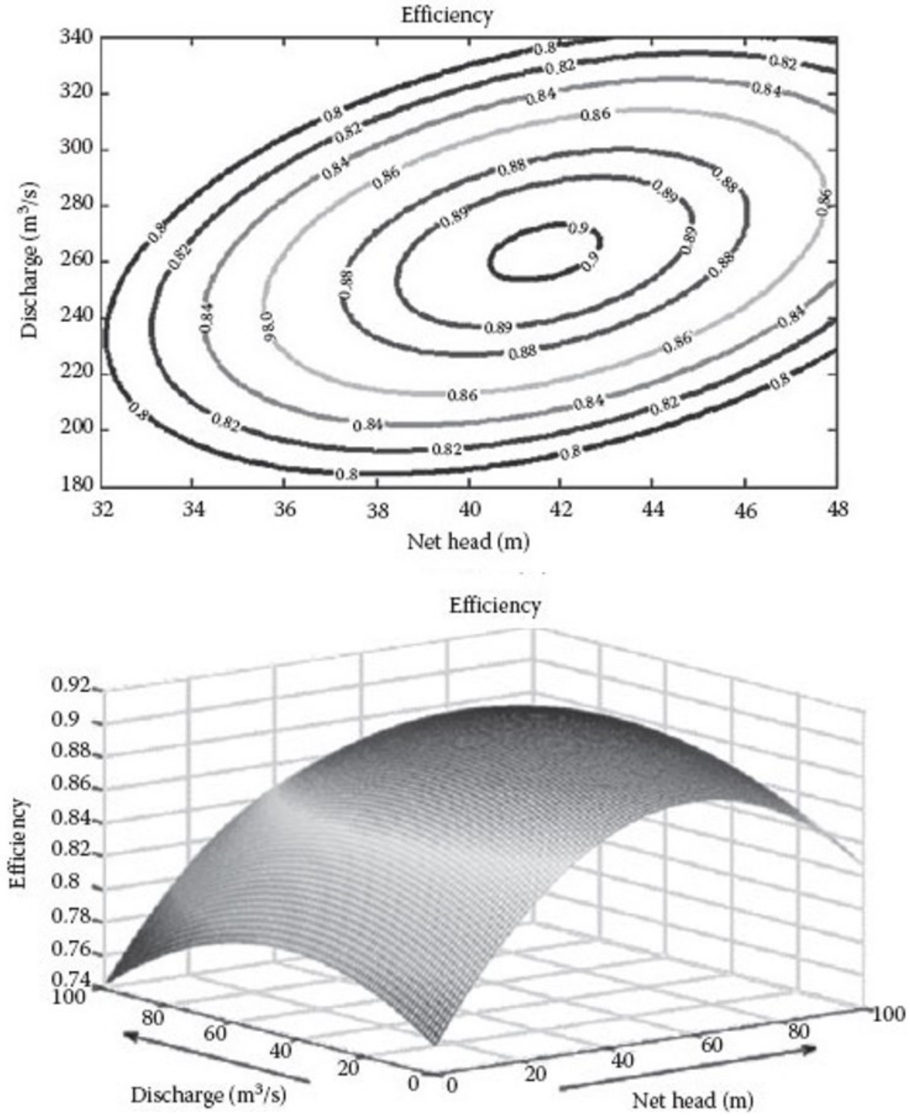


Figure 6.2. Efficiency of a Francis turbine as a quadratic function of the net head and the water discharge (Catalao, 2012).

6.2. The Constraints in the Optimization of Hydropower System

There are several constraints in the optimization modelling of a hydropower system. They can be classified as;

- continuity of the reservoir,
- physical limits of the reservoir,
- constraints of hydroelectricity generation,

- constraints of the net head calculations,
- constraints of hill diagram,
- constraints of technical efficiency and power output,
- constraints of start-up and shutdown units,

6.2.1. Continuity of the Reservoir

The water volume is equal to the sum of water volume in previous condition and total inflow and the subtraction of outflow.

6.2.2. Physical Limits of Reservoir

Stored water volume, the net head and spillage are limited between their minimum and maximum values.

6.2.3. Constraints on Hydroelectricity Generation

The amount of water discharged, volume discharged and power generation are limited. They should be between in their upper and lower bounds.

6.2.4. Constraints of the Net Head Calculations

The net head is calculated for each time period. The water level is a quadratic function of stored water volume. Further, the lower level is computed by the elevation tail which is dependent on the water discharge.

6.2.5. Constraints of Hill Diagram

Hydropower systems are operated and their turbine can be taken the grant as standard turbines. Their values of net head and water discharge are associated with a unique Hill diagram for each turbine. Therefore, the parameters of net head and water discharge for a Hill Diagram transformed linearly.

6.2.6. Constraints of Technical Efficiency and Power Output

The change in the net head and water discharge makes possible to calculate efficiency unit of the generation and the amount of power output.

6.2.7. Constraints of Start-up and Shutdown Units

At this point, the variables that should be nonnegative are defined in the modelling. These are technical efficiency unit, net head in the reservoir, net head in Hill Diagram, power generation, flow, water discharge in Hill Diagram, reservoir spillage and water volume.

6.3. Simplified Optimization of Arkun Dam Basin

In Section 5, the hydrological modelling of Arkun Dam is illustrated. The modelling now enables to make hydrological forecasts about the streamflow to the dam by taking temperature and precipitation as inputs. The results of the hydrological modeling and related forecasts will be much more meaningful with the existence of optimal operation of the Arkun dam.

As already explained, there might be seven constraints for the operation of a dam. In this study, for simplicity purposes and because of the limited information about the operation which the operating company can provide, the optimization work is limited with the streamflow values forecasted in this study and physical limits of the reservoir. The water level tries to be optimized while preventing and minimizing the spillage amount. The other factors and constraints are either neglected or assumed to be constant.

The capacity of the dam is provided as 200 hm^3 and the daily capacity of turbines is 10 hm^3. As daily streamflow values are forecasted and known, the maximation of water volume and the minimization of spillage amount can be solved by linear programming. Thanks to this, the spillage amount can be easily calculated daily and the authorities can make related flood emergency plans which is very crucial for environmental purposes.

One of the most problematic points of the Arkun dam basin is that the daily streamflow during spring season is much higher than the daily capacity of the turbines. Hence, even if the turbines work with full time capacity, the prevention of the spillage during spring and early summer is not possible.

$$\begin{aligned}
&DailyLevel_{(i)} = DailyLevel_{(i-1)} + Streamflow_{(i)} - TurbineDis_{(i)} \\
&0 < DailyLevel_{(i)} < 200 \\
&0 < TurbineDis_{(i)} < 10 \\
&obj = \max\left[\sum \left(DailyLevel_i\right)\right]
\end{aligned} \tag{6.3}$$

This mathematical representation shows that the daily level will converge the value of 200 and it will likely skip the spillage part. Therefore, the spillage needs to be calculated and the problem should be solved simultaneously. The aim is to determine the variable of daily discharge values of the turbines.

$$\begin{aligned}
&DailyLevel_{(i)} = DailyLevel_{(i-1)} + Streamflow_{(i)} - TurbineDis_{(i)} \\
&if\ DailyLevel > 200, Spillage = DailyLevel - 200 \\
&obj = \min\left[\sum Spillage\right]
\end{aligned} \tag{6.4}$$

The maximization of daily level and the minimization of the spillage needs to be solved simultaneously which makes the calculation complex. For simplicity purposes, the goal and penalty points are defined so that the problem is solved more easily. The java code of the optimization model can be found in the Appendix. The maximized of reservoir volume can be seen in below graph.

