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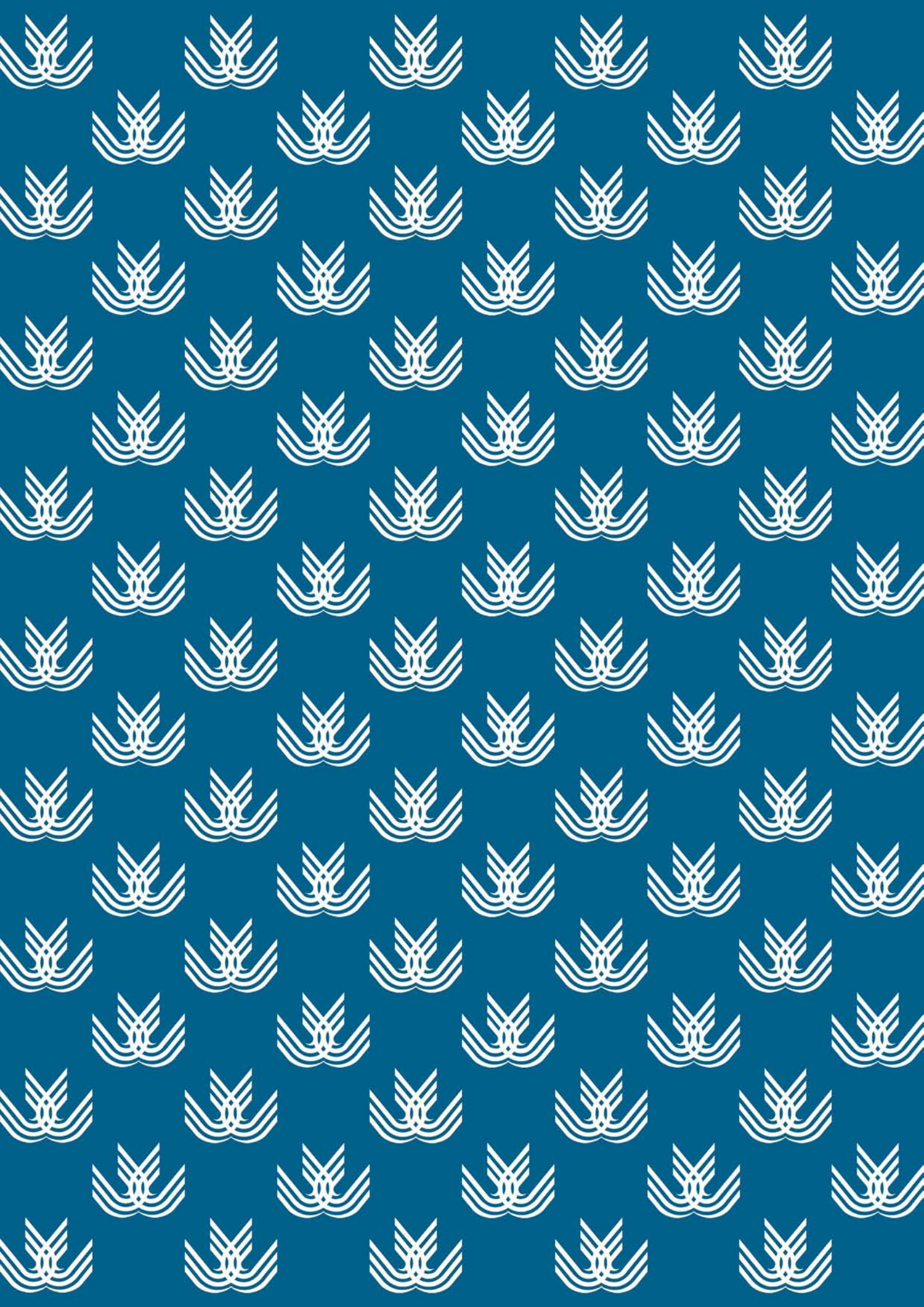

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B.1 PROJECT REPORT

1. Project description

In this project an implementation and calibration of a simulator is realized. The simulator works using a new version of a model named “Variable Infiltration Capacity” (VIC). This model simulates the hydrologic cycle, concretely the land surface behavior (processes such as infiltration of water, evaporation from soil and plants, runoff…) for the catchment located in the target land. The model is used to predict the amount of water available in that catchment per year for hydropower production applications.

The VIC model has been created at the University of Washington, in concrete at the Department of Civil and Environmental Engineering and under the direction of Dennis P. Lettenmaier. Development and maintenance of the current official version of the VIC model is conducted at the same departments. Every new application addresses new problems and conditions which the model may not currently be able to handle, and as such the model is always under development.

VIC is a research model and in its various forms it has been applied to many watersheds including the Columbia River, the Ohio River, the Arkansas-Red Rivers, and the Upper Mississippi Rivers, as well as being applied globally.

2. Context

This project has been done at the company Agder Energi, a leading company in the Norwegian renewable energy sector. Agder Energi is Norway’s fourth-largest energy supplier measured by hydroelectric power generation. The group’s activities comprise generation, distribution and sale of renewable energy, as well as providing energy-related services. The company owns many hydropower plants at the southern part of Norway where the electricity is generated by damming a waterway and using the water to run turbines for the purpose of making electricity. For better understanding, in Annexe1: Hydropower engineering, plant and development is explained how hydropower plant works.

The project has been done at the Research and Development department as part of a training program. The purpose is to contribute to optimization and improvement of hydropower production.

It is important to get clear some basic concepts that help to understand the work carried out at this department. They are explained in Annexe1: Hydropower engineering, plant and development. For better understanding, it is explained how a hydropower plant works and the sciences that study this field.

3. Objectives

The long-term goal is that the tool set will be deployed to assist hydropower operators in market, schedule, dispatch, and operational decisions at the company. In Norway, 99% of all power produced from hydropower, most of which is generated by reservoir systems. Therefore, it is very important estimates the annual average quantity and value of hydropower produced by the reservoirs. The main research interest of this project is identify how much water yield or value each part of the landscape contributes annually to hydropower production in the region under study. Also, modeling and predicting the role of land hydrology in the climate system and understanding the nature of hydrologic variability and change.

The tool set was demonstrated using data from hydropower sites that are representative of different operational and environmental conditions. Modification and refinements were made as necessary to help to ensure that the tool set is practical and useful in helping hydropower planners and operators in how to operate conventional hydropower plants more efficiently: this is the major challenge facing hydropower suppliers such as Agder Energi today, concretely, increasing electricity generation and power sales while dealing with an increasingly uncertain water-constrained operating environment and complex electricity markets.

Hydropower production comes from watershed-fed reservoir systems that generally deliver energy consistently and predictably. The systems are designed to account for annual variability in water volume, given the likely levels for a given watershed, but are vulnerable to variation caused by land use and land cover changes. These changes can alter hydrologic cycles, affecting patterns of evapotranspiration, infiltration and water retention, and changing the timing and volume of water that is available for hydropower production.

Changes in the landscape that affect annual average water yield upstream of hydropower facilities can increase or decrease hydropower production capacity.

Some Hydrological models estimates the contributions of water from different parts of a landscape, offering insight into how changes in land use patterns affect annual surface water yield and hydropower production. For more information about hydrological models go to the Annexe2: Hydrological models

For this reason, simulate land-surface behavior assists hydropower planners and operators in market, schedule, dispatch, and operational decisions such as:

- Manage the risks associated with hydrological uncertainty and adverse environmental impacts
- Reduce costs
- Increase unit availability and plant capacity factors
- Enhance the economic value of hydropower resources

- Dam safety. It is possible to get more information about dam safety in the **Annexe1: Hydropower engineering, plant, and development**

4. Simulation of Hydrological processes

Hydropower systems are designed around knowledge of the hydrologic cycle: hydrological cycle is a conceptual model that describes the storage and movement of water between the following major reservoirs: atmosphere, oceans, lakes, rivers, soils, glaciers, snowfields and groundwater. Water moves from one reservoir to another by way of processes like evaporation, condensation, precipitation, deposition, runoff, infiltration, sublimation, transpiration, melting and groundwater flow.
VIC is a hydrological model that simulates the hydrological cycle for a catchment. It represents physical processes within the watershed and their interaction. In this project, VIC model is applied to a watershed called “Skjerka”, a region located in the south of Norway. The implemented model works as a transformation operator that uses mathematical equations and logical statements to transform Inputs I(t) into outputs, O(t). VIC is a precipitation-runoff model (explained in **Annexe 2: Hydrological models**) where the inputs are meteorological variables and the outputs contains the total amount of runoff for the catchment. Data for input contents is provided by meteorologist at the company, and other relevant information is collected by specialist. The model then simulates the hydrological cycle for this catchment transforming the inputs, I(t) into outputs, O(t) and calculates the total amount of runoff for the catchment. This data is useful for hydropower planning and operation since it tells us the amount of available water for hydropower production.

The watershed Skjerka is looked upon as an operator transforming the moisture inputs, I(t) into outputs, O(t). A representation of the processes is shown on Figure 4. VIC works transforming the inputs,I(t): precipitation, evapotranspiration, windspeed and air temperature into outputs, O(t), which contains the total runoff. Figure 4.a represents a map of the region under study, Skjerka with its lakes and waterpaths. Figure 4.b represents part of Skjerka as if it were a box. VIC simulates land-surface behavior and takes into account the thickness of the soil. For this reason, VIC divides the soil into layers. The program uses different statements and equations for each layer in order to represent the different processes and their links.

INPUTS, I (t)



OUTPUTS, O (t)

Figure 4.a

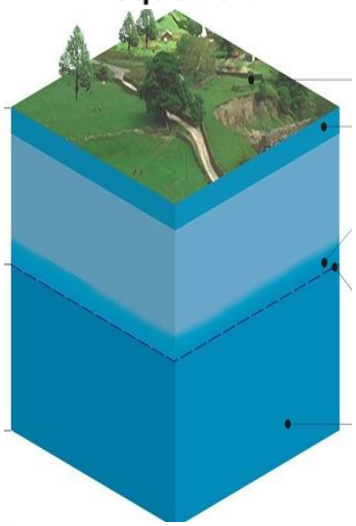
Precipitation

Air Temperature

Evapotranspiration

Wind speed

transformation operator equation



TOTAL RUNOFF Q , m3/s

AVAILABILITY OF WATER

Figure 4.b

Figure4: Skjerka looked upon as an operator transforming the moisture inputs, I(t) into Outputs, O(t). VIC works transforming the inputs,I(t): precipitation, evapotranspiration, windspeed and air temperature into outputs, O(t): total runoff for the catchment Skjerka. Figure (a) illustrates map of Skjerka, and figure (b) part of the system which is divided into layers.

The input data is collected in the input files. They have to contain information that characterizes the watershed such as vegetation and soil parameters. These parameters need to be adjusted in order to make sure that inputs represent properly the system.

The variables to introduce to run the model are the meteorological variables mentioned above. The outputs are given in output files after running each simulation. More information about hydrological cycle and its processes, components and modeling is collected in the **Annexe2: Hydrological models**. Specific information about the VIC model (how it works as a transformation operator, its equations, statements, schemes of the processes…) is located in the **Annexe 4: VIC model overview**.

5.Running the VIC model

Characterization of Skjerka has to be taken into account in order to make it run successfully. The first task in this project is to install the model and make it run. In general, running VIC successfully involves preparation of different input files, downloading the source code, configuring output files, and entering a few commands. Approaching the task in steps will ease the process:

1. Prepare all the input files: unfilled input files are available at the website, on the download page:

http://www.hydro.washington.edu/Lettenmaier/Models/VIC/SourceCode/Download.shtml. Input files need to be filled in with variables and parameters that are indicated on their structure and they may be constructed using various programs and datasets. The variables and parameters need to be set according with the catchment characterization (type of vegetation, soil, weather conditions, modes of operations….) in order to simulate as good as possible land-surface behave. AIso, it is possible to configure the output files (the result files of each simulation) before you run the model. It is possible to specify which files you want to get and the units and variables that you need.

Below there are general descriptions of each input file with its structure. For more information, you can see the Annexe5: Input files, where all the parameters and the structure of the files are described.

- *Global Parameter File:* This is the main input file for VIC. It points VIC to the locations of the other input/output files and sets parameters that govern the simulation (e.g., start/end dates, modes of operation).
- *User_def.h File*: While this is not technically an "input" file (it is a header file in the model source code), it is worth mentioning because some simulation options are set in this file.
- *Meteorological Forcing Files*: VIC can take daily or sub-daily timeseries of meteorological variables as inputs. These can be gridded or point station data or reanalysis fields.
- *Soil Parameter File:* Cell ID numbers, lat/lon, soil texture and other characteristics.
- *Vegetation Library File:* Descriptions of the available land cover types

- *Vegetation Parameter File*: Landcover types, fractional areas, rooting depths, and seasonal LAIs of the various landcover tiles within each grid cell.

And a few more are optional:

- Initial State File: Moisture storages (soil moisture, snow pack, etc), energy storages (soil temperatures, etc) and other information describing the current state of the system. A state file saved from a previous VIC simulation may be used as the initial state for another run.
- Elevation Band File: File summarizing the distribution of elevations in each grid cell. By default, VIC assumes grid cells are flat.
- Lake/Wetland Parameter File: File containing lake model parameters. By default, VIC does not simulate lakes or other impoundment of surface water.

Typically a few key parameters in the Soil Parameter File are calibrated. Some parameters in the Lake/Wetland Parameter File are also calibrated

2.Running VIC: The source code is compressed in a package. The VIC model has been developed for use on LINUX and UNIX platforms. To extract the code, compile it, and make it run it is necessary to insert commands in the UNIX emulator. This step is explained with detail in the Annexe 4: How to run VIC. To install VIC, it is necessary to download the source code from the website: http://www.hydro.washington.edu/Lettenmaier/Models/VIC/SourceCode/Download.shtml. To use VIC on a windows platform, a UNIX emulator such as Cywin is needed to compile/run this model.

3. Configuring output files: the contents of the result files can be controlled by the user**.** After running VIC successfully, you will find a new folder in the same directory where you saved source code. This folder contains the output files that contain the "results" of each simulation. You can adjust some options in the input files to choose which output files and variables you want to get. Information about this files and their structure are described with detail in **Annexe 6: Output files.**

6. Calibration the VIC Model

Calibration in this project is focus on minimize the difference between the observed vs simulated values of runoff, Q m3/s for the catchment Skjerka. The VIC model is characterized by complex functional relationships and a large number of parameters that are usually conceptual representations of the watershed. That means that the calibration **of the VIC model in Skjerka is the estimation of model parameters to achieve a system that closely resembles the actual system that the model represents.** In this project most of the information based on satellite observations or geological surveys is provided. Meteorologist and other specialist at the company have collected meteorological data-series based on measurements at the area under study, Skjerka. This information is collected in order to prepare the input files (information about meteorology, vegetation type, soil properties and textures…is needed). The parameters that cannot be directly measured or are not exactly known of spatial variability measurement error must be calibrated. For these parameters, we either must make assumptions about their values or calibrate them (find optimal values for them) that minimize the differences between model output and observations.