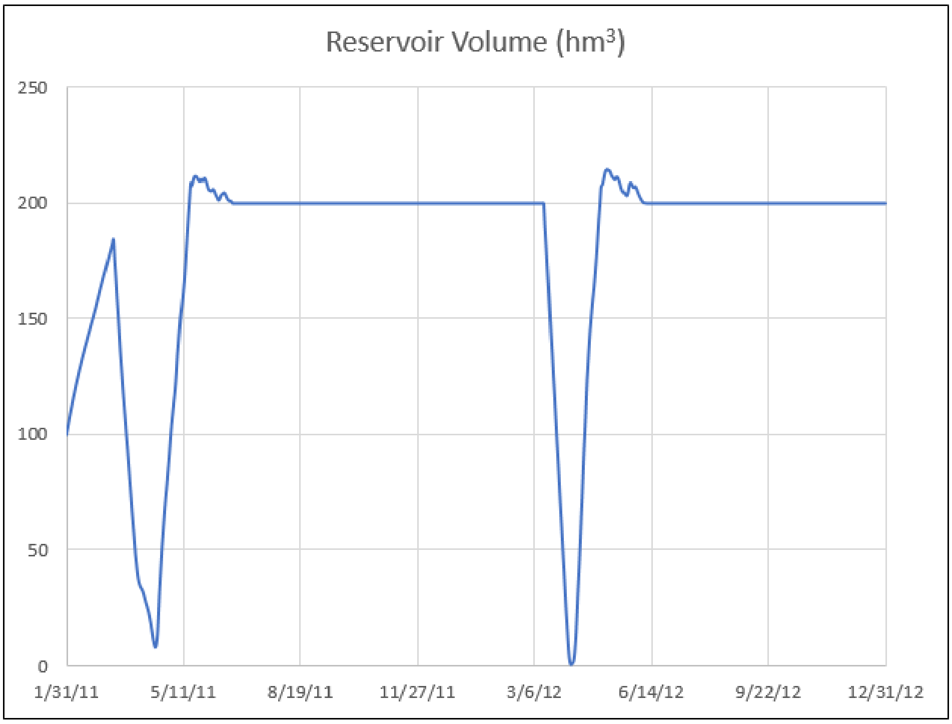


Figure 6.3. Maximized reservoir volume of Arkun Dam according to the forecasted streamflow values for 2011-2012.

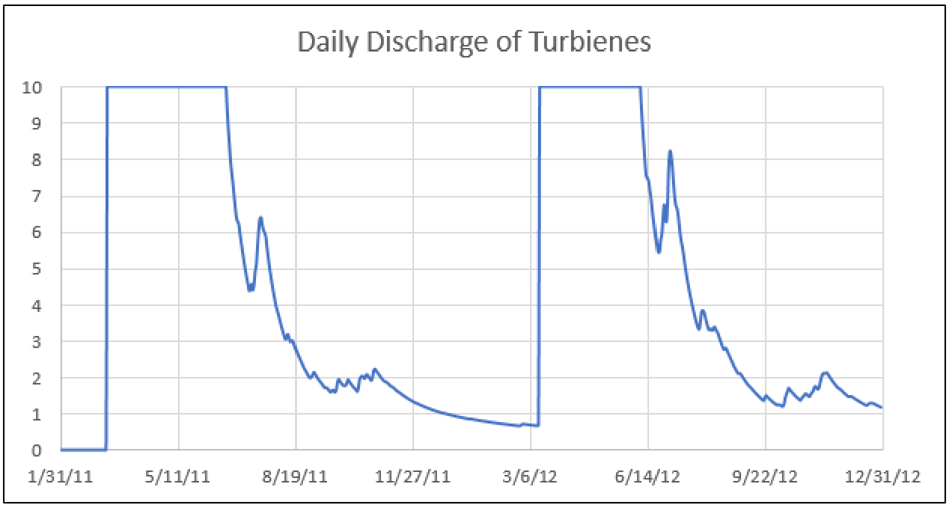


Figure 6.4. Daily discharge values of the turbines by maximizing the reservoir volume and minimizing the spillage over 2011-2012.

As can be seen, the spillage during the peak of streamflow due to the snow-melting is inevitable. It is remarkable that, the turbines should work with their full-time daily capacity during the peak season. Even, the full-time working period of the turbines should start earlier than the time when the daily streamflow exceeds the daily capacity of the turbines. Although the aim of the optimization is to have max reservoir volume so that the efficiency of the generation would be higher, the reservoir volume should decrease drastically so that the spillage amount will be minimized at the end of peak season.

Furthermore; during the rest of the year, the optimization model presented here results that the turbine discharge would be equal to the daily streamflow values in order to keep the reservoir volume maximum. The model results in this way since the electricity market price and company interests are neglected. Between 23.06.2011 and 14.03.2012, the daily discharge values of the turbines can be increased by the operating company according to the market price and their profit strategies.

To sum up, the model illustrates when the spillage will occur and its daily amount. This enables the authorities to make proper flood plans for the region. Besides, it enables the operating company to know exactly when they should open the valves of the dam without generating energy and the amount of the water that needs to be spilled from the valves in order to protect the dam.

7. CONCLUSION

The large part of total annual flow in the high mountainous in the eastern region of Turkey is made by the runoff which is resulted by snow melting during the spring and the first month of summer. Therefore, especially for the ï¿½oruh Basin where the large dams producing energy locate, the spatial and time-wise following of the amount of snow accumulated during the winter is extremely important from the point of view of efficient use of water resource. Furthermore, the optimistic operation of the dams locates on the river can only be achieved by the hydrological modellings. For this purpose, Arkun dam basin whose edges are determined by ArcGIS software is modelled in the GR4J-CemaNeige model compound.

The basin is first modeled in only GR4J rainfall-runoff precipitation model. Since the model excludes the snow accumulation and melting and the basin is constituted by mainly mountains, the model has failed. In this example, the importance of a snow accounting routine is clearly recognized. Following, Arkun dam basin is modelled in the model compound of GR4J precipitation runoff model and CemaNeige snow accounting routine. Two parameters are added to the model due to the snow calculation. Six parameters in total are calibrated by using data between 1979-2010 gathered from Peterek Streamgage Gauge Station. Afterwards, the parameters are set for Arkun dam basin by considering its mountainous area and elevation differences.

Instead of creating only one parameter set by evaluating some functions of the model for different purposes according to one criterion, it can be said that successful hydrological modelling is possible by generating multiple parameters which can represent whole basin.

The model is followingly used for the forecast purpose in Arkun dam basin with the provided parameters. The daily streamflow values are forecasted for the basin and this data is used for a possible optimization of the dam operation with the simplified optimization model.

In this study, GR4J rainfall-runoff precipitation model is compounded with the CemaNeige snow accounting routine as a first time for the Arkun dam. With its sufficient results, GR4J-CemaNeige model compound whose usage is not prevalent in Turkey can be good alternatives for the hydrological models widely used like HBV and SRM. The accuracy of the model compound for the mountainous basins is showed for the basins located in eastern/northeastern Turkey.