VIC is tested for a concrete period of time (1/08/2002/ - 31/12/2008). Real dataseries of total runoff,Q (observed runoff, Qobs) are available for this time period in order to compare them with the simulated total runoff, Qsim. Once we validate the model, we can use it for simulating hydrological processes and predict the total amount of water (runoff, Q, m3/s) that is going to be available for hydropower applications. **Figure 6.1** shows a general scheme of the general procedure:

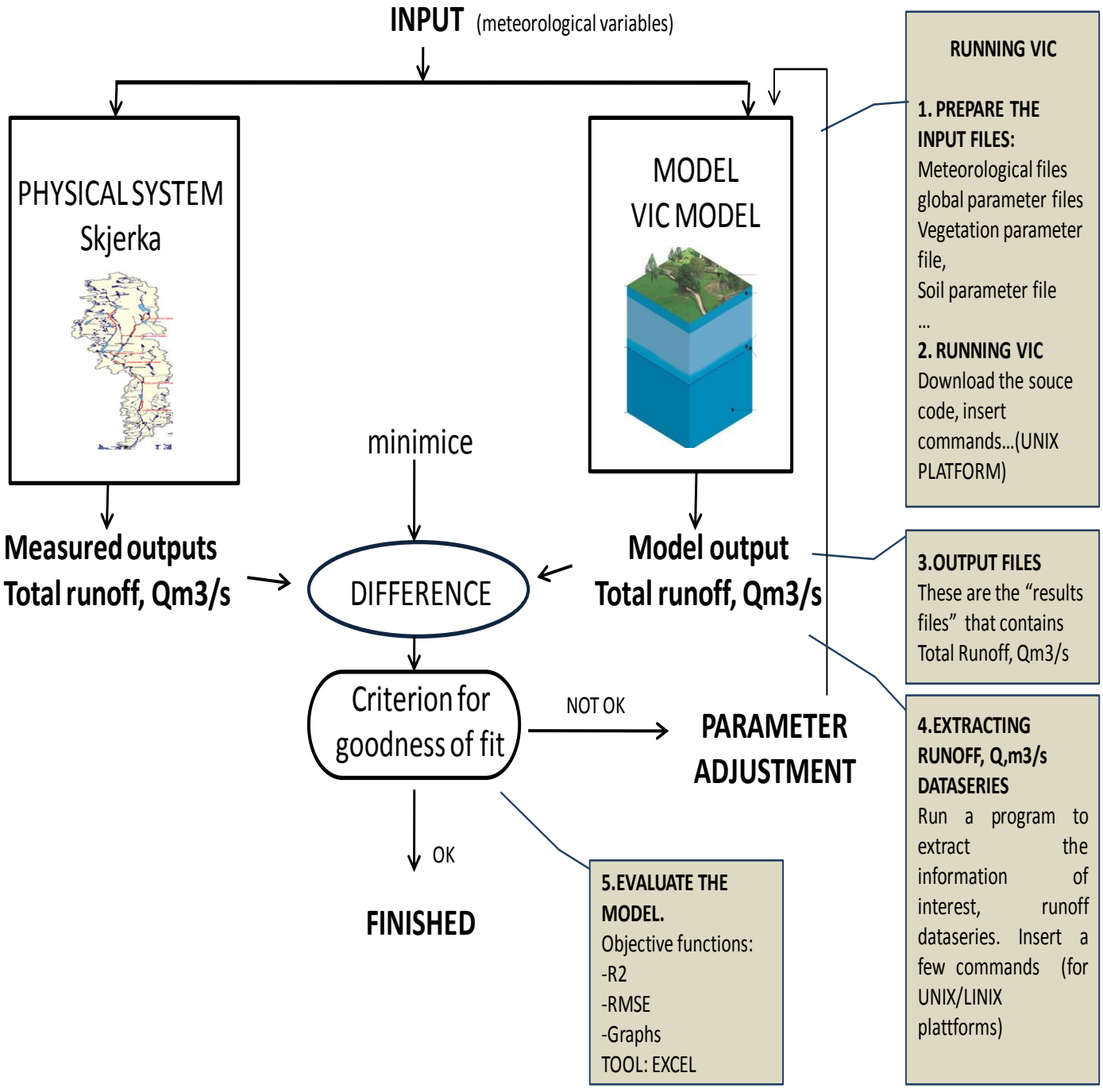


Figure6.1: general scheme of implementation and calibration the VIC model

THE METHOD OF ANALYSIS THE RESULTS was carried out systematically:

1. Extracting runoff data series from the output files to a excel sheet (step 4 of the scheme). Output files not only contain information of runoff data. VIC calculates other variables such as the soil moisture content on each layer, amount of snowmelt….that are not relevant for calibration. For extracting the dataseries of interest (in concrete, a couple of columns of the file), a program is created. This program is a file that contains a code that I have created by myself using tools C/C++ and Phyton programming. To make it run it is necessary to introduce a few commands in the same linux/Unix platform (Cywing) that is used for running the VIC model. After running this program, you will find files in your directory with the desirable data, ready for being analyzed in a excel sheet. More information about this program is given in the section 7: Scope, on this document.

2. Secondly, excel calculations to compare the results with the observed (measured) values (step 5 of the scheme). Excel is an excellent tool for the analysis of data series and the evaluation of the model. It allows to make graphical and mathematical (objective functions) analysis of the results. The calibration of parameters is conducted via a trial and error procedure that leads to an acceptable match of model-predicted discharge with observations. Besides visual comparison of simulated and observed hydrographs, three objective functions are often used:

- **Nash-Sutcliffe efficiency (*R2 or Ef*)**: describes the prediction skill of the modeled streamflow as compared to the observed value. When R2 equals to 1.0, the model perfectly predicts the observations.

$$E_f = 1 - \frac{\sum_{i=1}^{N}(Q_{\mathrm{mod},i} - Q_{obs,i})^2}{\sum_{i=1}^{N}(Q_{obs,i} - \overline{Q_{obs}})^2}$$

- **The relative error (*Er*)**: the Bias error between simulated and observed mean annual runoff. *Er* is calculated as:

$$E_r = (\overline{Q_{\mathrm{mod}}} - \overline{Q_{obs}}) / \overline{Q_{obs}}$$, and

Er= 1-Qsim/Qobs

In some of the results only Qsim/Qobs is calculated (It easy to understand, for example, if Qsim/Qobs=0.7, you know that the bias error is 0.3)

- **Average root mean square error, RMSE:**

$$RMSE=((1/n)*(\sum Q_{obs,i} - Q_{sim,i})^2)^{0.5}$$

$Q_{mod,i}$ =monthly modeled streamflow for month *i*,
Q_{obs} = monthly observed streamflow for month *i*,
N =the number of months
$\overline{Q_{\mathrm{mod}}}$ = mean of the monthly modeled
$\overline{Q_{obs}}$ =observed streamflows, respectively.

During the model calibration it is always necessary to have a clear understanding of the model structure and how different parameters affect the model response. A brief description is given below though you can find more information in Annexe3: VIC model overview, and Annexe 8: VIC model calibration.

MODEL STRUCTURE

As it is shown in the picture 6.2, VIC simulates the land-surface behavior by dividing the land in three layers. For this reason the model structure is called also "VIC 3L". The layers are: top thin layer (layer 0), top layer (layer 1) and the bottom layer (layer 2). The different layers are responsible for different events of the hydrological cycle. Since the top thin soil layer is very thin, it is considered that the soil is divided into two soil layer: the upper layer (on the top) and the bottom layer. These two layers behaviors are described by different hydrological processes. In consequence, they are represented by different equations with different parameters. R is the stream flow that results from the upper layer processes, Runoff; B is the stream flow that results from the processes that occur in the lower layer, it is called Baseflow. R and B sum to the total runoff, Q m3/s.

Figure 6.3 shows how VIC simulates land-surface behavior: it considers the peace of land as if it were a box, or a "grid-cell". The box is divided into cells, and VIC computes all the calculations for each cell. One single cell is shown at the picture. VIC simulates a grid-cell because it considers the spatial variability of the region (more information about VIC model structure is located in the Annexe3: VIC model overview). In the figure it is shown the couple of equations (with a graph) that characterize the behavior of the upper layer and the bottom layer respectively. Among other processes, Upper layer is characterized by infiltration of water through the soil and bare soil evaporation. Infiltration of water is represented by the Variable infiltration Curve. Bottom layer, among other processes, is characterized by the Baseflow curve and evapotranspiration (transpiration from roots of the plants). Both curves with their parameters are described briefly on this section of the project, though more information is located at the Annexe3: VIC model overview.

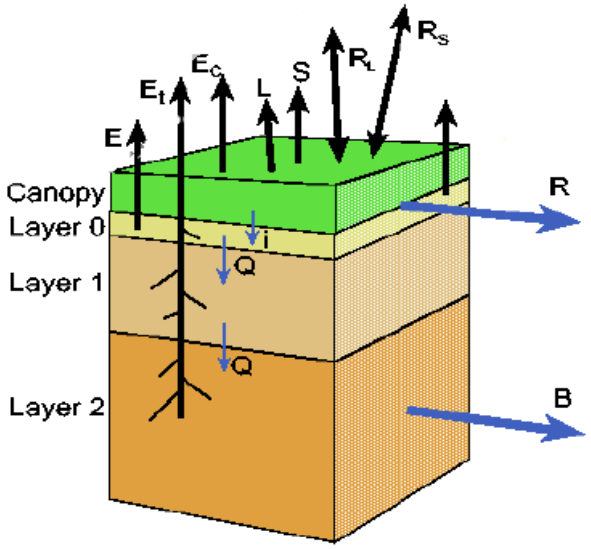


Figure6.2: model structure, VIC 3L. VIC divides soil into three layers. These layers are responsible for different processes of the hydrological cycle. R and B are the stream flows that come from different layers. They are the response of the soil to different processes. They sum the total runoff, Qsim that is compared with the observed data.

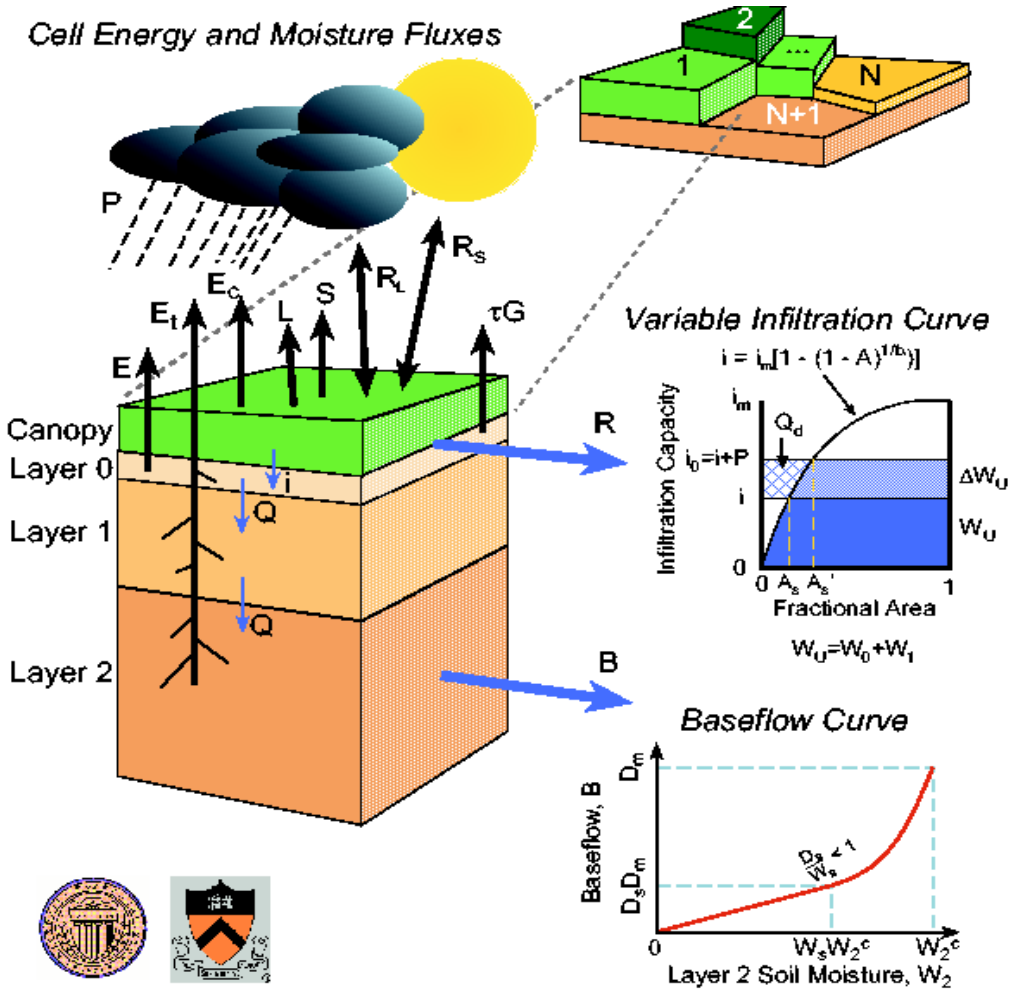


Figure 6.3: VIC represents soil as if it were a cell. For this cell the surface is divided into different vegetation tiles, and soil is divided into layers. Vegetation tiles represent different vegetation types. Main processes that affect calibration of the model are: soil infiltration and movement of water through the bottom layer. These processes are described by the variable infiltration curve, and the baseflow curve. They occur in the upper layer and lower layer respectively.

According with the general procedure for the calibration of hydrological models, and taking into account the structure of the VIC model,(see Annexe2:Hydrological models) the calibration process in this project is the following:

PROCEDURE

1. **INITIAL SIMULATIONS:** this step is based on intuition, and several parameters need to be changed simultaneously. The subjective method is most efficient in this part, when objective methods are more suitable during the final 'fine tuning' of the model where parameters are close to their optimal values. More detailed information of this step is located in the **Annexe 9: Initial simulations.** The next picture is an example of one of the first plots that I've made:

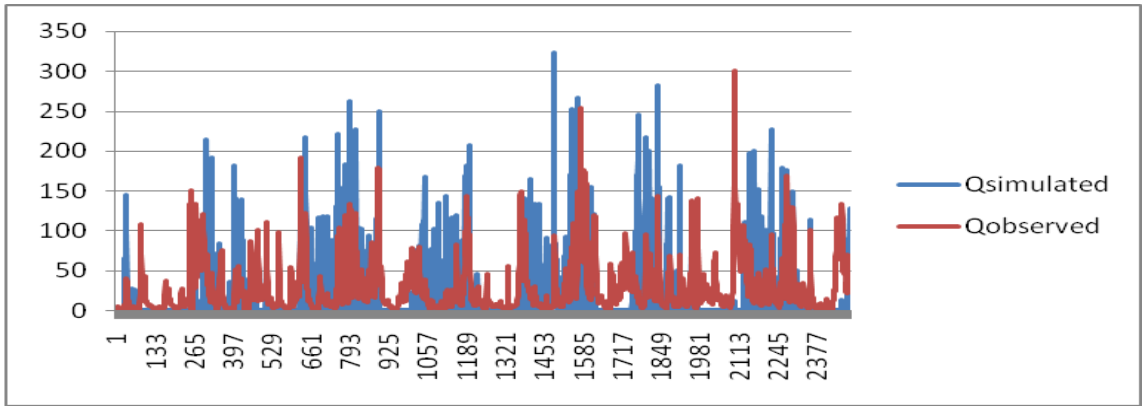


Figure6.4: graph of Qsimulated versus Qobserved. Y axis represents Q in m3/day and X axis represents number of days.

2. **PARAMETER ESTIMATION**

Parameter estimation is conducted in two blocks:

- UPPER LAYER PARAMETERS ADJUSTMENT: in this phase the parameters that are involved on this layer characterization are adjusted. Two combinations that best fit the runoff are chosen. Then, the runoff response of the soil is adjusted. Detailed information of this step is available at the Annexe10: Upper layer adjustment
- BOTTTOM LAYER PARAMETERS ADJUSTMENT. For these two selected cases, baseflow parameters are calibrated to fit the low flow. First I adjust baseflow

for one of the best cases from the upper Then, I repeat the same process for the other upper layer best selected case. Detailed information is located in the Annexe11: Baseflow adjustment

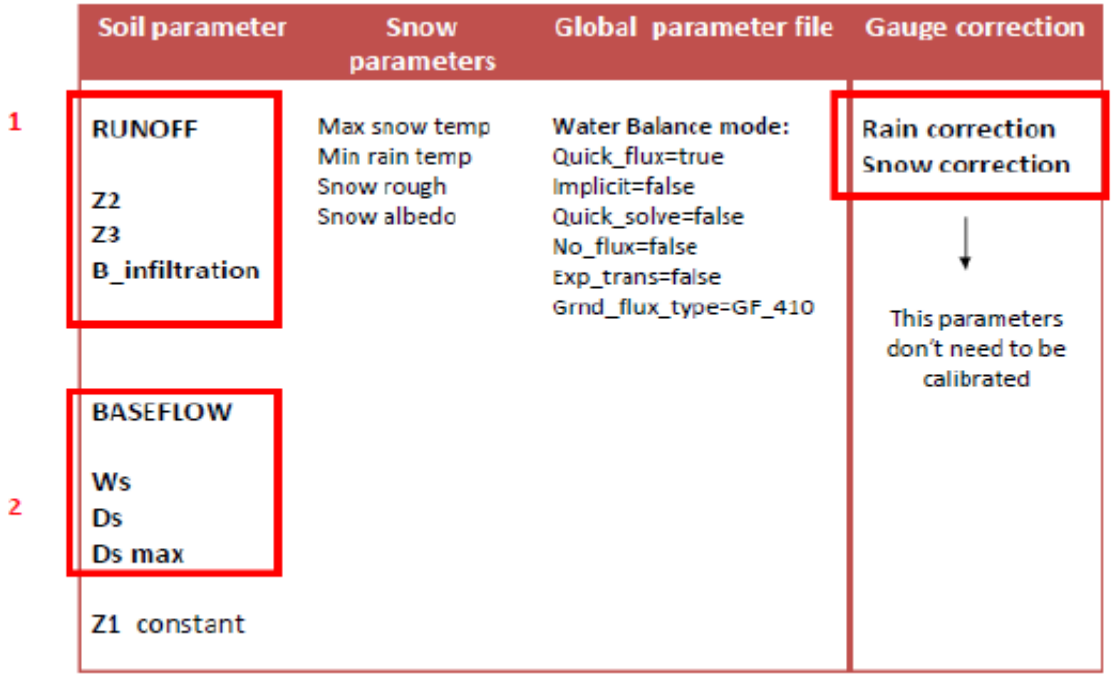


Figure 6.5: Table with parameters that can affect VIC model calibration. First row has the names of the files where the parameters are located. Parameters inside of the frame are the parameters under study on this project. On the initial phase it was realized that snow and rain correction parameters didn't need to be changed. Therefore, parameter was conducted in two blocks (frame 1 and 2) that correspond to the upper layer first, and the bottom layer.