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APPENDIX A: RAINFALL, OBSERVED STREAMFLOW

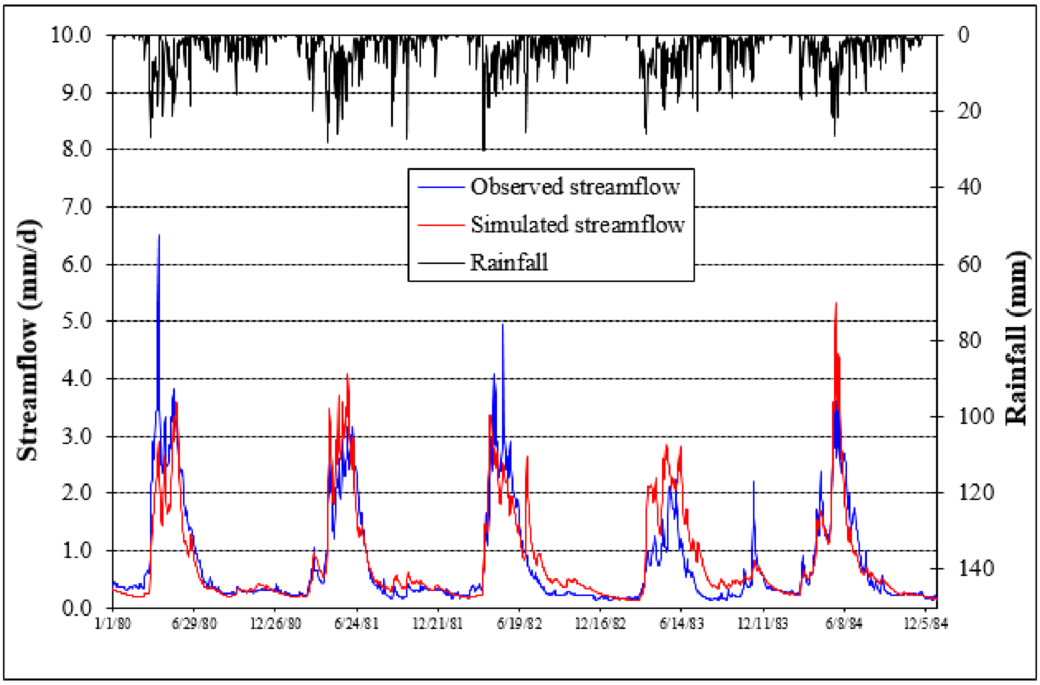

Figure A.1. Rainfall, observed streamflow and calculated streamflow values for Arkun Dam Basin between 1980-1984.

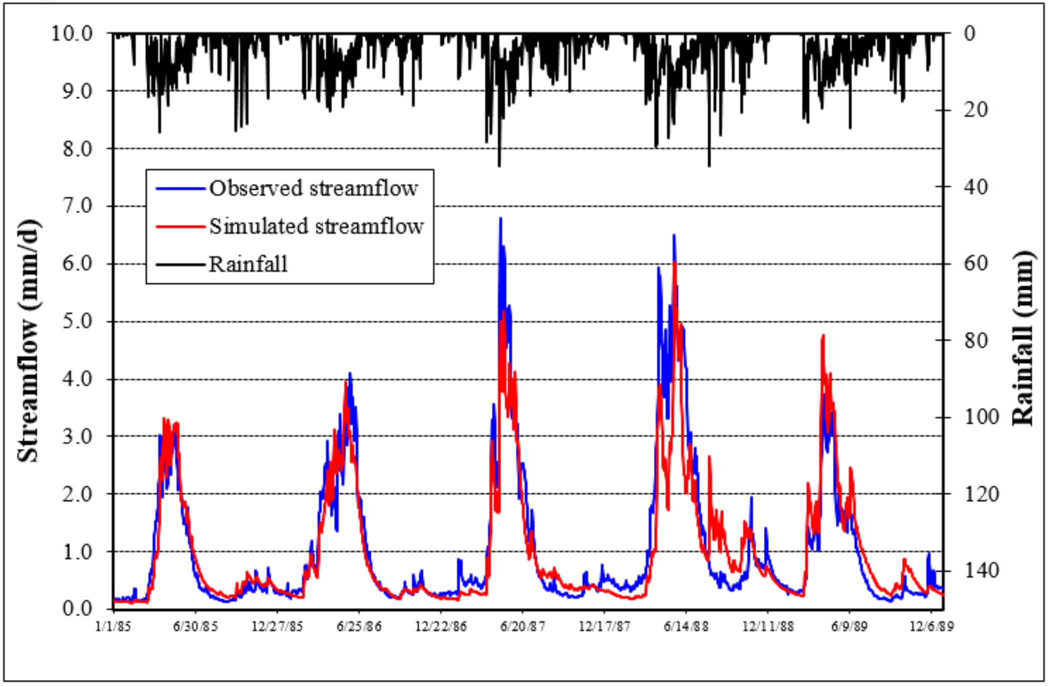

Figure A.2. Rainfall, observed streamflow and calculated streamflow values for Arkun Dam Basin between 1985-1989.

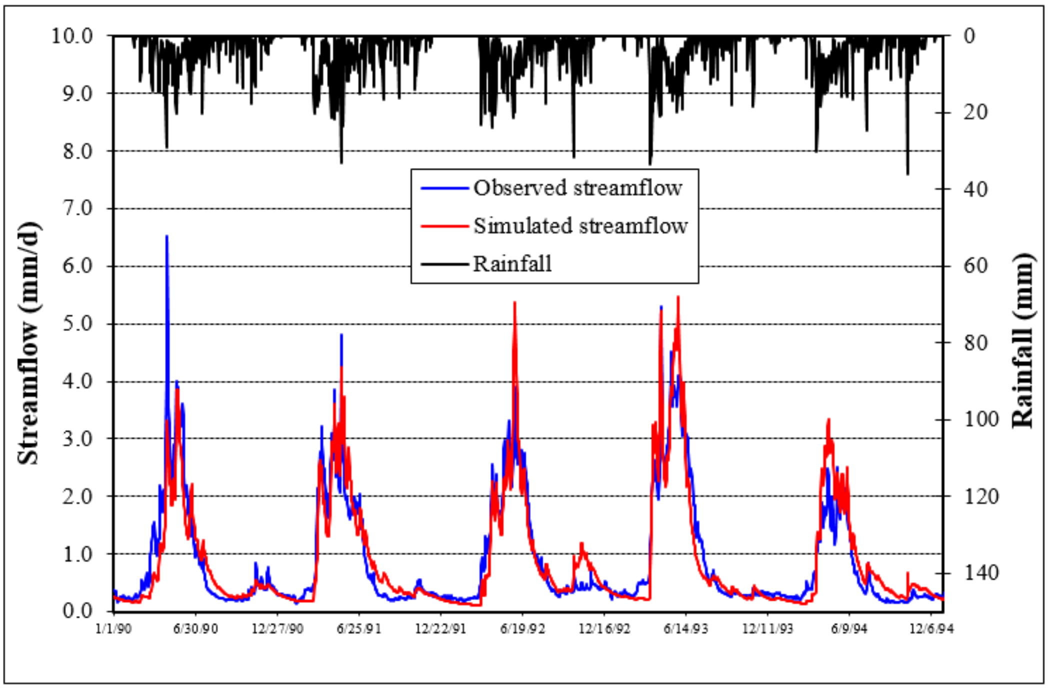

Figure A.3. Rainfall, observed streamflow and calculated streamflow values for Arkun Dam Basin between 1990-1994.

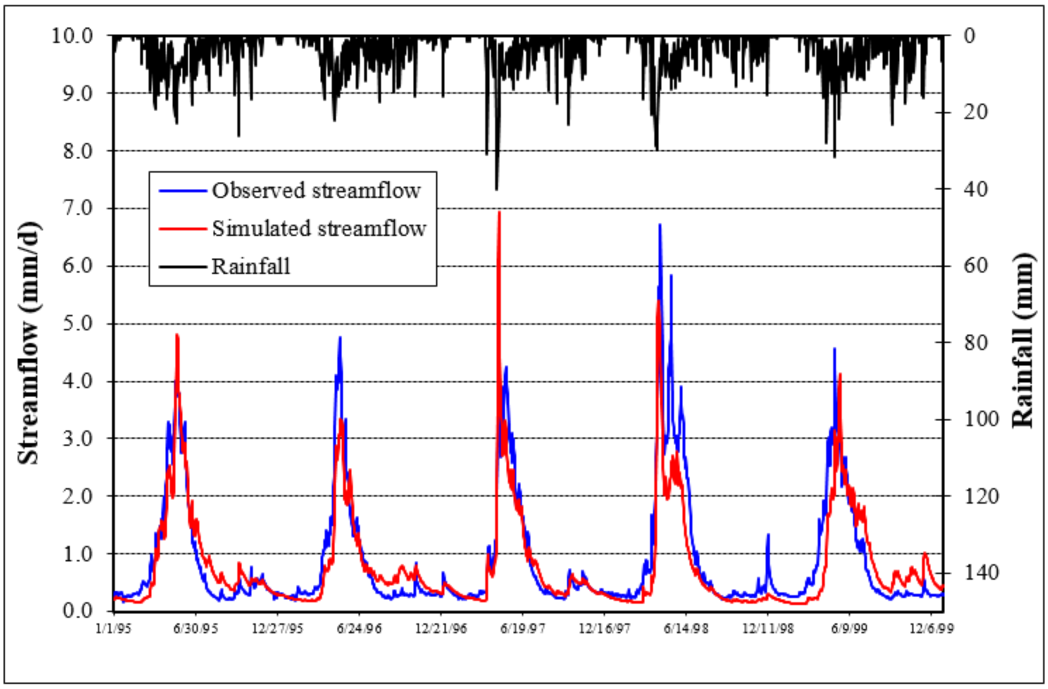

Figure A.4. Rainfall, observed streamflow and calculated streamflow values for Arkun Dam Basin between 1995-1999.

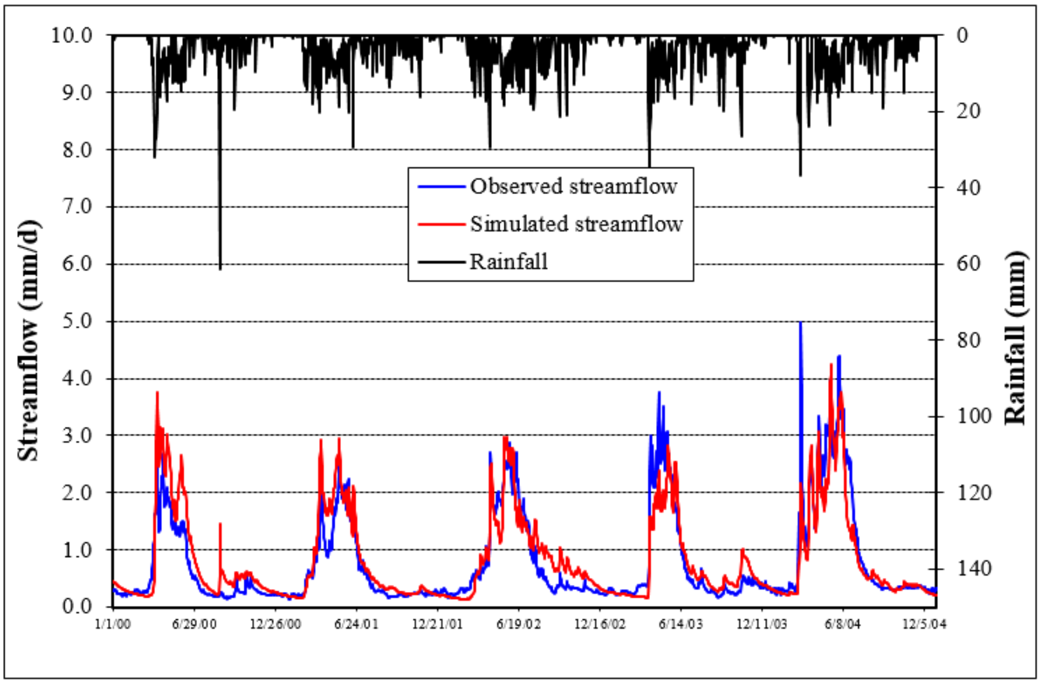

Figure A.5. Rainfall, observed streamflow and calculated streamflow values for Arkun Dam Basin between 2000-2004.

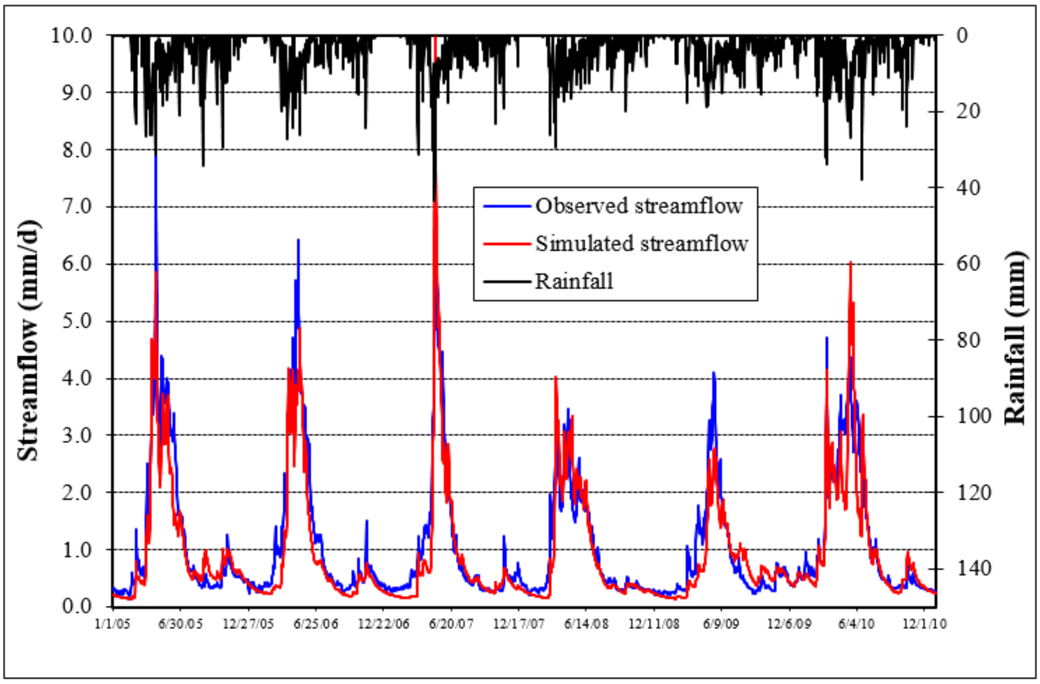

Figure A.6. Rainfall, observed streamflow and calculated streamflow values for Arkun Dam Basin between 2005-2010.