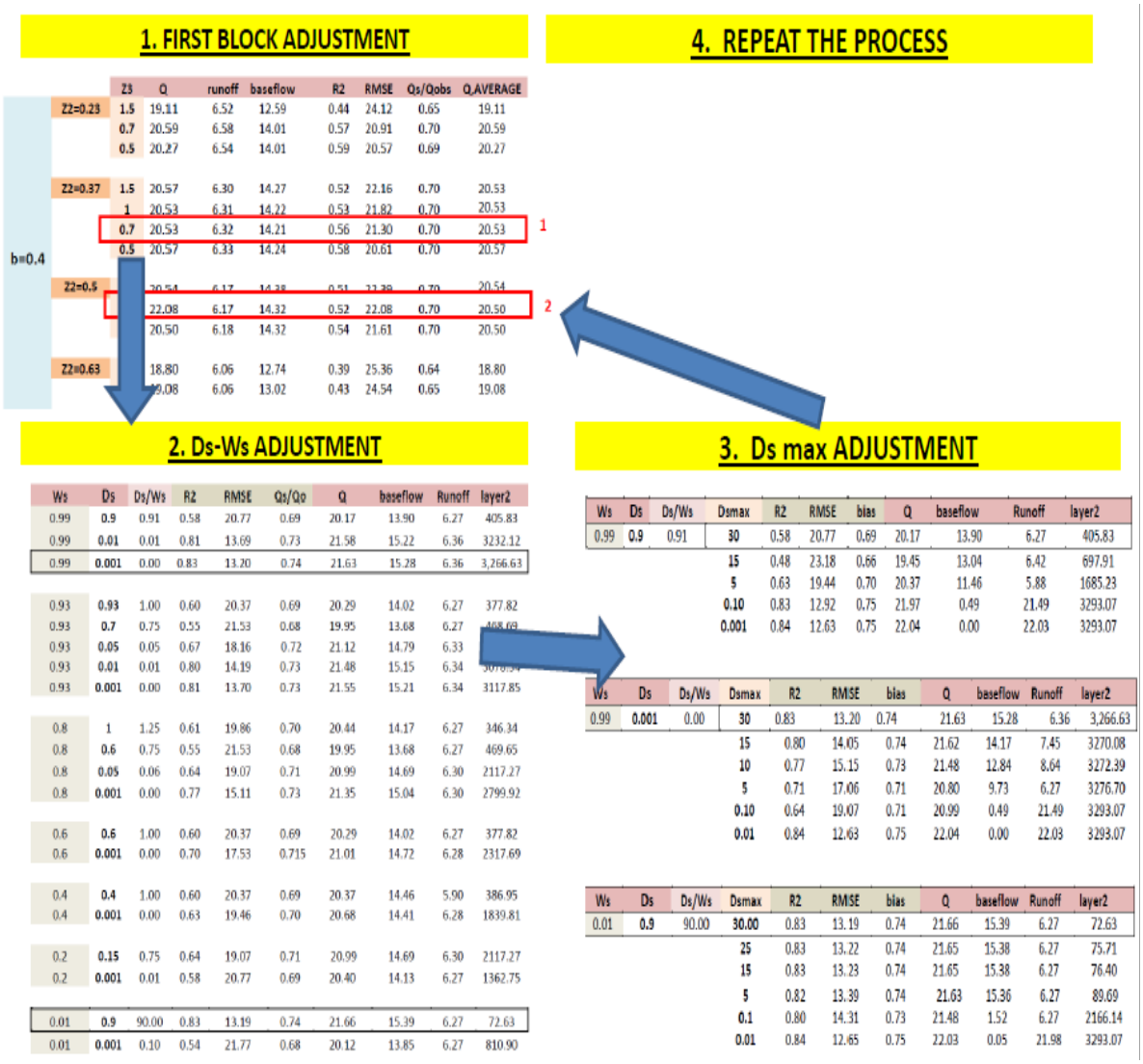


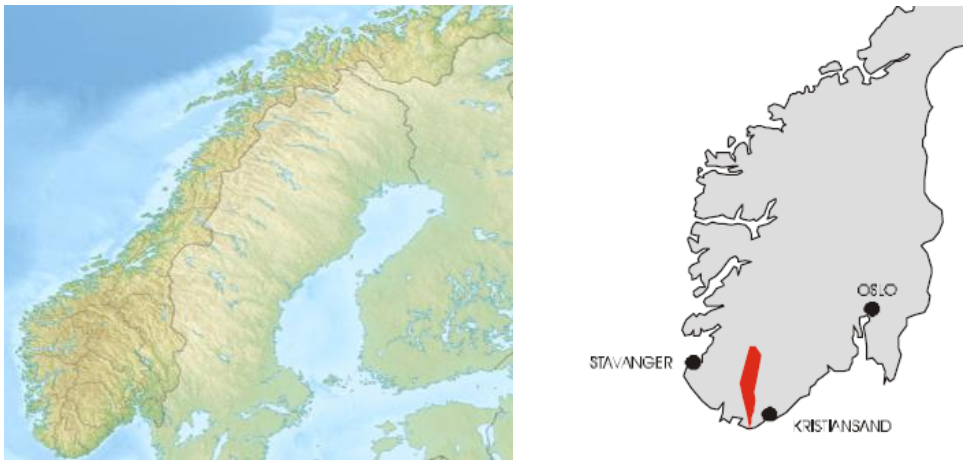
Figure 6.6: Scheme with the calibration procedure. Files with results from an Excel sheets are located. 1) First block adjustment: results with two best selected cases. 2)BOTTOM LAYER ADJUSTMENT: for the “best case 1”, adjust Ws and Ds together. 3) Adjust Ds max for this combination.4) Repeat the process for the “best case 2”.

FINAL “FINE” ADJUSTMENT: this step is a final adjustment of parameters to get the best simulation results. Small variations are made to parameters to make sure that there are no best possible combinations. For more information of this step go to Anexe 12: Final adjustment

7. Scope

AREA OF STUDY: SKJERKA

This project has been applied to a region located in the south of Norway called Skjerka. It is located in the southern part of the country, as it is illustrated in figure 7.1:



(a) (b)

Figure7.1:(a) Map of Norway, (b) Skjerka located in the map of Norway.

In this region, air temperature, precipitation, evapotranspiration, wind speed and availability of water data is collected and provided by meteorologists. All these data is collected for the time of period: **1/08/2002 -31/12/20012.** For model calibration, using the whole entire period record is not representative: it requires using long data series and would take a long time for users (it takes more time running longer dataseries). Simulated data is going to be compared with real database for the adjustment for one year, concretely, 2006.

Skjerka covers an area of 425 km^2. The model is going to simulate hydrological processes in this area. For this purpose, the VIC model treats Skjerka as a gridcell which contains 160 cells. According with this, collected data is needed to characterize each cell, or each "piece of land" (land is not uniform: type of vegetation, soil properties, porosity…varies along the catchment). VIC computes each cell, so after running a simulation, 160 output files are given : each outputfile contains the streamflow R and B for each cell. Since the interest of this work is to get the total runoff, Q (m3/s) for the whole catchment (and Q= S+R), total runoff is computed as: Q= S(sum of 160 cells) + B (sum of 160 cells).

It is made by the program (the code that I wrote) that I mention on section 5. This program extracts Runoff from each output file and sums it, and does the same with Baseflow, as it is shown on Table 7.1 and figure 7.2:

OUTPUT FILES			FILE READY TO USE ON EXCEL	EXCEL FILE CALIBRATION
1.(Cell 1)	Runoff, R Baseflow, B … Other data	**RUNNIG THE CODE**	Total runoff, R: R=(R1 + R2+…R160) Total baseflow, B: B= (B1+B2+…+B160)	Qsim (R+Q) versus Observed , Qobs
2.(Cell 2)	Runoff, R Baseflow, B … Other data			
…	…			
160.(Cell 160)	Runoff, R Baseflow, B			

Table A.7.1: Scheme of how the program extracts the information from output files

RUNOFF DATA SIMULATION , m3/s				
Date	Cell n1	Cell n2	Cell n3	SUM
1979				...
... ...				...
2008				...

BASEFLOW DATA SIMULATION, m3/s				
Date	Cell n1	Cell n2	Cell n3	SUM
1979				...
... ...				...
2008				...

Figure 7.2 Calculated runoff and baseflow for the catchment (for all cells). They are given in a file ready to use in excel. After running this program you get both columns “sum” in a single file.

8. Requirements

It is important to mention some aspects related with the database.

-Hydrology variability and the need for long data series: exists a large hydrology variability mainly due to climatic variability. A correspondingly variability in future flow conditions must generally be expected. To obtain a best possible estimate, a flow series as long as possible is desirable. It is important to make clear: long data series are recommended for VIC applications, but not for the calibration process. Long data series takes longer time for simulation (VIC has to compute more data). When calibration of the model, many simulations must be run until the model is adjusted and it would take too much time.

-Automatic data acquisition systems: for hydropower operation, more input data and frequent model updating is required. It has created a demand for completely automatic data acquisition systems, when the flow of data from sensors into the forecasting models can be made automatically and without human interruption or delays. Sources of error and methods used to reduce or eliminate such errors are needed due to the different measuring methods.

-Unix/linux plattforms*:* they are necessary for running VIC. All the workers at the department of Research of Development at Agder Energi own excellents skills of C/C++ programming. Also, was required that I acquired knowledge of programming during my stay at the company.

9. Results and conclusions

As mentioned before, simulation results are in the output files (more information about outputfiles in **Annexe6: output files**). Three types of output files are given after each simulation: fluxes files, water balance files, and snow balance files. The main interest in this project is analyzed the components of the water balance: they contain runoff and baseflow results and other information, like the components of the water balance (you can see more information about water balance in Annexe 3: VIC model overview)

Figure 9.1 is a scheme of the given output files. As mentioned before, Skjerka is divided into 160 cells and VIC computes all calculations for each one. Therefore, we get after each simulation 160 water balance files.

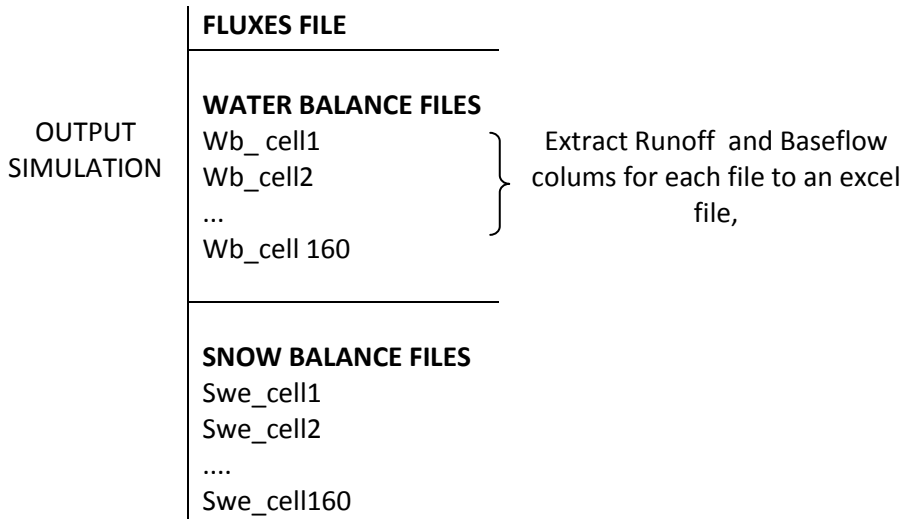


Figure 9.1: three type of output files are given after each simulation.

Each Water balance output files contain the following variables (In this order):

Column number	Parameter	Meaning
0	Year	Day of simulation-period. VIC computes daily data.
1	Month	
2	Day	
3	Out_prec	Precipitation , mm
4	Out_evap	Total net evaporation, mm
5	Out_runoff	Direct runoff (surface), mm
6	Out_baseflow	Subsurfacerunoff. Baseflow out from the bottom layer, mm
7	Out_delintercept	Change in canopy interception storage, mm
8	Out_delswe	Change in snow water equivalent, mm
9	Out_delsurfstor	Change in surface liquid storage, mm
10	Out_delsoilmoisture	Change in soil water content, mm
11	Out_Wdew	Total moisture interception storage in canopy, mm
11	Out_swe	Snow water equivalent in the snowpack, mm

It is important to mention that the water balance is:

P=Q + ET +Δsoil + Δswe ➔ Q= P - ET + Δsoil + Δswe

Where:
P = precipitation = out_prec
ET= evapotranspiration = out_evap
Q= total runoff = out_runoff + out_baseflow
Δsoil = out_delsoilmoisture
Δswe= out_delswe

Therefore, in columns:
[5] + [6] = [3] - [4] + [8] - [10]

The result of interest is the total amount of water (Total runoff, Q m3/s) per year for the whole catchment. For this purpose, total baseflow and runoff for the whole catchment (columns 5 and 6) are analyzed. Their values are calculated separately in order to see the different layers behave and how different parameters affect to them (remember, runoff comes from the upper layer and baseflow comes from bottom layer).

Sometimes other variables are also calculated, like soil moisture storage, for example, when we want to plot the baseflow curve (baseflow versus soil moisture storage). Total runoff, Q (Q= baseflow + runoff) is always calculated. This step is easy to carry out with the program I created (see section 6 of this project). For example, if the main interest is total baseflow, by specifying "column 6" in the code, the program sums column 6 (baseflow) for all cells and gives it in a single file.

9.1 PARAMETER ESTIMATION RESULTS

The following parameters as explained in section 6 of this document, are estimated. To measure the good of fitness three objective functions are used (described in section 6) to compare simulated versus observed results. The objectives functions are:

- **R2, Nash-Sutcliffe efficiency.** When R2 equals to 1.0 means that the model perfectly predicts the observations. It is the most important parameter.
- **The relative error, called Bias error as well**. The interest is to minimize this error.
- **Average Root mean square error:** higuer values indicate better predictions.

9.1.1 UPPER LAYER ADJUSTED PARAMETERS.

These parameters describe the upper layer behave, what means, the response of the soil (runoff) to hydrological processes that occur in this layer. By changing these parameters, processes like infiltration or evaporation are affected, and, in consequence there would be variations on the runoff. In this section, a set of parameters that best fit the upper soil layer behave is founded (see more information about procedure of calibration in Annexe 10: Upper Layer adjustment). These parameters are Z2, Z3, b_infiltration

Z2, Z3: are the thicknesses of the upper layer and bottom layer respectively. Though Z3 is the thickness of the third soil layer, is analyzed in this section in order to see the connection between both layers. A sensitivity analysis of this parameters and their interaction is carried out. The procedure consists in varying Z2 and Z3 and the comparison of the resulted Q simulated with Q observed. R2 is used to measure the good of fitness.

Figure 9.2.a is a table from an excel file that contain R2 values for different combinations of Z2 and Z3 (in meters). Figure 9.2.b is an analysis of the error: a plot of R2. In this graph is possible to appreciate that in general, thicker soil depths yield worse adjustment (R2 gets closer to 0) and combinations for thinner soil dephs yield to a R2 closer to 1. It has sense, since we take into account that thicker soil layers can hold more roots and these roots release water (evapotranspiration). Also, thicker soil layer can hold more water until saturation. When it happens, the streamflow from the soil takes place. When selecting the best cases, it is necessary to compromise the thickness of the soil layers with reasonable values. For example, it has no sense to set Z2 to 0.2 meters: it is too thin as to represent a soil layer and the use of the model would lose sense.