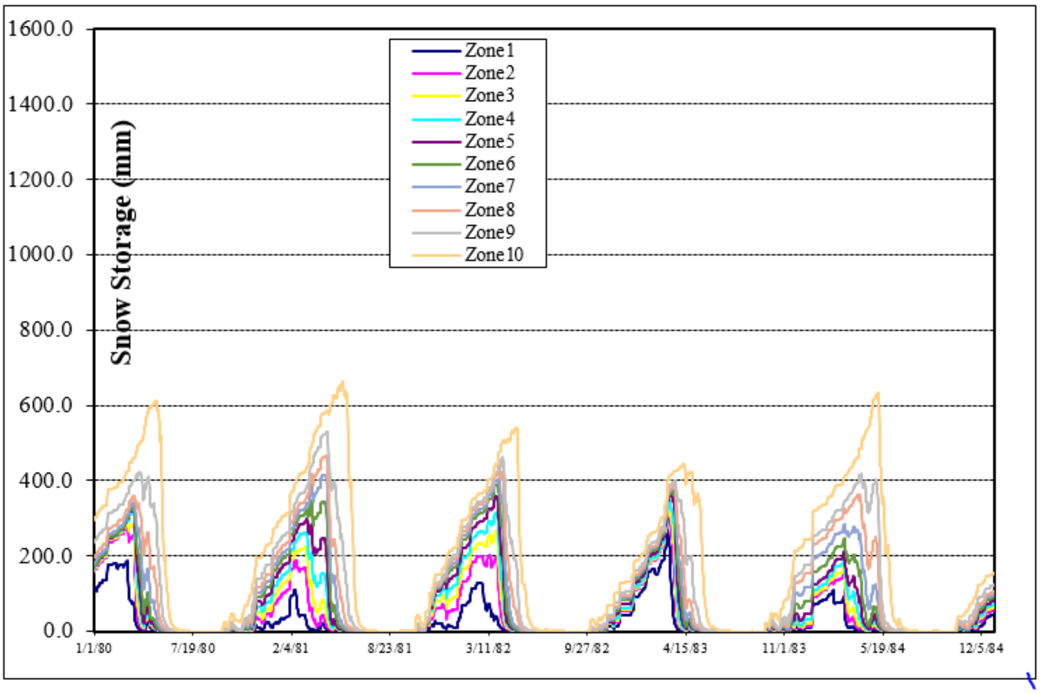

Figure A.7. The amount of snowpack over the all ten zones between 1980-1984.

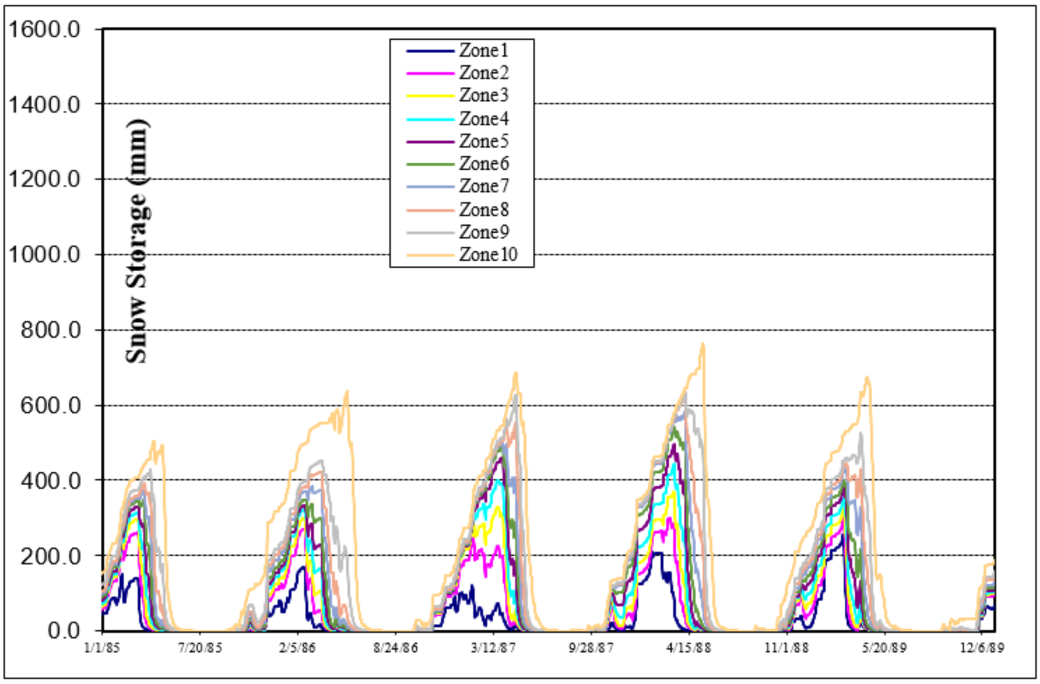

Figure A.8. The amount of snowpack over the all ten zones between 1985-1989.

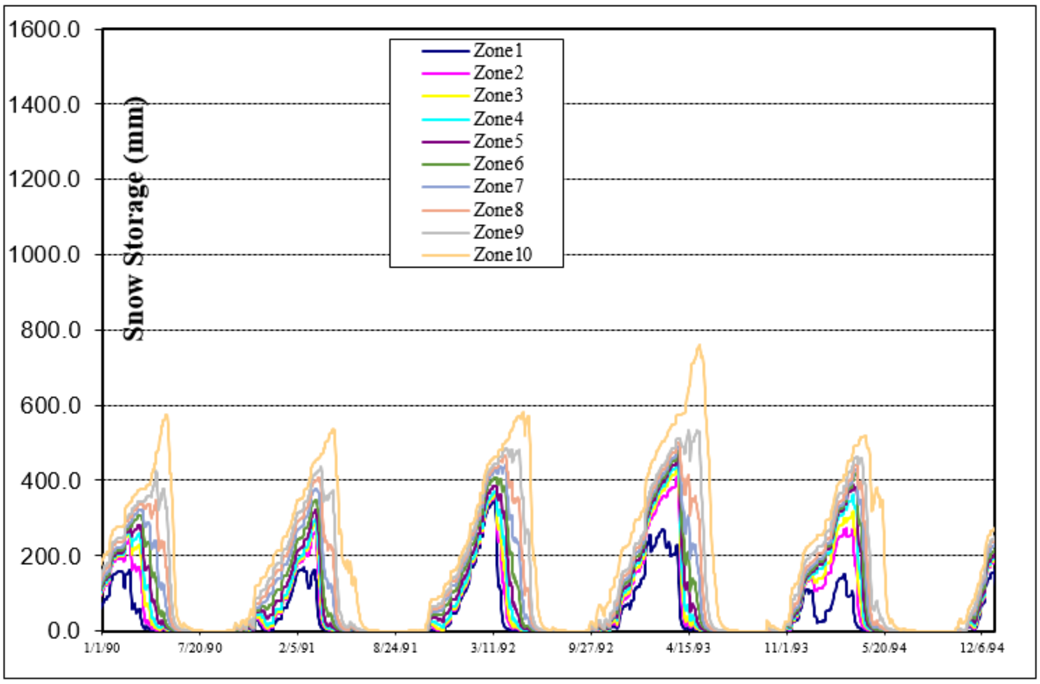

Figure A.9. The amount of snowpack over the all ten zones between 1990-1994..