		Z3										
		1.8 m	1.6 m	1.5 m	1.4 m	1.3 m	1 m	0.94	0.9 m	0.7 m	0.5 m	0.18 m
Z2=	0.14 m											0.77
	0.23 m	0.46		0.29			0.39	0.39		0.54	0.58	
	0.37 m			0.36			0.48		0.49	0.52	0.55	
	0.5 m			0.25			0.47			0.49		
	0.625 m	0.22	0.43	0.43	0.43	0.44	0.29					
	0.75 m			0.42								

Figure 9.2.a: Table with R2 for different combinations of Z2-Z3 (expressed in meters)

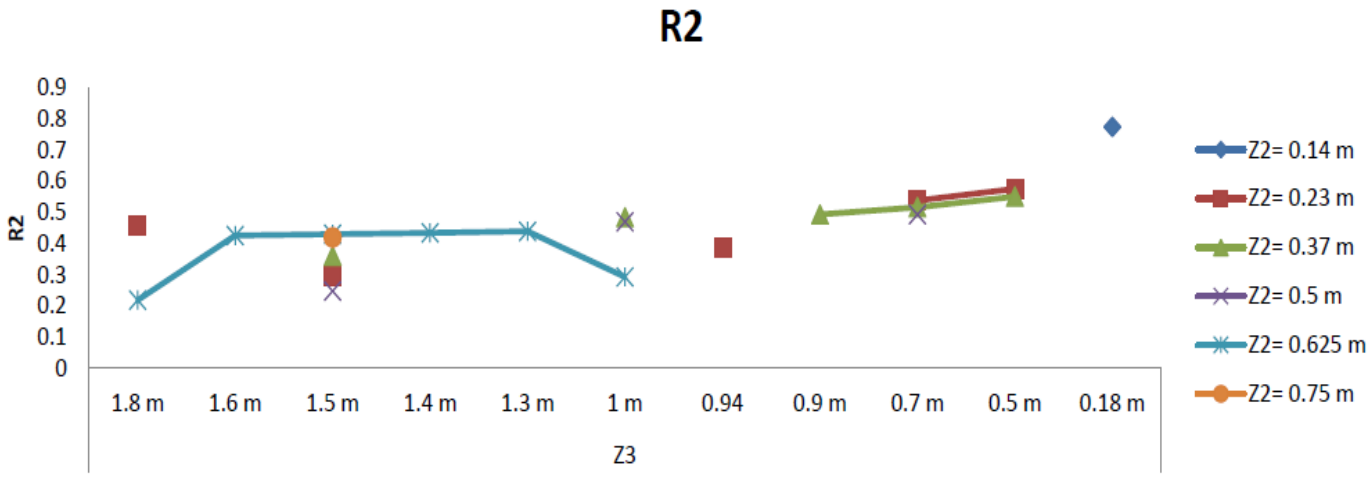


Figure 9.2.b: graph R2 versus Z3 for different Z2 thicknesses. R2 gets closer to 1 when Z2 and Z3 decrease.

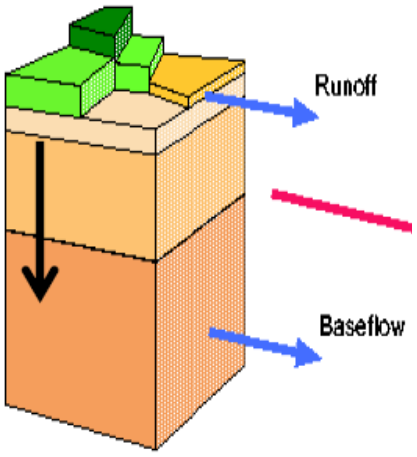
An analysis of Runoff and Baseflow is carried out for different combinations of Z2-Z3 and results were obtained as expected. A couple of logical conclusions are important to mention:

A) An increment of the second soil layer thickness (upper layer) yield to decrease in the amount of runoff.

B) An increment of the third soil layer (bottom layer) yield to a decrease in baseflow.

Both conclusions have sense, as explained before: thicker soil layers can hold more amount of moisture (therefore, less outflow from the soil since it can hold more water until it gets saturated) and soil can hold more roots what gives more losses due to evapotranspiration. Figure 9.3 gives an illustration with results:

CASE A

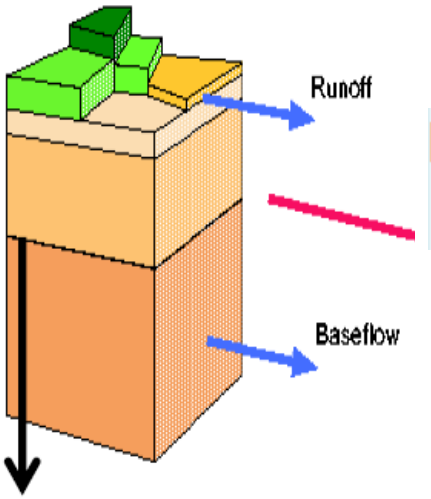


	Z3	Q	runoff	baseflow
Z2=0.23	1.5	19.11	6.52	12.59
Z2=0.37	1.5	20.57	6.30	14.27
Z2=0.5	1.5	20.54	6.17	14.38
Z2=0.63	1.5	18.80	6.06	12.74

Figure 9.3 a: An example when increments of the second soil layer produce less amount of runoff. Z2 is the thickness of the second soil layer and Z3 of the third soil layer in meters. While keeping constant Z3= 1.5 m, an increment of Z2 (from 0.23 m to 0.63 m) produces less

in runoff, which is expressed in m3/s

CASE B



	Z3	Q	runoff	baseflow
Z2=0.5	1.5	20.54	6.17	14.38
	1	22.08	6.17	14.32
	0.7	20.50	6.18	14.32

Figure 9.3.b: Increments of the third soil layer produce less amount of baseflow. Z2 is the thickness of the second soil layer and Z3 of the third soil layer, in meters. While keeping constant Z2= 0.5 m, an increment of Z3 (from 0.7 m to 1.5 m) yields to a decreasement in baseflow, which is expressed in m3/s

9.1.2 B_infiltration parameter:

This parameter is related with the shape of the VIC curve and represents infiltration capacity as a function of relative saturated gridcell area. Higuer values give lower infiltration and yields higuer surface runoff. The range of this parameter is between 0 and 0.4. As expected, value 0.4 gave better adjustment. Figure 9.4 is a representation of R2 versus b_infiltration. Two cases are shown in the figure: when Z2= 0.23 m (blue line) and Z2= 0.625 m (red line). The rest of parameters were kept constant. In both cases better adjustment is given when b_inf= 0.4.

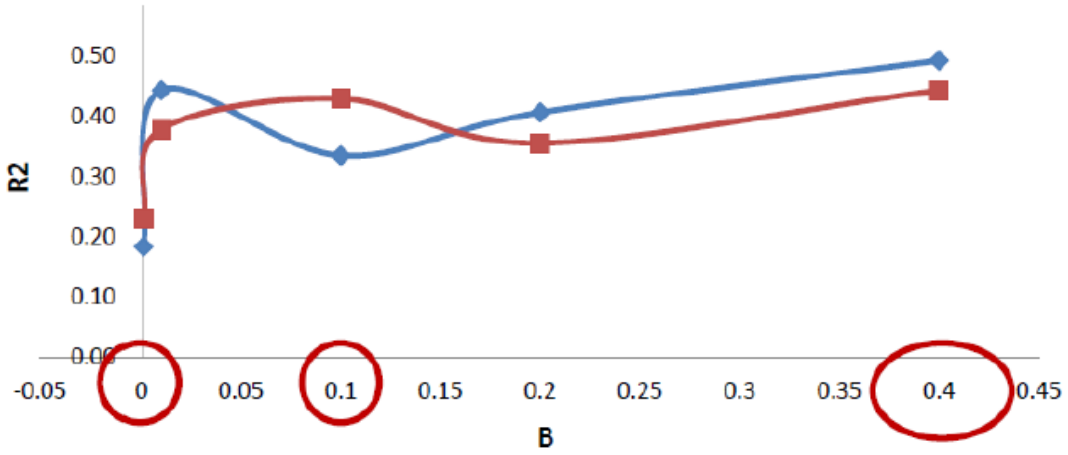


Figure 9.4: Plot of R2 versus B_infiltration for two different values of Z2: 0.23 (blue) and 0.625 (red)

In this project is convenient to get the maximum amount of total runoff, since Qobserved > Qsimulated. Also, it is convenient to get as much water as possible available for storage in the catchment: more water in the reservoirs, more for hydropower production.
Taking into account the aspects mentioned before, two cases were selected. It is what we called “upper layer best cases”. Best combinations are the following:

	Z2 m	**Z3 m**	**Q M3/s**	**Runoff M3/s**	**Basefow M3/s**	**R2**	**RMSE**	**Qs/Qobs**	**Q average M3/s**
1	0.37	0.7	20.53	6.32	14.21	0.56	21.30	0.7	20.53
2	0.5	1	22.08	6.17	14.32	0.52	22.08	0.7	20.50

As we can see in the table, R2 results are 0.52 and 0.56: it is a good adjustment if we take into account that second soil layer parameters are not adjusted at this point of the project. We consider a valid adjustment when R2 >0.8 (perfect adjustment for hydrological models does not exist). Qs/Qobs is another way to represent the bias error. Bias error = 1- Qs/Qobs = 0.3 (30% of error).
Average of total runoff is 20.53 and 20.50 m3/s in these cases. The main goal of the calibration is to increase this amount, since we still have 30% of error.

9.2 BASEFLOW ADJUSTED PARAMETERS

To see more information about this procedure go to Annexe 11: baseflow adjustment.
Parameters that describes baseflow curve are the following (more information in **Annexe 3: VIC model overview**)

- **Ds:** is the fraction of Dsmax where non-linear (rapidly increasing) baseflow begins. Higher value of Ds, the baseflow will be higher at lower water content in lowest soil layer.
- **Dsmax**= Maximum baseflow that occurs from the lowest soil layer (in mm/day). It happens when the third soil layer moisture gets saturated.
- **Ws**: This is the fraction of the maximum soil moisture (of the lowest soil layer) where non-linear baseflow occurs. This is analogous to Ds. A higher value of Ws will raise the water content required for rapidly increasing: non-linear baseflow.

For selected cases from the upper layer, the procedure is the following:

1. Adjust Ws and Ds
2. Adjust Ds max

These parameters characterize the baseflow curve (the response of the bottom layer behave, more information in the **Annexe3: VIC model overview**). Baseflow curve is represented in Figure 9.5:

$$Qbaseflow = \frac{D_s \cdot D_{smax}}{W_s W_2^c} \cdot W_2$$

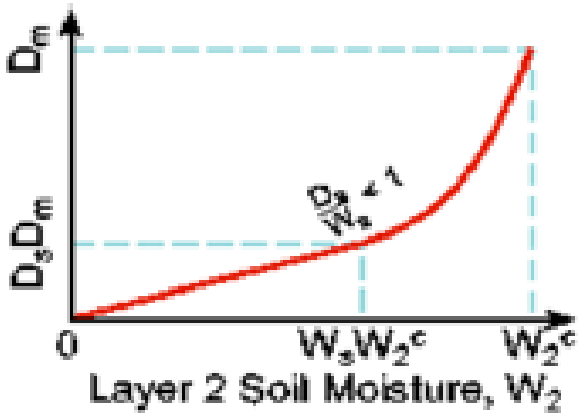


Figure 9.5: baseflow curve

Main conclusions for the adjustment:

1.Better adjustment when non linear baseflow occurs. It happens when the third soil layer gets saturated: baseflow increases rapidly**.** Figure below is a representation of this case for different combinations (marked cases). Figure 9.6.a shows when the second soil layers can hold water (Ws=0.99) until gets saturated. Once it happen, baseflow increases rapidly. In figure 9.6.b it is possible to appreciate that the second soil layer cannot hold much water until saturation (Ws= 0.001). When it happens, baseflow occurs suddenly.

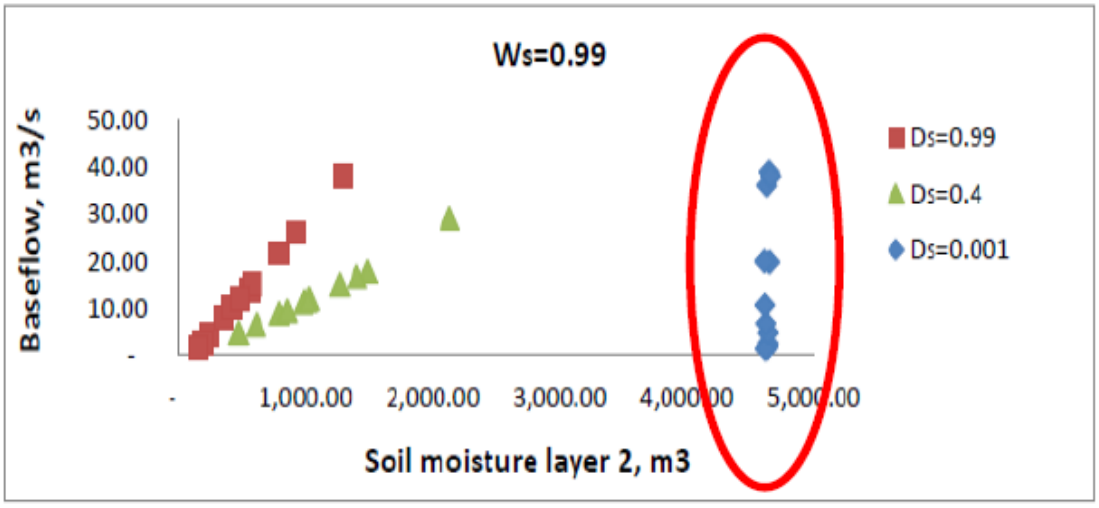


Figure 9.6.a: Baseflow curve for 3 cases: Ws=0.99 and Ds= 0.99, 0.4, 0.001.

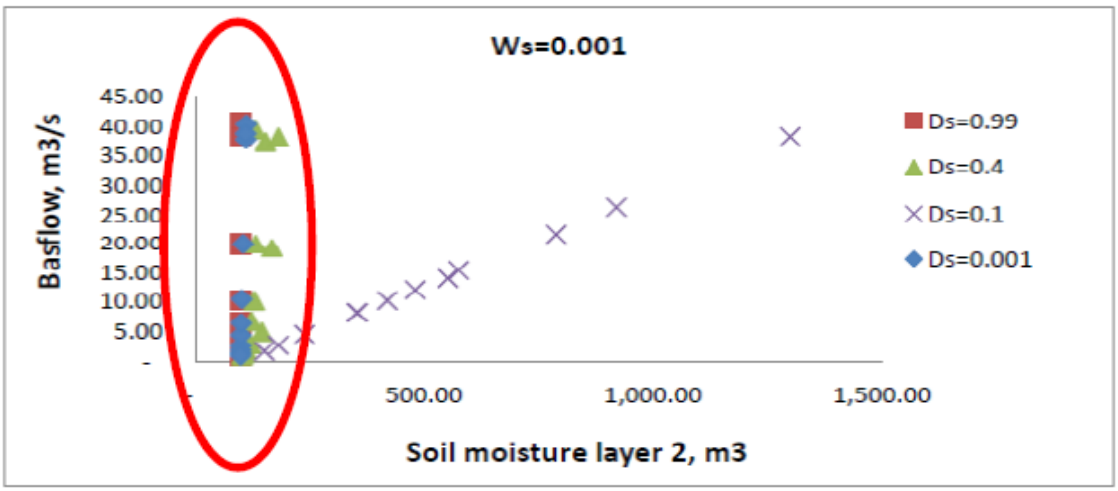


Figure 9.6.b: baseflow curve for different cases. Cases: Ws = 0.001 (cannot hold much amount of water) and Ds = 0.99, 0.4, 0.1, 0.001.