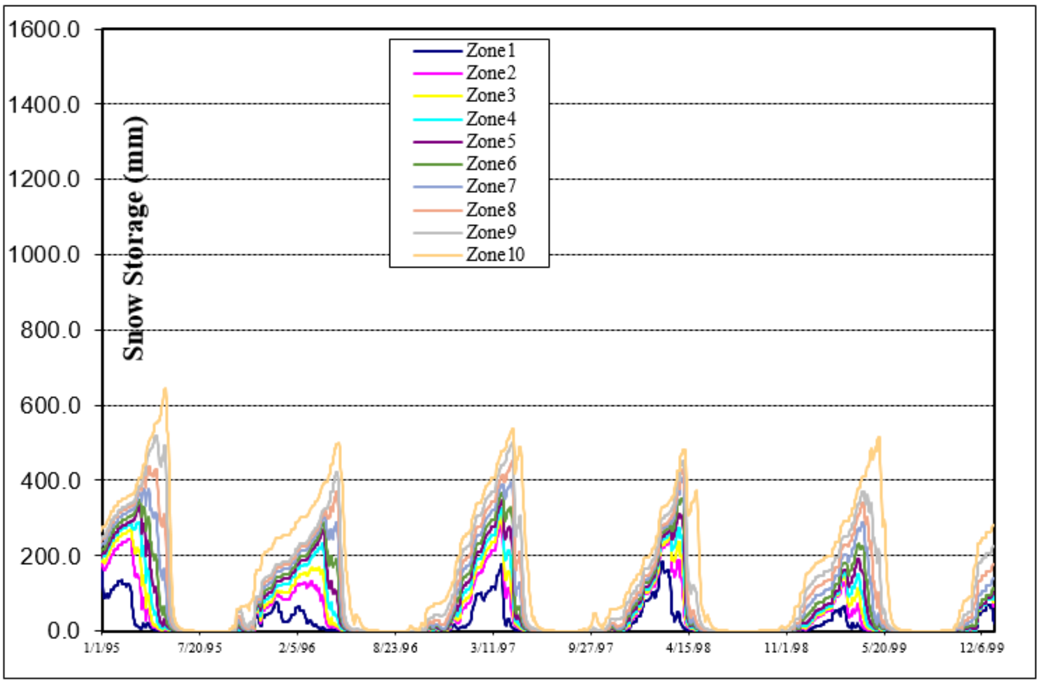

Figure A.10. The amount of snowpack over the all ten zones between 1995-1999.

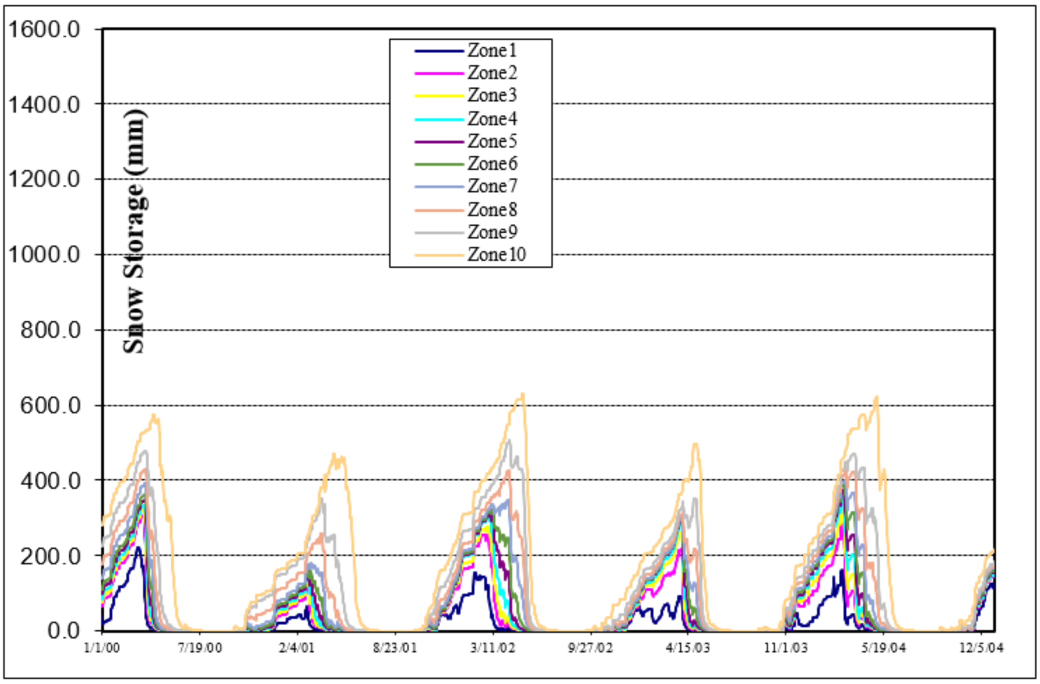

Figure A.11. The amount of snowpack over the all ten zones between 2000-2004.

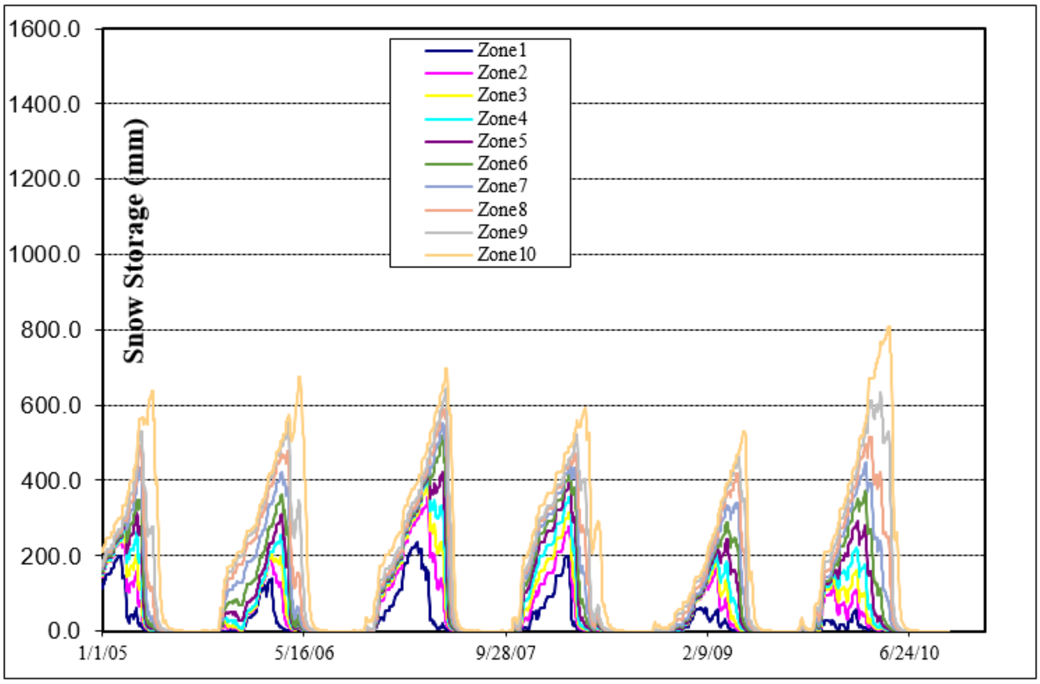

Figure A.12. The amount of snowpack over the all ten zones between 2005-2010.