Ws	Ds	Ds/Ws	R2	RMSE	Qs/Qo	Q	baseflow	Runoff	layer2
0.001	0.99	990.00	0.81	13.75	0.73	21.54	15.39	6.14	98.87
0.99	0.001	0.00	0.80	14.24	0.73	21.46	15.25	6.21	4633.38

Figure 9.6.c: Table with simulation results when baseflow increases rapidly(when gets non linear)

2. Ds max = 0.001 yield always best results: this is because there is no baseflow and all the runoff comes from the upper layer. Best results were obtained for these cases since there are no evapotranspiration losses. Another consecuence, Ws-Ds values don't have any effect since there is no baseflow. Results are shown in figure 9.7:

Ws	Ds
0.99	0.001

Dsmax	R2	RMSE	Qs/Qo	Q	B	R	layer2
30	0.80	14.24	0.73	21.46	15.25	6.21	4633.38
20	0.80	14.25	0.73	21.49	14.92	6.57	4671.27
10	0.73	16.52	0.72	21.18	13.04	8.14	4676.66
0.05	0.84	12.83	0.75	22.00	0.24	21.75	4704.39
0.001	0.84	12.69	0.75	22.03	0.00	22.02	4704.39
0.005	0.84	12.70	0.75	22.03	0.02	22.00	4704.39

Ws	Ds
0.001	0.99

Dsmax	R2	RMSE	Qs/Qo	Q	B	R	layer2
30	0.81	13.75	0.73	21.54	15.39	6.14	98.87
20	0.81	13.75	0.73	21.54	15.39	6.14	99.12
10	0.81	13.76	0.73	21.53	15.39	6.14	99.85
0.05	0.73	16.44	0.71	20.94	14.84	6.10	1475.70
0.001	0.84	12.69	0.75	22.03	0.00	22.02	4704.39
0.005	0.82	13.40	0.74	21.86	0.64	21.21	3747.76

Figure 9.7: Simulation results from baseflow parameters adjustment.

9.3 FINAL "FINE" ADJUSTMENT: this is the final step of the parameters adjustment. Once we have desired which are the best combinations of parameters, some small variations on their values are carried out to make sure that there is no possible to get better results. Effectively, It happened in this case. Figure 9.8 shows some of the results:

Ws	Ds	Dsmax	R2	RMSE	Qs/Qo	Q	baseflow	Runoff	layer2	EVAP
0.99	0.001	0.05	0.84	12.83	0.75	22.00	0.24	21.75	4704.39	4.15
		0.001	0.84	12.69	0.75	22.03	0.00	22.02	4704.39	4.15
		0.005	0.84	12.70	0.75	22.03	0.02	22.00	4704.39	4.15

Ws	Ds	Dsmax	R2	RMSE	Qs/Qo	Q	baseflow	Runoff	layer2	EVAP
0.001	0.99	0.05	0.73	16.44	0.71	20.94	14.84	6.10	1475.70	4.13
		0.001	0.84	12.69	0.75	22.03	0.00	22.02	4704.39	4.15
		0.005	0.82	13.40	0.74	21.86	0.64	21.21	3747.76	4.13

Figure 9.8: results of the step "final adjustment". Small variations in Ds max parameter make sure that there are no better options. Dsmax is set to 0.001. On this step Dsmax is set to 0.05 and 0.005 to make sure that there are no better options. R2 does not increase with those changes.

9.4 COMPARISON OF THE VIC MODEL WITH OTHER HYDROLOGICAL MODELS, SUCH AS HBV MODEL

Another objective in this project was the comparison the VIC model with other hydrological models. Agder Energi uses other hydrological model such as the Scandinavian HBV model. Main differences between models are described in the table below. For better understanding about hydrological models, go to Annexe 2: Hydrological models. For the comparison I used the same meteorological data separately as input into the HBV and VIC model, and then I compared the two outputs with observed data to quantify the uncertainty.

HBV MODEL	**VIC MODEL** **SVATS (soil-vegetation-atmosphere transfer scheme)**
Semidistributed (subcatchments) Data is collected from specific points in skjerka. No spatial variability is taking into account.	**Distrubuted land-surface** (gridcell). Takes into account regional-variability: each cell is characterized.
Conceptual • Does not exactly describe physical procesess that are important for the simulation of timing, flood and droughts	**Physically-based** • Uses physicall laws (material balance, energy balance equations and complex algorithms) • Represents reallity better
Required forcing data,3: • T, P, PET • Only need daily values	**Atmospheric input dataseries, 7:** • P, T, specific humidity, air pressure, downward radiation (shortwave and long wave) and windspeed. • Hourly values: required for daily variation of T (needed for computation of net long wave radiation, only when calculating energy fluxes)
Less parameters to be adjusted:	**Large number of parameters for the adjustment:**

Set of free parameters • Rain correction, snow correction, degree day factor, precipitation gradient, temperature gradient precipitation, constants: Kuz1, Kuz2, Klz	**Set of free parameters:** • Soil parameter file: Depth of soil layers (3), rain correction, Ws, Ds, B infiltration • Snow parameter:Max snow temp, min rain temp, snow rough, snow albedo, snow correction • Other parameter: exponential decay, roughness heights and vegetation type

CONCLUSION: More complex modelling does not always lead to better results

- The complex VIC model describes well the current situation, but If certain charasterictics of the basin change it is not adecuated because of an over-parametization
- An improvement for HBV model could be to introduce gradually the complexity required
- The main cause of error in the runoff forecast lies in the hydrological model, secondly the error comes from the weather forecast.
- Total runoff for VIC simulations is considerably smaller than observed values, it can be possible because of the higher values of potential evaporation (which are calculated using innovative methods, while for the HBV model I was using a simple equation)
- When calibration the VIC model the maximum value of R2 is 0.84. Better results were obtained with HBV, (about R2=0.9).

IMPROVEMENTS: the main task when calibration VIC is how to get values of total runoff. Two options for possible consideration in the future:

a) **Less potential evapotranspiration:** center the study in possibilities that could allow reduce the amount of losses due to evapotranspiration
b) **Gauge correction parameters:** all gauge devices give an error on the measurements. Gauge correction parameters refer to rain and snow fall measurement devices. These parameters are not under study in this project, but could be another line of study. By varying this parameters, more amount of rain or snow could be obtained, and therefore an increasement of total runoff.

10.Biblyography

WEBSITE: http://www.hydro.washington.edu

ARTICLES: http://journals.ametsoc.org

Global Retrospective Estimation of Soil Moisture Using the Variable Infiltration Capacity Land Surface Model, 1980–93

A parameter estimation scheme of the land surface model VIC using the MOPEX databases

Surface soil moisture parameterization of the VIC-2L model: Evaluation and modification

Multi-objective calibration of land surface model evapotranspiration predictions using streamflow observations and spaceborne surface radiometric temperature retrievals

Predicting discharge of global rivers

An application of the VIC- 3L land surface model in simulating streamflow for continental-scale river basins in China.

B.2: ANNEXES

ANNEXE 1: HYDROPOWER ENGINEERING, PLANT AND DEVELOPMENT

HYDROPOWER DEVELOPMENT

Hydropower development is a form of development which focuses on identifying sites which can be used for hydropower and exploiting their available energy. Nations all over the world rely on hydropower for some of their energy needs. Studies indicate that few, in any nations are utilizing all of their hydropower resources. Like any form of development, hydropower development is not entirely unproblematic. There are a number of issues to consider when evaluating potential sites of hydropower facilities, ranging from energy needs to concerns about fish populations.

Humans have been harnessing the kinetic energy of water for thousands of year. Numerous human societies developed an assortment of creative ways to use water for energy. The waterwheel is a classic example, with wheels being used to power saws and milling facilities for grain long before the development of steam and electric power.

In the case of hydropower development, the goal is usually to generate electricity. The electricity is generated classically by damming a waterway and using the water to run turbines for the purpose of making electricity. However, hydropower development also includes facilities which use the ocean to generate wave power.

When embarking of hydropower development, one of the key issues to consider if whether or not a site can be used sustainably. A site with a sufficient supply of water is critical, as is a site which can be used without generating excessive negative environmental impacts. Damming waterways can have tremendous impact on the environment. While controlling seasonal floods, dams also block the flow nutrient-rich silt, make it difficult for fish populations to travel up river and sometimes flood arable land, communities or sites of historical importance. All of these issues must be weighed when evaluating a site to determine whether or not the benefits of the dam are worth the costs.

The environmental complexity of hydropower development is one reason why nations are not utilizing their full hydropower potential. Hydropower development is also very costly, which can be a limiting factor. It can sometimes meet with considerable opposition from local communities. Although hydropower is a renewable resource

which does not generate greenhouse gas emissions, making it an appealing source of energy for environmentally conscious nations, it is clearly only one among many renewable energy solutions.

HYDROPOWER PLANT

Hydropower plants, which energy sources is water, sometimes are called hydroelectric plants. They use water to produce nearly a quarter of the world's total requirement of electricity.

A hydropower plant takes very little to create: running water, a dam, turbines and a generator. These components, when put together in the right order, harness water power to create electricity. Components of a hydropower plant work as following:

Hydropower dam: is constructed to hold back water to create a reservoir from which to draw a steady stream. Often, this reservoir is used as a recreational lake.
Intake: gates on the dam open and gravity pulls the water through the penstock, a pipeline that leads to the turbine. Water builds up pressure as it flows through this pipe.

Turbine: The water strikes and turns the large blades of a turbine, which is attached to a generator above it by way of a shaft. The most common type of turbine for hydropower plants is the Francis Turbine, which looks like a big disc with curved blades. A turbine can weigh as much as 172 tons and turn at a rate of 90 revolutions per minute (rpm), according to the Foundation for Water & Energy Education(FWEE).

Generators: As the turbine blades turn, so do a series of magnets inside the generator. Giant magnets rotate past copper coils, producing **alternating current** (AC) by moving electrons**.**

Transformer: The transformer inside the **powerhouse** takes the AC and converts it to higher-voltage current.

Power lines: Out of every power plant come four wires: the three phases of power being produced simultaneously plus a neutral or ground common to all three.

Outflow: Used water is carried through pipelines, called **tailraces**, and re-enters the river downstream

Water in the reservoir is considered **stored energy**. When the gates open, the water flowing through the penstock becomes **kinetic energy** because it's in motion. The amount of electricity that is generated is determined by several factors. Two of those factors are the volume of **water flow** and the amount of **hydraulic head**. The head refers to the distance between the water surface and the turbines. As the head and

flow increase, so does the electricity generated. The head is usually dependent upon the amount of water in the reservoir.

DAM SAFETY

Dam safety, together with the protection of life, property and the environment from the consequences of dam failure, is a major priority for any hydropower project.

Safety is an issue underpinning every stage of a hydropower development, from creating a stable and sustainable asset, to ensuring safety on the construction site, and creating and maintaining safe operational conditions for workers and the community.
A major risk for a hydropower development is dam failure, which may arise as a result of foundation problems, internal erosion or overtopping. Environmental, social and economic consequences of dam failure can be considerable, with potentially widespread detrimental impacts.
Comprehensive dam safety risk assessments, including seismic risk, should be completed for all sites being assessed for hydropower development. Once a site has been selected, dam safety should be factored into all phases of the planning, design, construction and operation of a hydropower scheme.
Design and construction practices need to ensure that defined safety requirements, as identified in the risk assessment and agreed with appropriate regulatory authorities, are met. It needs to be recognized that changes in flood frequency may lead to changes in land-use activities and population distribution. These changes should be included in risk assessment.
All operating dams should have a dam safety management plan. This should define the scale, frequency and nature of monitoring requirements, including types of instrumentation required. The levels of expertise needed to implement the plan should also be specified in planning documentation.
Identification of potential problems during dam monitoring needs to be followed-up in a timely manner with detailed investigations and, when required, the rectification of the problem.

HYDROPOWER ENGINEERING

Hydropower engineering is the science of how flowing water is used to generate electricity. Structures such as dams and water diversion channels are typically designed on the principles of how water flows from high elevations to low lying areas. **Hydropower systems are also designed around knowledge of the hydrologic cycle. Ocean water evaporates from the heat of the sun, weather patterns create clouds which drop rain over landscapes, and water runs along rivers back to the sea. River elevations, prevailing weather patterns, and knowledge of how to concert running**

water to electricity are generally essential to understanding hydropower engineering.

Water wheels have been used for many years on farms, to move water and process grains. Hydropower engineering for power generation typically involves using water to drive turbines. The energy of the water is converted to a form that can be used by generators to make electricity.

ANNEXE 2: HYDROLOGICAL MODELS

Water is the basis resource or fuel for hydropower generation, and knowledge about the availability of water resources is of vital importance for both, planning and operation of hydropower systems.

BASIC CONCEPTS

In this part of the project some basic concepts are described for better understanding hydrological processes and how VIC operates.

SYSTEM: Hydrological phenomena are extremely complex, and difficult both to measure and understand in full detail. In absence of perfect knowledge, however, they may be represented in a simplified way by means of the system concept: "A system is a set of connected parts that forms a whole". It is possible to apply this concept to hydrological phenomena giving the following definition

HYDROLOGICAL SYSTEM: "structure or volume in space, surrounded by a boundary that accepts water and other inputs, operates on them internally and produces an output" The objective of hydrological system analysis is to study the system operation and predict its internal states and output.

HYDROLOGICAL MODEL SYSTEM: is an approximation of the actual system. Its inputs and outputs are measurable hydrological variables and the model's structure is a set of equations linking input to output.

SYSTEM TRANSFORMATION: Central to the model structure is the concept of system transformation, the input and output can be expressed as function of time I(t) and O(t) respectively. A system performs a transformation of the input into the output represented by a transformation operator or equation.

Figure A.2.1 shows a system transformation: a transformation operator computes input to outputs by mathematical equation:

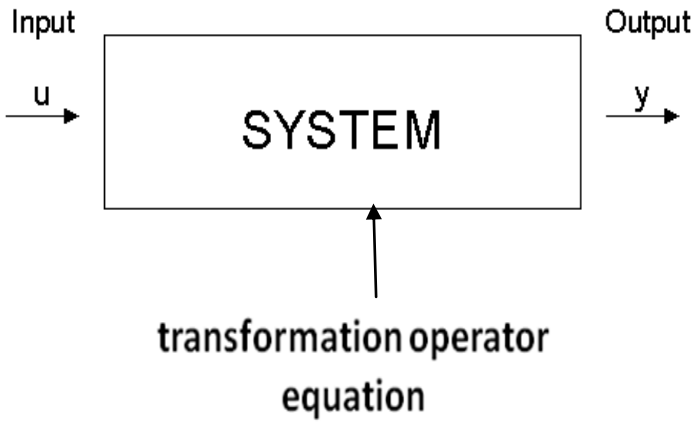


Figure A.2.1: system transformation scheme

A simplified representation, a model of this transformation operator can be written by mathematical equations and logical statements, describing the structure for a precipitation-runoff model for the catchment (precipitation-runoff models are described on this annexe)

An example of a hydrologic model system can be a watershed. The watershed can be looked upon as an operator transforming the moisture inputs I (t) into outputs O (t).

If the surface and soil of watershed are examined in detail, the number of possible flow paths above or below the surface becomes very large. Along any path the shape, slope, soil texture and boundary conditions may change continuously from place to place. Also, the processes interacting with water may vary in time. Precipitation varies randomly in space and time.

A conceptual knowledge of the physical system will be still valuable to determine the main processes, and to develop a simplified but useful model.

Because of these great complications, it is not possible to describe all the physical processes within the watershed with exact physical laws. Using the system concept the effort is instead directed to the construction of a model. This model is represents the most important processes, and their interaction within the total system.

HYDROLOGYCAL CYCLE

A hydrologic cycle is a conceptual model that describes the storage and movement of water between biosphere, atmosphere, lithosphere, and the hydrosphere. Water in our planet can be stored in any of the following major reservoirs: atmosphere, oceans, lakes, rivers, soils, glaciers, snowfields and groundwater.

Water moves from one reservoir to another by way of processes like evaporation, condensation, precipitation, deposition, runoff, infiltration, sublimation, transpiration, melting and groundwater flow.

The oceans supply most of the evaporated water found in the atmosphere. Of this evaporated water, only 91% of it is returned to the ocean basins by way of precipitation. The remaining 9% is transported to areas over landmasses where climatologic factors induce the formation of precipitation. The resulting imbalance between rates of evaporation and precipitation over land and ocean is corrected by runoff and groundwater flow to the oceans.

Figure A.2.2 illustrates an example of the hydrologic cycle. The picture shows the movement of water between land and atmosphere reservoirs as well as the movement of water between them. Processes such as evaporation, condensation, precipitation, infiltration are shown in the picture. For better understanding the movement of water and the roll that meteorology plays in the hydrological cycle, some descriptions are given after the picture.

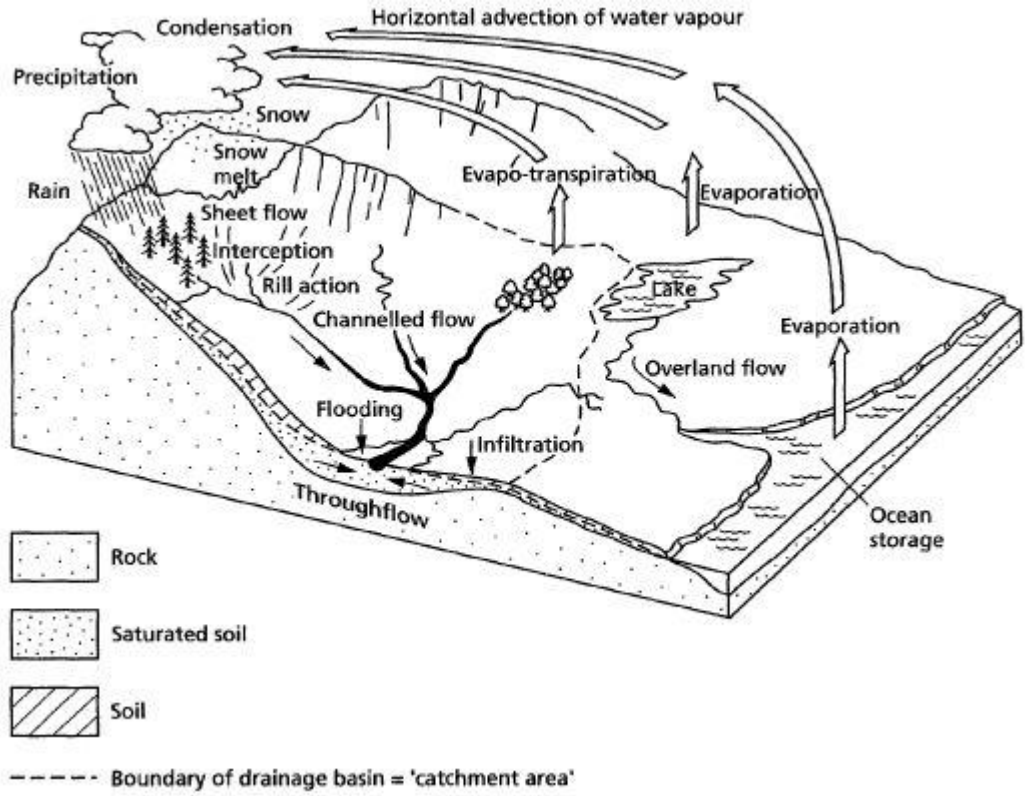


Figure A.2.2: Hydrological cicle. Hydrological processes: movement of water between land and atmosphere reservoirs

Major movements of water

Water is more or less constantly moving and changing from one state to another (solid, liquid, or vapor/gas) while interacting with the physical processes present in the atmosphere, lithosphere, and biosphere. These changes and movements of water are linked together in the hydrologic cycle.Components of the hydrologic cycle include water vapor and clouds in the atmosphere, but also include liquid surface waters (oceans, lakes and streams) on continents as well as groundwater.

Other important components of the hydrologic cycle include glacial ice held on continents, and water contained in biomass. Plants and animals are about 70% water, by volume. Water evaporates in enormous quantities from the oceans and then falls as precipitation either on land or ocean. That portion which falls on land evaporates, is transpired by plants, runs off, or infiltrates by some measure. Between the various stages of the hydrologic cycle, water moves between temporary storage areas often called reservoirs. These movements are controlled by climatic conditions, which include rain, snow, wind, and other meteorological processes. Eventually, all water ends up back in the ocean.

Role of meteorological variables

Various pathways exist in the hydrologic cycle. In non-vegetated systems interception processes usually do not occur, however, within vegetated systems, precipitation can be intercepted and lost to evaporation. In vegetated systems, some precipitation may reach the ground by streamflow, but most often reaches the soil by a process called throughfall. Precipitation that reaches the soil surface can then infiltrates and recharges soil waters. From there it can percolate through soil to deeper soil layers or groundwater supplies. The rate of evaporation from soils or surface waters (including oceans) can be influenced by several factors including radiation, temperature, relative humidity, and wind. Warmer air can hold more water vapor, thereby generating increased evaporation rates. Drier air can accept much more water vapor than air that is nearly saturated, and windy conditions generally accelerate evaporation. Transpiration from plants takes place via water loss from the stomates. The stomates act as an important cooling mechanism for plants by means of latent heat absorbed and transferred from the plants through evaporation/transpiration processes. This process is also that which supplies the tensional forces necessary to help draw water into roots from the surrounding soil. Transpiration is often lumped with evaporation and is then called evapotranspiration. With enough energy added, water can be converted directly from a solid (ice) to water vapor. This process is called sublimation. Sublimation is the result of ice going directly from a solid to water vapor without passing through a liquid state.
Air can only hold a certain amount of water vapor. The amount depends largely upon temperature; thus, as mentioned, hotter air can hold more water vapor than colder air. When air is saturated with water vapor, the water vapor condenses into droplets of water, forming clouds. When the droplets gain enough mass, they fall to the ground as rain or snow.

Surface infiltration and runoff

Water that falls as snow or rain evaporates, sublimates, runs off the ground surface (runoff) or soaks into the ground (infiltration). Whether the water runs off or infiltrates is controlled by a number of mechanisms including precipitation rate, soil water content, slope and vegetation. With increased rates of precipitation, runoff rates tend to increase. In extreme cases, rapid cloudbursts of precipitation can result in flash floods and potential land slides. Prior to rainfall, the relative amount of soil water content can dictate the amount of water that soil can hold before saturation. Generally, more water will infiltrate into dry soil than into a wet soil, and more water will run off steeper slopes than off moderate slopes. The presence of vegetation can counteract this process by holding more water than the hill slopes would by themselves. Hillsides that have undergone timber harvest or have been burned will often suffer severely from mudslides and flooding. Runoff processes within the

hydrologic cycle include streamflow and groundwater flow, each of which eventually results in flow to ocean reservoirs. Lakes and streams may occur in low points of the landscape due to streamflow, or where the groundwater table emerges above the surface. Other contributors of the runoff process include melting of glacial ice, and calving of icebergs into the sea. On a global basis, precipitation exceeds evapotranspiration over continents, and evaporation exceeds precipitation over ocean reservoirs, while excess water moves from continents to oceans as runoff. The ratio of precipitation rate to evaporation rate can vary dramatically between regions. For example, in tropical rainforests, precipitation may greatly exceed evapotranspiration.

Residence times

Often, rates of hydrologic activity are measured in terms of "mean residence time", or the average amount of time that water remains in its various states or reservoirs. For example, the mean residence time of a water molecule in the atmosphere is very short, usually from days to a week or two. Water tends to move quickly through plant and animal tissues, but can be stored in cells for a much longer period of time. It can take weeks to months for water to move through surface drainage networks depending upon the complexity of the geomorphologic network. Water may be stored for months to years in soil water and individual water molecules may remain in deep groundwater, glaciers and ocean basins for decades to 10,000 or more years.

MAIN COMPONENTS

A hydrologic cycle may be treated as a system whose components are precipitation, evaporation, snow melt, infiltration, runoff and other processes in the hydrologic cycle. The different components can each be grouped together into subsystems or broken down into new sub-processes, depending of the level of detail in the analysis and the purpose of the analysis.
The global hydrologic cycle is represented in a system and it can be divided into three subsystems:

- The atmospheric water system
- The surface system
- The subsurface water system

THE ATMOSPHERIC WATER SYSTEM: containing the processes of precipitation, evaporation, interception and transpiration.

-Precipitation: can be in form of snow, sleet or rain. The form of precipitation is not only determined by the air temperature at ground level, but also by the temperature distribution between the cloud base and the ground. Snow precipitation normally occurs when air temperature falls below 0-1 C, though a closer investigation reveals

that the form of precipitation has a distribution probability of rain even when air temperature is below 0 C, and high probability if snow even if the temperature is above 0C. The transition temperature, TS, is the temperature with 50/50 probability of rain and snow (usually is found to be +1C)

-Evapotranspiration: is a collective term for all the processes by which water in the liquid or solid phase at or near the earth\s land surfaces becomes atmospheric water vapor. That term thus includes: evaporation of liquid water from liquid and lakes, bare soil and vegetative surfaces, interception losses from vegetative surfaces, transpiration (evaporation from within the leaves of plants) and sublimation from ice and snow surfaces. Table A.2.1 summarizes these processes.

	TYPE OF SURFACE	DEFINITION
FREE WATER EVAPORATION	Open water	Evaporation that would occur from an open-water surface in absence of advection and changes in hear storage
LAKE EVAPORATION	Open water	Determined by adjusting mapped or computed free-water evaporation to account for the advection and heat-storage effects
TRANSPIRATION	Leaf or leaf canopy	Evaporation of water from the vascular system of plants into the atmosphere. Involves: absorption of soil water by plants roots, translocation in liquid form through the vascular system of the roots.
INTERCEPTION LOSS	Leaf or leaf canopy	Process by which precipitation falls on vegetative surfaces (the canopy), where it is subject to evaporation
POTENTIAL EVAPOTRANSPIRATION	Land area	The rate at which evapotranspiration would occur from a large area completely and uniformly covered with growing vegetation which has access to an unlimited supply of soil water without advection or heat

		storage
ACTUAL EVAPOTRANSPIRATION	Land area	Can be determined by measuring liquid-water inputs and outputs and solving the water balance equation, just as for open-water evaporation. Is function on the actual evapotranspiration, but could be limited of the availability of water

Table A.2.1: evaporation processes

THE SURFACE WATER SYSTEM: containing the processes of snow accumulation and melt, overland flow, overland flow, surface runoff, subsurface and groundwater outflow and runoff to streams and the ocean. When subsurface and groundwater outflow occurs, and runoff to streams and the ocean: ground water eventually discharges into river of lakes or, in coastal areas, directly into the ocean. Also, can leave the ground water reservoir by moving upward from the water table (fluctuating boundary of the ground water zone)

THE SUBSURFACE WATER SYSTEM: containing the processes of infiltration, groundwater recharge, subsurface flow and groundwater flow.
Infiltration is the process by which water arriving at the soil surface enters the soil.
Groundwater recharge or percolation: is the movement of infiltrated water to recharge ground water.
Subsurface flow: following a rain or a snowmelt event, infiltrated water is subject to redistribution by gravity and pressure forces and to remove by evapotranspiration or redistribution, which is the subsequent movement of infiltrated water in the unsaturated zone of a soil.
Ground water flow: as with all hydrological stocks, ground water is in continual motion, albeit slow. In spite of its slow pace, ground water is a crucial link in the hydrologic cycle because it is the source of most of the water in rivers and lakes.

HYDROLOGICAL MODEL CLASSIFICATION

Several systems for classification of hydrologic models have been used, and they commonly divided into two main categories:

-*Physical models*: include scale models such as hydraulic models of a spillway, and analog models which use another physical system having properties similar to those of the real system.

-*Abstract models*: represent the system in mathematical form. The system operation is described by a set of equations and logical statements. A mathematical model can also be transformed to a computer program describing an algorithm for the system. Almost all useful hydrological models are in fact implemented as computer programmer.Models are classified according to three main criteria as well:

-*Randomness*: deterministic or stochastic.

-*Spatial variation:* lumped or distributed.

-*Time variability:* time-dependent, time-independent.

In hydropower planning and operation the most important types of hydrological models can be classified in the following main groups:

-*Precipitation-runoff models,* which are mostly used for inflow and flood forecasting for operational use. Such models are also used to fill in missing data in runoff series or to extend such data in series.

-*Stochastic time-dependent* models are used to model the statistical structure of runoff-series, and then to generate long time-series of synthetic run-off data.

-*Probabilistic* (stochastic time-independent) models are used for frequency analysis for design flood computations.

-*River and reservoir routing* models are used mainly during design flood computations, to determine flood levels in reservoirs and along rivers. Such models are also used in operational mode to forecast flood levels and determine reservoir operation.

-*Regression models* are used for many purposes, for example:

To forecast seasonal runoff volumes based on snow storage measurements or precipitation measurements.

To forecast river level or discharge downstream, based on one or several observations of level or discharge upstream

As seen from hydropower operator, a model type that has proved is very useful both for planning and operation of hydropower schemes, conceptual precipitation-runoff models.

CALIBRATION OF HYDROLOGICAL MODELS

Most hydrologic models are characterized by complex functional relationships and a large number of parameters that are usually conceptual representations of the watershed. In the most cases, these parameters cannot be directly measured or are not exactly known of spatial variability measurement error, hence the need for model calibration.

Calibration is the estimation of model parameters to achieve a system that closely resembles the actual system that the model represents. Figure A.2.3 illustrates the general procedure of hydrological models calibration:

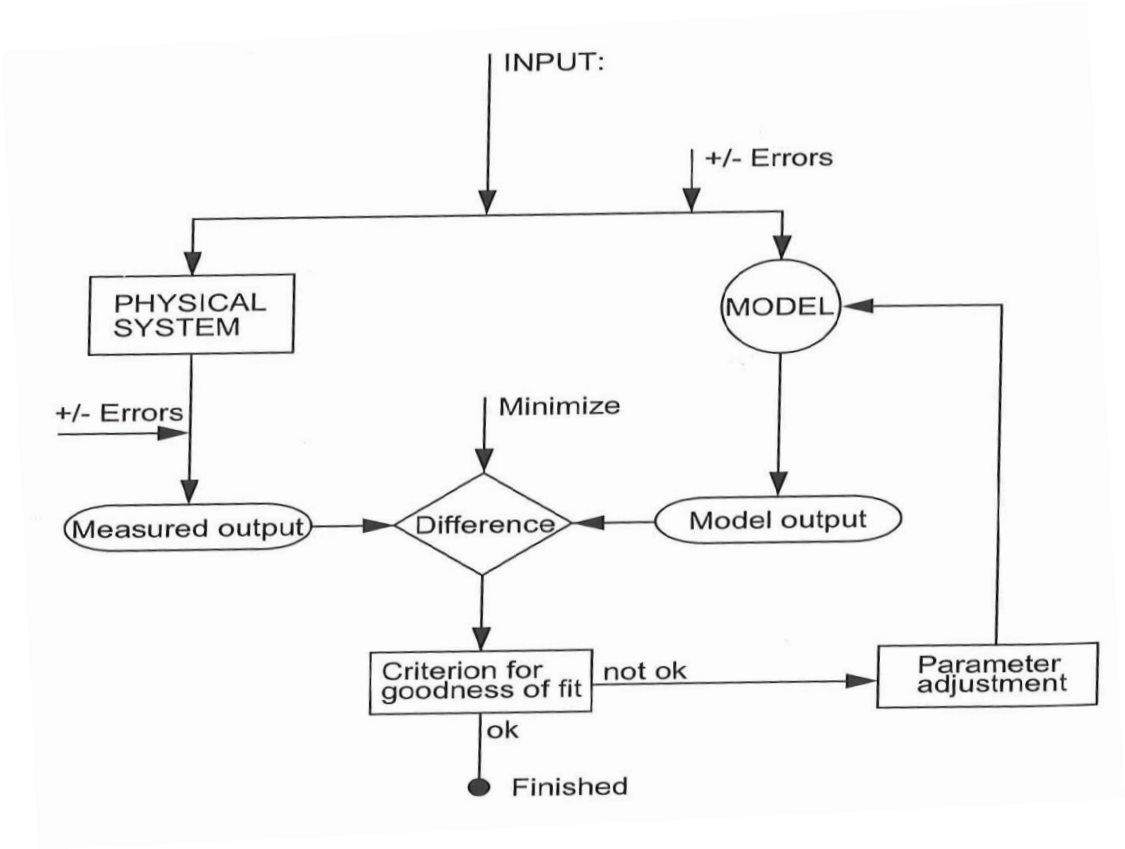


Figure A.2.3. Hydrological models calibration

Manual trial and error calibration is time consuming and depends on the modeler's experience, skill, and knowledge of the model's processes and dynamics.

While overcoming the shortcomings of manual trial and error calibration of complex hydrologic models requires a tremendous amount of computation.

Multiple objective optimization improve model calibration but further increase the computational requirements. Classical multi-objective optimization involves transforming multiple objectives into a singles function. The most common method is the weighted sum principle where the objectives are multiplied with user-defined weighs and added together to form a single function. To avoid the disadvantages of converting multi-objective functions into a single optimization problem, Pareto

optimization has gained use and popularity in hydrologic modeling. In problems with at least two conflicting objectives, a set of optimal solutions exist as a result of the trade-offs between these objectives.

A Pareto optimal solution set is achieved when a solution cannot be improved upon without degrading at least one of its objective criteria. The cardinality of the Pareto optimal set is one if the objective functions are not conflicting to each other. This means that the optimum solution corresponding to any objective is the same and the Pareto front in the search space will converge into a single solution. Otherwise, a front of different solutions is searched for conflicting objectives. This optimal front can be established after several iterations and function evaluations that require tremendous amount of computation.