APPENDIX B: The Python Code of GR4J Rainfall-Runoff Model Compound

```
from numba import njit
from .cemaneige_model import run_cemaneige
from .gr4j_model import run_gr4j
def run_cemaneigegr4j(prec, mean_temp, etp, frac_solid_prec, snow_pack_init,
thermal_state_init, s_init, r_init, params):
liquid_water, G, eTG = run_cemaneige(prec, mean_temp, frac_solid_prec,
snow_pack_init, thermal_state_init,
params)
qsim, s_store, r_store = run_gr4j(liquid_water, etp, s_init, r_init, params)
return qsim, G, eTG, s_store, r_store
import numbers
import numpy as np
from scipy import optimize
from .basemodel import BaseModel
from .cemaneigegr4j_model import run_cemaneigegr4j
from .cemaneige_utils import (extrapolate_precipitation,
extrapolate_temperature,
calculate_solid_fraction)
from ..utils.array_checks import validate_array_input, check_for_negatives
from ..utils.metrics import calc_mse
class CemaneigeGR4J(BaseModel):
_param_list = [’CTG’, ’Kf’, ’x1’, ’x2’, ’x3’, ’x4’]
_default_bounds = ’CTG’: (0, 1),
’Kf’: (0, 30),
’x1’: (10, 2000),
’x2’: (-100, 3),
’x3’: (20, 750),
```

```
’x4’: (1.1, 2.9)
_dtype = np.dtype([(’CTG’, np.float64),
(’Kf’, np.float64),
(’x1’, np.float64),
(’x2’, np.float64),
(’x3’, np.float64),
(’x4’, np.float64)])
def __init__(self, params=None):
super().__init__(params=params)
def simulate(self, prec, mean_temp, min_temp, max_temp, etp,
met_station_height, snow_pack_init=0, thermal_state_init=0,
s_init=0, r_init=0, altitudes=[], return_storages=False,
params=None):
prec = validate_array_input(prec, np.float64, ’prec’)
mean_temp = validate_array_input(mean_temp, np.float64, ’mean_temp’)
min_temp = validate_array_input(min_temp, np.float64, ’min_temp’)
max_temp = validate_array_input(max_temp, np.float64, ’max_temp’)
etp = validate_array_input(etp, np.float64, ’pot. evapotranspiration’)
if check_for_negatives(prec):
msg = ”The precipitation array contains negative values.”
raise ValueError(msg)
if any(len(ar) != len(prec) for ar in [mean_temp, min_temp, max_temp, etp]):
msg = ”All meteorological input arrays must have the same length.”
raise RuntimeError(msg)
if not isinstance(altitudes, list):
raise TypeError(”’altitudes’ must be a list.”)
if len(altitudes) > 0:
for val in altitudes:
if not isinstance(val, numbers.Number):
msg = ”All elements in ’altitudes must be numbers.”
raise TypeError(msg)
if met_station_height is None:
```

```
msg = [”The height of the meteorological station is missing.”]
raise ValueError(msg)
if not isinstance(met_station_height, numbers.Number):
raise TypeError(”’met_station_height’ must be a number.”)
altitudes = np.array(altitudes)
if not isinstance(met_station_height, numbers.Number):
raise TypeError(”’met_station_height’ must be a Number.”)
if not isinstance(snow_pack_init, numbers.Number):
raise TypeError(”’snow_pack_init’ must be a Number.”)
if not isinstance(thermal_state_init, numbers.Number):
raise TypeError(”’thermal_state_init’ must be a Number.”)
if not isinstance(s_init, numbers.Number):
raise TypeError(”’s1_init’ must be a Number.”)
if not isinstance(r_init, numbers.Number):
raise TypeError(”’r_init’ must be a Number.”)
snow_pack_init = float(snow_pack_init)
thermal_state_init = float(thermal_state_init)
s_init = float(s_init)
r_init = float(r_init)
if len(altitudes) > 0:
prec = extrapolate_precipitation(prec,
altitudes,
met_station_height)
(min_temp,
mean_temp,
max_temp) = extrapolate_temperature(min_temp, mean_temp,
max_temp, altitudes,
met_station_height)
else:
prec = np.expand_dims(prec, axis=-1)
mean_temp = np.expand_dims(mean_temp, axis=-1)
min_temp = np.expand_dims(min_temp, axis=-1)
```

```
max_temp = np.expand_dims(max_temp, axis=-1)
altitudes = np.array([met_station_height])
frac_solid_prec = calculate_solid_fraction(prec, altitudes, mean_temp,
min_temp, max_temp)
if params is None:
params = np.zeros(1, dtype=self._dtype)
for param in self._param_list:
params[param] = getattr(self, param)
else:
if params.dtype != self._dtype:
msg = [”The model parameters must be a numpy array of the ”,
”models own custom data type.”]
raise TypeError(””.join(msg))
if isinstance(params, np.void):
params = np.expand_dims(params, params.ndim)
qsim = np.zeros((prec.shape[0], params.size), np.float64)
if return_storages:
G = np.zeros((prec.shape[0], len(altitudes), params.size),
np.float64)
eTG = np.zeros((prec.shape[0], len(altitudes), params.size),
np.float64)
s_store = np.zeros((prec.shape[0], params.size), np.float64)
r_store = np.zeros((prec.shape[0], params.size), np.float64)
for i in range(params.size):
if return_storages:
(qsim[:, i],
G[:, :, i],
eTG[:, :, i],
s_store[:, i],
r_store[:, i]) = run_cemaneigegr4j(prec, mean_temp, etp,
frac_solid_prec,
snow_pack_init,
```

```
thermal_state_init,
s_init, r_init,
params[i])
else:
qsim[:, i], _, _, _, _ = run_cemaneigegr4j(prec, mean_temp, etp,
frac_solid_prec,
snow_pack_init,
thermal_state_init,
s_init, r_init,
params[i])
if return_storages:
return qsim, G, eTG, s_store, r_store
else:
return qsim
def fit(self, obs, prec, mean_temp, min_temp, max_temp, etp,
met_station_height, snow_pack_init=0, thermal_state_init=0,
s_init=0, r_init=0, altitudes=[]):
obs = validate_array_input(obs, np.float64, ’obs’)
prec = validate_array_input(prec, np.float64, ’prec’)
mean_temp = validate_array_input(mean_temp, np.float64, ’mean_temp’)
min_temp = validate_array_input(min_temp, np.float64, ’min_temp’)
max_temp = validate_array_input(max_temp, np.float64, ’max_temp’)
etp = validate_array_input(etp, np.float64, ’pot. evapotranspiration’)
if check_for_negatives(prec):
msg = ”The precipitation array contains negative values.”
raise ValueError(msg)
if any(len(ar) != len(prec) for ar in [mean_temp, min_temp, max_temp, etp]):
msg = ”All meteorological input arrays must have the same length.”
raise RuntimeError(msg)
if not isinstance(altitudes, list):
raise TypeError(”’altitudes’ must be a list.”)
if len(altitudes) > 0:
```

```
for val in altitudes:
if not isinstance(val, numbers.Number):
msg = ”All elements in ’altitudes must be numbers.”
raise TypeError(msg)
if met_station_height is None:
msg = [”The height of the meteorological station is missing.”]
raise ValueError(msg)
if not isinstance(met_station_height, numbers.Number):
raise TypeError(”’met_station_height’ must be a number.”)
altitudes = np.array(altitudes)
if not isinstance(met_station_height, numbers.Number):
raise TypeError(”’met_station_height’ must be a Number.”)
if not isinstance(snow_pack_init, numbers.Number):
raise TypeError(”’snow_pack_init’ must be a Number.”)
if not isinstance(thermal_state_init, numbers.Number):
raise TypeError(”’thermal_state_init’ must be a Number.”)
if not isinstance(s_init, numbers.Number):
raise TypeError(”’s1_init’ must be a Number.”)
if not isinstance(r_init, numbers.Number):
raise TypeError(”’r_init’ must be a Number.”)
snow_pack_init = float(snow_pack_init)
thermal_state_init = float(thermal_state_init)
s_init = float(s_init)
r_init = float(r_init)
if len(altitudes) > 0:
prec = extrapolate_precipitation(prec,
altitudes,
met_station_height)
(min_temp,
mean_temp,
max_temp) = extrapolate_temperature(min_temp, mean_temp,
max_temp, altitudes,
```

```
met_station_height)
else:
prec = np.expand_dims(prec, axis=-1)
mean_temp = np.expand_dims(mean_temp, axis=-1)
min_temp = np.expand_dims(min_temp, axis=-1)
max_temp = np.expand_dims(max_temp, axis=-1)
altitudes = np.array([met_station_height])
frac_solid_prec = calculate_solid_fraction(prec, altitudes, mean_temp,
min_temp, max_temp)
args = (obs, prec, mean_temp, frac_solid_prec, etp, snow_pack_init,
thermal_state_init, s_init, r_init, self._dtype)
bnds = tuple([self._default_bounds[p] for p in self._param_list])
res = optimize.differential_evolution(_loss, bounds=bnds, args=args)
return res
def _loss(X, *args):
obs = args[0]
prec = args[1]
mean_temp = args[2]
frac_solid_prec = args[3]
etp = args[4]
snow_pack_init = args[5]
thermal_state_init = args[6]
s_init = args[7]
r_init = args[8]
dtype = args[9]
params = np.zeros(1, dtype=dtype)
params[’CTG’] = X[0]
params[’Kf’] = X[1]
params[’x1’] = X[2]
params[’x2’] = X[3]
params[’x3’] = X[4]
params[’x4’] = X[5]
```

```
outflow, _, _, _, _ = run_cemaneigegr4j(prec, mean_temp, etp,
frac_solid_prec, snow_pack_init,
thermal_state_init, s_init, r_init,
params[0])
loss_value = calc_mse(obs, outflow)
return loss_value
```

APPENDIX C: THE JAVA CODE OF OPTIMIZATION

```
    package poolproblem;
import java.io.BufferedReader;
import java.io.FileReader;
import java.util.ArrayList;
import java.util.HashMap;
import java.util.Map;
public class PoolProblem
public static int totNumOf200 = 0;
public static int totNumOfLessThan200 = 0;
public static int totNumOfMoreThan200 = 0;
public static double total = 0;
public static void main(String[] args)
BufferedReader reader; v   try
ArrayList<Map<String, Double>> records = new ArrayList();
reader = new BufferedReader(new FileReader(”C:
Users
Developer
Desktop
op_da.txt”));
String line = reader.readLine();
line = reader.readLine();
while (line != null)
String[] str = line.split(”
t”);
Map<String, Double> map = new HashMap<>();
map.put(str[0], Double.valueOf(str[1]));
records.add(map);
line = reader.readLine();
```

```
double poolSize = 200;
int numOfBiggerThanTen = 0;
double totNumOfBiggerThanTen = 0.0;
int firstMoreThanTenDay = 0;
boolean check = true;
for (Map<String, Double> rec : records)
Map.Entry<String, Double> entry = rec.entrySet().iterator().next();
Double amount = entry.getValue();
if (amount > 10)
numOfBiggerThanTen++;
totNumOfBiggerThanTen = totNumOfBiggerThanTen + amount;
check = false;
else if (check)
firstMoreThanTenDay++;


double maxPoolSize = poolSize - (totNumOfBiggerThanTen - 10 * numOfBiggerThanTen);
boolean firstCheck = true;
boolean secondCheck = false;
if (maxPoolSize <= 0 —— maxPoolSize >= 200)
maxPoolSize = 200;

double currentPoolSize = 100;
for (Map<String, Double> rec : records)
Map.Entry<String, Double> entry = rec.entrySet().iterator().next();
Double val = entry.getValue();
String date = entry.getKey();
firstMoreThanTenDay–;
if(currentPoolSize >= 183 && firstCheck)
Double res = currentPoolSize + val - 10;
currentPoolSize = res;
System.out.println(date + ””⁀ + val + ””⁀ + res + ””⁀ + 10);
```

```
calculateResult(currentPoolSize);
firstCheck = false;
secondCheck = true;
else if (firstMoreThanTenDay >= -28 && secondCheck && currentPoolSize > 0 )
Double res = currentPoolSize + val - 10;
System.out.println(date + ””̑ + val + ””̑ + res + ””̑ + 10);
currentPoolSize = res;
calculateResult(currentPoolSize);
else
if (currentPoolSize + val > maxPoolSize)
Double bosalt = (currentPoolSize + val) - maxPoolSize;
currentPoolSize = maxPoolSize;
if (val <= 10)
System.out.println(date + ””̑ + val + ””̑ + currentPoolSize + ””̑ + bosalt);
calculateResult(currentPoolSize);
else
Double res = currentPoolSize + val - 10;
System.out.println(date + ””̑ + val + ””̑ + res + ””̑ + 10);
calculateResult(res);

else if (currentPoolSize + val <= maxPoolSize)
currentPoolSize = currentPoolSize + val;
System.out.println(date + ””̑ + val + ””̑ + currentPoolSize + ””̑ + 0);
calculateResult(currentPoolSize);


if (val > 10)
numOfBiggerThanTen–;
totNumOfBiggerThanTen = totNumOfBiggerThanTen - val;
double recentMax = maxPoolSize;
maxPoolSize = poolSize - (totNumOfBiggerThanTen - 10 * numOfBiggerThanTen);
if (maxPoolSize <= 0 —— maxPoolSize >= 200)
```

```
maxPoolSize = 200;
else if (recentMax - maxPoolSize + val> 10)
maxPoolSize = recentMax;



System.out.println(”Total Number of Days equals 200 : ” + totNumOf200);
System.out.println(”Total Number of Days more than 200 : ” + totNumOfMoreThan200);
System.out.println(”Total Number of Days less than 200 : ” + totNumOfLessThan200);
System.out.println(”Average : ” + total / records.size());
catch (Exception e)
e.printStackTrace();


public static void calculateResult(double value)
total = total + value;
if (value == 200)
totNumOf200++;
else if (value > 200)
totNumOfMoreThan200++;
else if (value < 200)
totNumOfLessThan200++;
```