Objective functions and model evaluation: the goal is to minimize the differences of the observed vs. simulated peak flows. Figure A.2.4 is a representation of Qsimulated and Qoberseved.To measure the error, three objective functions are often used:

- **Nash-Sutcliffe efficiency (***R2 or Ef***)**: describes the prediction skill of the modeled streamflow as compared to the observed value. When R2 equals to 1.0, the model perfectly predicts the observations.

$$E_f = 1 - \frac{\sum_{i=1}^{N} (Q_{\mathrm{mod},i} - Q_{obs,i})^2}{\sum_{i=1}^{N} (Q_{obs,i} - \overline{Q_{obs}})^2}$$

- **The relative error (***Er***)**: the Bias error between simulated and observed mean annual runoff. *Er* is calculated as:

$$E_r = (\overline{Q_{\mathrm{mod}}} - \overline{Q_{obs}}) / \overline{Q_{obs}}$$, and

- **Average root mean square error, RMSE:**

$$\mathrm{RMSE} = ((1/n) * (\sum Q_{obs,i} - Q_{sim,i})^2)^{0.5}$$

When the model has been properly calibrated it can be many different types of applications:

- Runoff forecasting
- Flood forecasting
- Generate runoff time-series from meteorological data (precipitation and temperature)
- Fill in missing runoff observations
- Tool in quality control of runoff data
- Determine the effects of changes in the catchment
- To study the effect of climate change

ANNEXE 3: VIC MODEL OVERVIEW. GENERAL GUIDE

This document is a general guide of the VIC model. Characteristics, processes, structure, algorithms and equations, validation and applications are well described in this document. This can be considered as the "Algorithm Theoretical Basis document".
As mentioned, algorithms and equations that VIC computes are described. In this document models and equations are mentioned (Penman Montheith equation, Xianjiang model, Richards equation, US Army Corps of Egineers, Tennese Valley Authority Algorithm….).For further information, there is a list at the end of the document where you can find references.

CHARACTERISTICS OF THE VIC MODEL

VIC is a semi-distributed macro scale hydrological model that treats the peace of land under study as if it were a box, dividing the catchment into cells. Therefore, the catchment is looked as a grid cell (for more information go to annexe 2: Hydrological models). VIC balances both the water and surface energy budgets within the grid cell; and its sub-grid variations are captured statistically

Distinguishing characteristics of the VIC model include: Subgrid variability in land surface vegetation classes; subgrid variability in the soil moisture storage capacity; drainage from the lower soil moisture zone (base flow) as a nonlinear recession; and inclusion of topography that allows for orographic precipitation and temperature lapse rates resulting in more realistic hydrology in mountainous regions.

To simulate streamflow, VIC results are typically post-processed with a separate routing model based on a linear transfer function to simulate the streamflow.

USES

VIC has been adapted to allow representation of water management effects including reservoir operation and irrigation diversions and return flows. The variable infiltration capacity (VIC) model with a variety of updates, has been extensively used in studies on topics ranging from water resources management, land-atmosphere interactions and climate change. It has been well calibrated and applied in a number of large river basins over the continental US and the globe. VIC has participated in the WCRP Intercomparison of Land Surface Parameterization Schemes (PILPS) project and the North American Land Data Assimilation System (NLDAS), where it has performed well relative to other schemes and to available observations. It has also been evaluated using soil moisture observations in the U.S. and global snow cover extent data

Driven by high-quality meteorological forcings, VIC had been used to provide a long-term data record of land surface fluxes and states for the conterminous United States and Mexico.

Applications using such a data record have covered many areas, such as:

- Simulating ensembles of streamflow and hydrologic variables for forecast purpose
- Reconstructing and analyzing drought events
- Studying the North American monsoon teleconnections
- Drought prediction
- conducting hydrologic studies over the Pan-arctic region
- Water management
- Many others

OVERVIEW OF VIC MODEL PROCESSES

This section explains the classic algorithms of VIC model for calculation the state variables, surface fluxes, and streamflow as well as the newly implemented algorithms for the water management. Here are the main characteristics of the processes:

VIC REPRESENTS VEGETATION HETEREOGENITY: (more information about variables is located in the Annexe5: VIC input files)

- **Vegetation characteristics assigned for each vegetation tile:** LAI, albedo, minimum stomatal resistance, architectural resistance, roughness length, relative fraction of roots in each soil layer, and displacement.
- **Evapotranspiration:** is calculated according to the Penman-Monteith equation, in which the evapotranspiration is a function of net radiation and vapor pressure deficit.
- **Total actual evapotranspiration**: is the sum of canopy evaporation and transpiration from each vegetation tile and bare soil evaporation from the bare soil tile, weighted by the coverage fraction for each surface cover class.

MULTIPLE SOIL LAYERS WITH VARIABLE INFILTRATION:

- **Canopy layer***:* intercepts rainfall
- **Top two soil layers:** are designed to represent the dynamic response of soil to the infiltrated rainfall, with diffusion allowed from the middle layer to the upper layer when the middle layer is wetter.
- **Bottom soil layer:** receives moisture from the middle layer through gravity drainage. The bottom soil layer characterizes seasonal soil moisture behavior and it only responses to short-term rainfall when the top soil layers are saturated.

NON LINEAR BASEFLOW:

- **Runoff from the bottom soil layer**: is according to the drainage described by the Arno model.
- **Moisture**: can also be transported upward from the roots through evapotranspiration. Although vegetation subgrid-scale variability is a critical feature for the VIC model, the soil characteristics (such as soil texture, hydraulic conductivity, etc.) are held constant for each grid cell.

In the model, soil moisture distribution, infiltration, drainage between soil layers, surface runoff, and subsurface runoff are all calculated for each land cover tile at each time step. Then for each grid cell, the total surface and subsurface runoff are obtained by summing over all the land cover tiles weighted by fractional coverage.

The VIC model can be run in either a water balance mode or a water and energy balance mode. They are described below, though you can see more information in the annexe7: modes of operation.

THE WATER BALANCE MODE:

The water balance mode does not solve the surface energy balance. Instead, it assumes that the soil surface temperature is equal to the air temperature for the current time step. By eliminating the ground heat flux solution and the iterative processes required to close the surface energy balance, the water balance mode requires significantly less computational time than other model modes. These simplifications, combined with the daily time step that is typical of water balance mode simulations, yields a substantial savings in computational time. The exceptions to this are that the snow algorithm and the frozen soil algorithm, both of which run at a sub-daily time step, and which solve the surface energy balance to determine the fluxes needed to drive accumulation and ablation processes, or to solve the frozen soil penetration, respectively.

WATER AND ENERGY BALANCE MODE:

The full water-and-energy balance mode not only solves the complete water balance but also minimizes the surface energy balance error. The surface energy balance is closed through an iterative process which tries to find the surface temperature that yields surface energy fluxes (sensible heat, ground heat, ground heat storage, outgoing longwave and indirectly latent heat) so that balance the incoming solar and longwave radiation fluxes. This mode requires more computational time than the water balance mode as well as requiring a sub-daily simulation time step. However, it is critical for studies in which the land-atmosphere interactions are of interest (e.g., coupling with climate models).

In the VIC model, each grid cell is modeled independently without horizontal water flow. The grid-based VIC model simulates the time series of runoff only for each grid cell, which is non-uniformly distributed within the cell. Therefore, a stand-alone routing model is employed to transport grid cell surface runoff and base flow to the

outlet of that grid cell then into the river system thought it is not an object of study in this project.

ALGORITHMS AND EQUATIONS: in this section the equations and algorithm that VIC operates are described:

WATER BALANCE: The water balance in the VIC model follows the continuous equation for each time-step:

$$\frac{\partial S}{\partial t} = P - E - R$$ where:

dS/dt = change of water storage
P = precipitation
E = evapotranspiration
R =runoff
Within the time step, all units of above variables are mm.

Over vegetated areas the water balance equation in the canopy layer (interception) is:

$$\frac{\partial W_i}{\partial t} = P - E_c - P_t$$

Where:
W= canopy intercepted water (mm),
E_c= evaporation from canopy layer (mm),
P_t =througfall (mm).

Components of the water balance are described as following:

$$\frac{\partial S}{\partial t} = P - E - R$$

WATER BALANCE COMPONENT: Total evapotranspiration, E: The VIC model considers three types of evaporation, and total evapotranspiration over a grid cell is computed as the sum of the below components, weighted by the respective surface cover area fractions. The formulation of the total evapotranspiration is:

$$E = \sum_{n=1}^{N} C_n \cdot (E_{c,n} + E_{t,n}) + C_{N+1} \cdot E_1$$, where:

E_c, mm= evaporation from the canopy layer of each vegetation tile,
E_t, mm= transpiration from each of the vegetation tiles,
E_1, mm=Evaporation from the bare soil
C_n is the vegetation fractional coverage for the nth vegetation tile,

C_{N+1} is the bare soil fraction, and $\sum_{n=1}^{N+1} C_n = 1$.

a)Canopy evaporation: when there is intercepted water on the canopy, the canopy evaporates at the maximum value. The maximum canopy evaporation (E_c^* , mm) from each vegetation tile is calculated using the following formulation:

$$E_c^* = (\frac{W_i}{W_{im}})^{2/3} E_p \frac{r_w}{r_w + r_o}, \quad \text{where:}$$

W_{im} = maximum amount of water the canopy can intercept (mm), which is 0.2 times LAI.
r_0 = architectural resistance is caused by the variation of the humidity gradient between the canopy and the overlying air (s m^{-1}). In the model, r_0 is assigned for each land cover type according to the vegetation library.
r_w = aerodynamic resistance: represents the transfer of heat and water vapor from the evaporating surface into the air above the canopy (s m^{-1})

$$r_w = \frac{1}{C_w u_z}, \quad \text{where:}$$

u_z = wind speed (m s^{-1}) at level *z*
C_w = transfer coefficient for water which is estimated taking into account the atmospheric stability

E_p = potential evapotranspiration (mm) that is calculated from the Penman-Monteith equation with the canopy resistance set to zero, which is:

$$\lambda_v E_p = \frac{\Delta(R_n - G) + \rho_a c_p (e_s - e_a)/r_a}{\Delta + \gamma}$$

λ_v = latent heat of vaporation (J kg^{-1}),
R_n = net radiation (W m^{-2}), *G* is the soil heat flux (W m^{-2}),
$(e_s - e_a)$ = vapor pressure deficit of the air (Pa),
ρ_a = density of air at constant pressure (kg m^{-3}),
c_p = specific heat of the air (J kg^{-1} K^{-1})
Δ = slope of the saturation vapor pressure temperature relationship (Pa K^{-1}).
γ = psychrometric constant (66 Pa K^{-1}).

The Penman-Monteith equation as formulated above includes all parameters that govern the energy exchange and corresponding latent heat flux (evapotranspiration) from uniform expanses of vegetation.
When the continuous rainfall rate is lower than the canopy evaporation, the intercepted water is not sufficient for meeting the atmospheric demand within one time step. In such a case, the canopy evaporation (E_c, mm) is

$E_c = f \cdot E_c^*$, where f = fraction of the time step for canopy evaporation to exhaust the intercepted water: $f = \min\left(1, \frac{W_i + P \cdot \Delta t}{E_c^* \cdot \Delta t}\right)$

b) Vegetation transpiration: the vegetation transpiration (E^t, mm) is estimated using:

$$E_t = (1 - (\frac{W_i}{W_{im}})^{2/3}) E_p \frac{r_w}{r_w + r_o + r_c} \quad \text{where}$$

r_c is the canopy resistance (s m^{-1})

$$r_c = \frac{r_{0c} g_T g_{vpd} g_{PAR} g_{sm}}{LAI}, \quad \text{where}$$

r_{0c} is the minimum canopy resistance (s m^{-1}) according to the vegetation library,
g_T= temperature factor
g_{vpd}= vapor pressure deficit factor
g_{PAR}, = photosynthetically active radiation flux (PAR) factor
g_{sm} = soil moisture factor.

When canopy evaporation happens only for a fraction of the time step (*f*), the transpiration during that time step then has two parts as described by:

$$E_t = (1 - f) E_p \frac{r_w}{r_w + r_o + r_c} + f \cdot (1 - (\frac{W_i}{W_{im}})^{2/3}) E_p \frac{r_w}{r_w + r_o + r_c}$$

where the first term represents the part of the time step when there is transpiration but no canopy evaporation, and the second term represents the part of the time step when there is both evaporation from the canopy and transpiration.
The vegetation transpiration from a certain vegetation tile is the total contribution from all three soil layers, weighted by the fractions of roots in each layer.

c)Bare soil evaporation: the bare soil evaporation only occurs on the top thin layer. When the surface soil is saturated, it evaporates at the potential evaporation rate. When the top soil layer is not saturated, its evaporation rate (E_1) is calculated using the Arno formulation.

The infiltration capacity (*i*) uses the spatially heterogeneous structure described by the Xianjiang Model, which is expressed as
$i = i_m (1 - (1 - A)^{1/b_i})$ with $i_m = (1 + b_i) \cdot \theta_S \cdot |z|$, where:
i_m is the maximum infiltration capacity (mm),

A is the fraction of area for which the infiltration capacity is less than *i*,
b_i is the infiltration shape parameter,
ϑ_s is the soil porosity, and z is the soil depth (m).
All these variables are for the top thin soil layer.

The bare soil evaporation is described as

$$E_1 = E_p\left(\int_0^{A_S} dA + \int_{A_S}^{1} \frac{i_0}{i_m(1-(1-A)^{1/b_i})} dA\right)$$

with A_s denoting the fraction of the bare soil that is saturated, and i_0 representing the corresponding point infiltration capacity.

WATER BALANCE COMPONENT: Soil moisture. The VIC model uses the variable infiltration curve to account for the spatial heterogeneity of runoff generation. It assumes that surface runoff from the upper two soil layers is generated by those areas for which precipitation, when added to soil moisture storage at the end of the previous time step, exceeds the storage capacity of the soil. The formulation of subsurface runoff follows the Arno model conceptualization.

$$\frac{\partial S}{\partial t} = P - E - R$$

dS/dt = change of water storage (mm/time step)
E= evaporation (mm/time step),
R=Runoff (mm/time step)
P =precipitation (mm/time step))

Movement of moisture: the VIC model assumes there is no lateral flow in the top two soil layers; therefore the movement of moisture can be characterized by the one-dimensional Richard's equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}(D(\theta)\frac{\partial \theta}{\partial z}) + \frac{\partial K(\theta)}{\partial z}$$

ϑ is the volumetric soil moisture content,
$D(\vartheta)$ is the soil water diffusivity (mm^2 d^{-1}),
$K(\vartheta)$ is the hydraulic conductivity (mm d^{-1}), and *z* is soil depth (m).
By including the atmospheric forcing, the integrated soil moisture for the top two soil layers can be described as:

$$\frac{\partial \theta_i}{\partial t} \cdot z_i = I - E - K(\theta)\Big|_{-Z_I} + D(\theta)\frac{\partial \theta}{\partial z}\Big|_{-Z_I} \qquad \text{(i=1,2)}$$

Where:

I is the infiltration rate (mm d^{-1}). It is the difference between the precipitation (or thorughfall if there is vegetation coverage) and the direct runoff Qd.
z_1 and z_2 are soil depth for layer 1 and layer 2, respectively.

For the lower soil layer, an empirical formulation derived from large scale catchment hydrology is used in which the drainage and subsurface drainage are lumped together as base flow (Q_b). The soil moisture for the soil layer is described by the water balance equation including diffusion between soil layers as:

$$\frac{\partial \theta_3}{\partial t} \cdot (z_3 - z_2) = K(\theta)\Big|_{-Z_2} + D(\theta)\frac{\partial \theta}{\partial z}\Big|_{-Z_2} - E - Q_b$$

If it is bare soil, the evapotranspiration term *E* is zero because there is no evaporation from the lower soil layer. Otherwise, if the vegetation roots go through into the lower soil layer, the evapotranspiration term *E* needs to be considered.

WATER BALANCE COMPONENT: Runoff. Similar to the total evapotranspiration, the total runoff *Q* is expressed as:

$$\frac{\partial S}{\partial t} = P - E - R$$

Where $\mathbf{R = Q_d + Q_b}$, = Q

Similar to the total evapotranspiration, the total runoff *Q* is expressed as:

$$Q = \sum_{n=1}^{N+1} C_n \cdot (Q_{d,n} + Q_{b,n})$$

where $Q_{d,n}$ (mm) and $Q_{b,n}$ (mm) are the direct runoff (surface runoff) and base flow (subsurface runoff) for the nth land cover tile, respectively. They are described as:

Direct runoff, surface runoff, Q_d: Since the top thin soil layer has a very small water holding capacity, within each time step it is calculated for the entire upper layer (layer 1 and layer 2):

$$Q_d = \begin{cases} P - z_2 \cdot (\theta_S - \theta_2) + z_2 \cdot \theta_S \cdot (1 - \dfrac{i_0 + P}{i_m})^{1+b_i}, & P + i_0 \le i_m \\ P - z_2 \cdot (\theta_S - \theta_2), & P + i_0 \ge i_m \end{cases}$$

where the infiltration capacity associated terms (i_0, i_m, ϑ_s, and b_i) are explained before.

The formulation of base flow, subsurface runoff, Q_b: which used the Arno model formulation is expressed as:

$$Q_b = \begin{cases} \frac{D_S D_m}{W_S \theta_S} \cdot \theta_3, & 0 \le \theta_3 \le W_S \theta_S \\ \frac{D_S D_m}{W_S \theta_S} \cdot \theta_3 + (D_m - \frac{D_S D_m}{W_S})(\frac{\theta_3 - W_S \theta_S}{\theta_S - W_S \theta_S})^2, & \theta_3 \ge W_S \theta_S \end{cases}$$ where

D_m is the maximum subsurface flow (mm d^{-1}),
D_S is a fraction of D_m,
W_S is the fraction of maximum soil moisture (soil porosity) ϑ_s.
The base flow recession curve is linear below a threshold ($W_S \vartheta_s$) and nonlinear above the threshold. The first derivative at the transition from the linear to nonlinear drainage is continuous.

THE ENERGY BALANCE (without snow frozen or frozen soil)

Using the same scheme as most other land surface models do, the energy balance equation at the land surface for each land cover type within the grid cell is described as

$$R_n = H + \rho_w \lambda_v E + G \quad \text{where}$$

R_n is the net radiation (W m^{-2}),
H is the sensible heat flux (W m^{-2}),
$\rho_w \lambda_v E$ is the latent heat flux (W m^{-2})
ρ_w is the density of liquid water, kg m^{-3};
L_e is the latent heat of vaporization, J kg^{-1})
G is the ground heat flux (W m^{-2})

When the land surface is flat and homogeneous, the energy balance for a layer of air adjacent to the ground surface can be expressed as:

$$R_n = H + \rho L_e E + G + \Delta H$$

with ΔH representing the change of the energy storage rate in that air layer (W m^{-2}). The net radiation, and sensible and latent heat fluxes are from the top surface of the air layer, while the ground heat flux is from the bottom of the air layer.

The rate of energy storage change, when is considered to be significant, is

$$\Delta H = \frac{\rho_a c_p (T_S^+ - T_S^-) z_a}{2\Delta t} \quad \text{where:}$$

ρ_a is density of air (kg m^{-3}),
c_p is specific heat of air at constant pressure (J kg^{-1} K^{-1}),
T_S^+ and T_S^- are the surface temperature of the bottom of the air layer at the end and beginning of a time step (K).

z_a is the height of the air layer (m)

The net radiation which is the total of shortwave and longwave radiation is given by

$$R_n = (1-\alpha)R_S + \varepsilon(R_L - \sigma T_s^4) \qquad \text{where}$$

α is the surface albedo for the land cover type,
R_S is the downward shortwave radiation (W m^{-2}),
ε is the surface emissivity of the land cover type,
R_L is the downward longwave radiation (W m^{-2}).
σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}).
The water and energy balances are linked through the latent heat flux, with $E=E_c+E_t$ for vegetated land type and $E=E_1$ for bare soil (see Section 3.2.1 for more details).
The sensible heat is given by

$$H = \frac{\rho_a c_p}{r_h}(T_s - T_a) \qquad \text{where}$$

r_h is the aerodynamic resistance to heat flow (s m^{-1}),
T_s and T_a are surface temperature (K) and surface air temperature (K), respectively.
The ground heat flux for the top soil layer is described as:

$$G = \frac{k}{D_1}(T_S - T_1) \quad \text{where}$$

k is the soil thermal conductivity (W m^{-1} K^{-1}),
T_1 is the soil temperature between the first and second soil layers (K),
D_1 is the thickness of the first soil layer (m).
The calculation of T1 is described in Liang et al., 1999.

When snow is present, the surface energy balance is solved at the snow/air interface instead of soil/air interface. Ground heat flux is still computed, but it is the flux from the snowpack into the ground. The snowpack is treated as two layers, thermally.

SNOW MODEL AND FROZEN SOIL ALGORITHM

Subgrid variability in topography, land cover, and precipitation are modeled by a mosaic-type representation, where in each grid cell is partitioned into elevation (snow) bands each of which contains a number of land cover tiles. The snow model is then applied to each land cover/elevation tile separately, and the simulated energy and mass fluxes, as well as the state variables for each grid cell are calculated as the area-averages of the tiles.The main processes and factors that describe snow model and frozen soil algorithm are the following:

Snow pack accumulation and ablation: the snow model in VIC represents the snowpack as a two-layer medium, and solves an energy and mass balance for the ground surface snowpack in a manner similar to other cold land processes models. Energy exchange between the atmosphere, forest canopy and snowpack occurs only within the surface layer. The energy balance of the surface layer is:

$$\rho_w c_s \frac{dWT_S}{dt} = Q_r + Q_S + Q_l + Q_p + Q_m \quad \text{, where:}$$

c_s = specific heat of ice (J $kg^{-1}K^{-1}$, ρ_w is the density of water (kg m^{-3}).
W = water equivalent (mm), Ts is the temperature of the surface layer (°C), Q_r is the net radiation flux (W m^{-2}).
Q_s = sensible heat flux (W m^{-2}), Q_l is the latent heat flux (W m^{-2}), Q_p is the energy flux advected to the snowpack by rain or snow (W m^{-2}).
Q_m = energy flux given to the pack due to liquid water refreezing or removed from the pack during melt (W m^{-2}).

As snow accumulates on the ground, it goes through a metamorphism process, which causes the snowpack to compact and increase its density over time (except for depth hoar). In addition to the change in density caused by metamorphism, gravitational settling caused by newly fallen snow also contributes to the densification process.
Compaction is calculated as the sum of two fractional compaction rates representing compaction due to metamorphism and overburden, respectively. Snow albedo is assumed to decay with age, based on relationships published by the US Army Corps of Engineers (1956):

$$a_a = 0.85\lambda_a^{t_d^{0.58}}$$

$$a_m = 0.85\lambda_m^{t_d^{0.46}}$$

α_a, α_m = albedo during the accumulation and ablation seasons,
t_d = time since the last snowfall (in days),
λ_a = 0.92,
λ_m = 0.70. Accumulation and ablation seasons are defined based on the absence and presence of liquid water in the snow surface layer, respectively.

The latest official version of the model contains an option to use the algorithm of Sun et al. (1999) instead. Unlike the VIC implementation of the US Army Corps algorithm, this method determines whether the snowpack is in "accumulation" or "ablation" mode based on snowpack cold content, rather than on prescribed dates, and is therefore appropriate for simulations anywhere in the world.

Atmospheric stability: The calculation of turbulent energy exchange is complicated by the stability of the atmospheric boundary layer. During snowmelt, the atmosphere immediately above the snow surface is typically warmer. As parcels of cooler air near the snow surface are transported upward by turbulent eddies, they tend to sink back

toward the surface where turbulent exchange is suppressed. In the presence of a snow cover, aerodynamic resistance is typically corrected for atmospheric stability according to the bulk Richardson's number which is a dimensionless ratio relating the buoyant and mechanical forces acting on a parcel of air. While the bulk Richardson's number correction has the advantage of being straightforward to calculate based on observations at only one level above the snow surface, previous investigators have noted that its usage results in no turbulent exchange under common melt conditions and leads to an underestimation of the latent and sensible heat fluxes to the snowpack.

Snow interception and canopy effects: the snow interception algorithm in the snow model represents canopy interception, snowmelt, and mass release at the spatial scales of distributed hydrology models. During each time step, snowfall is intercepted by the overstory up to the maximum interception storage capacity according to:

$$I = fP_s \text{ , where:}$$

I is the water equivalent of snow intercepted during a time step (mm),
P_s is the snowfall over the time step (mm)
f is the efficiency of snow interception (taken as 0.6)

The maximum interception capacity (mm), B, is given by:

$$B = L_r m(LAI), \text{ where}$$

LAI is the single-sided leaf area index of the canopy.
m is determined based on observations of maximum snow interception capacity (mm).
Lr is the leaf area ratio which is a function of temperature.

Snowmelt is calculated directly from a modified energy balance, similar to that applied for the ground snowpack. Newly intercepted rainfall is calculated with respect to the water holding capacity of the intercepted snow, which is given by the total capacity of the snow. The bare excess rainfall then becomes throughfall. The intercepted snowpack can contain both ice and liquid water. Snowmelt in excess of the liquid water holding capacity of the snow results in meltwater drip. Mass release of snow from the canopy occurs if sufficient snow is available and the ratio of 0.4 is derived from observations of the ratio of mass release to meltwater drip.

Blowing snow: the blowing snow algorithm was developed to estimate topographically-induced sub-grid variability in wind speed, snow transport and sublimation. The blowing-snow algorithm is designed to work within the structure of the existing VIC mass and energy-balance snow model. The algorithm accounts for:

- The energy advected by rainfall, throughfall, or drip (when overstory is present).
- Net radiation, ground heat flux, and sensible and latent heat fluxes.
- Incoming shortwave and longwave radiation and wind speed are attenuated through the canopy, if present.
- If snow is present, it is assumed to cover the understory for purposes of radiation transfer.

For each vegetation fraction within the grid cell, the time rate of change of snow water (W_e) is:

$$\frac{dW_e}{dt} = P - M - p \cdot Q_v - Q_e, \quad \text{where:}$$

$\frac{dW_e}{dt}$ is the rate of snow water accumulation.
P is precipitation.
M is snowmelt and drainage.
Q_v is the sublimation from blowing snow.
Q_e is evaporation and sublimation from the snowpack, for a time increment *dt*.
All of the terms are in units of millimeters per time step. The spatial probability of occurrence of blowing snow, *p,* is unitless.

Along with the standard meteorological forcings, three additional parameters are needed to run the blowing snow algorithm: standard deviation of terrain slope, standard deviation of terrain elevations, and the lag-one autocorrelations for each model grid cell.

Snow model calibration: during the calibration for the VIC snow model, four parameters are adjusted for grid cells:

- Maximum air temperature at which snowfall occurs;
- Minimum air temperature at which rainfall occurs;
- The snow surface roughness;
- The value of *m*, which controls the maximum snow interception capacity as a function of LAI.

Usually the first two parameters are set to 0.5 ^{o}C and -0.5 ^{o}C, respectively. In addition, we suggest that the snow roughness parameter should be in the range from 0.001 m to 0.03 m.
The VIC snow model is intended primarily for large-scale applications. It has been incorporated as the standard snow scheme within the VIC model, which represents sub-grid spatial variability by simulating state and fluxes in land cover/elevation tiles. Within the VIC model, it is used in a real-time hydrologic forecast system, and has been used in numerous analyses, diagnoses, and predictions of climate variability and change.

METEOROLOGY

VIC can use any combination of daily or sub-daily meteorological forcings, from point observations, gridded observations, or reanalysis fields.
At minimum, VIC requires daily precipitation, max/min air temperature, and wind speed. If incoming shortwave radiation or humidity are not supplied as forcings, VIC can estimate them via algorithms. If incoming long wave radiation is not supplied, VIC

can estimate this via the Tennessee Valley Authority algorithm.VIC can also disaggregate daily forcings to sub-daily as needed (to see more information go to the Annexe 5: VIC input files)

Distributed precipitation: VIC can consider spatial heterogeneity in precipitation, arising from either storm fronts/local convection or topographic heterogeneity. Here we consider the influence of storm fronts and local convective activity. This functionality is controlled by the DIST_PRCP option in the global parameter file (see Annexe 5: VIC input files).

Elevation bands: VIC can consider spatial heterogeneity in precipitation, arising from either storm fronts/local convection or topographic heterogeneity. Here we consider the influence of topography, via elevation bands. This is primarily used to produce more accurate estimates of mountain snow pack. This functionality is controlled by the SNOW_BAND option in the global parameter file. Main features are the following:

- Can subdivide the grid cell into arbitrary number of elevation bands, to account for variation of topography within cell
- Within each band, meteorologic forcings are lapsed from grid cell average elevation to band's elevation
- Geographic locations or configurations of elevation bands are not considered; VIC lumps all areas of same elevation range into 1 band
- Fluxes and storages from the bands are averaged together (weighted by area fraction) to give grid-cell average for writing to output files
- However, the band-specific values of some variables can be written separately in the output files
-

FROZEN SOIL ALGORITHM

A frozen soil algorithm has been implemented into the VIC model to improve its modeling skills over the cold regions. The frozen soil algorithm uses the same soil moisture transport scheme as described before and it is characterized by the following features:

Soil thermal solution: Over the cold regions, the soil ice content of the frozen soil directly affects infiltration, and indirectly affects the heat transfer to and from the overlying snowpacks. The frozen soil penetration is calculated by solving the thermal fluxes through the soil column. For each time step, the thermal flux through the soil column is solved first to determine the soil layer ice content. Moisture fluxes are then computed using the ice content.

The heat flux through the soil column is:

$$C_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}(k \frac{\partial T}{\partial z}) + \rho_i L_f (\frac{\partial \theta_i}{\partial t}), \quad \text{where}$$

k = soil thermal conductivity ($Wm^{-1}K^{-1}$)
C_s = soil volumetric heat capacity ($J\ m^{-3}K^{-1}$)
T = soil temperature (°C)
ρ_i = ice density ($kg\ m^{-3}$),
L_f = latent heat of fusion ($J\ kg^{-1}$)
ϑ_i = ice content of the layer ($m^3\ m^{-3}$)
t = time (s),
z = depth (m).
The last term of the equation only applies when the soil is frozen.

Within the soil column, a number of nodes are specified by the user. There is a node at the surface, a node at the bottom of layer 1, and a node in the middle of layer 1. There is a node at a user-specified maximum depth (specified in the soil parameter file, typically 4m), but this node need not be at the bottom of the soil column. All remaining nodes are spaced evenly between the bottom of soil layer 1 and the user-specified maximum depth.

Permafrost enhacements: The model also has an option to space the nodes exponentially, i.e. close together near the surface and gradually further apart with depth, down to the user-specified maximum depth. This is good for simulating permafrost, for which it is often necessary to specify a maximum depth of as much as 40m. With the nodes specified, the soil temperature is then solved for numerically at an hourly time step via an explicit finite difference approximation of the soil thermal flux equation.
Thermal conductivity (k) and volumetric heat capacity (C_s) of the soil layer are calculated at each time step after the soil moisture and ice content are updated by the moisture flux solution. The soil thermal conductivity (k) is computed after a modification as:

$$k = (k_{sat} - k_{dry})k_e + k_{dry} \quad \text{where:}$$

k_{sat} ,k_{dry} = thermal conductivity of saturated soil and dry soil ($W\ m^{-1}\ K^{-1}$), respectively.
k_e = kersten number which weighs the two soil conductivities.

The volumetric heat capacity C_s is computed by summing the volumetric heat capacities of the soil constituents:

$$C_s = \sum \rho_j c_j \theta_j \quad \text{where:}$$

ρ_j, c_j, and ϑ_j = the density ($kg\ m^{-3}$), specific heat capacity ($J\ m^{-3}K^{-1}$), and volumetric fraction of the jth soil node, respectively.
By adding the ice content component in the heat flux equation, the impact of frozen soil on moisture transport can be simulated by the moisture flux algorithm.
The first way that the ice content in the frozen soil affects the moisture transport is through available moisture storage. Each of the three soil layers is divided into thawed, frozen, and unfrozen sublayers. The thickness of these sublayers depends on the soil temperatures at the nodes. When there is a frozen layer present, the ice content is

based on the average temperature of the sublayer. The fraction of the unfrozen water as by is:

$$W_i = W_i^c \left[\left(\frac{1}{g\psi_e} \right) \left(\frac{L_f T}{T + 273.16} \right) \right]^{-B_p}$$ where:

W_i = liquid water content of soil layer *i* (mm), W_i^c is the maximum water content of soil layer *i* (mm)
g =acceleration due to gravity (m s^{-2})
ψ_c = air entry potential (m).
B_p= pore-size distribution

Excess ice and subsidence mode: the second way the ice content affects soil moisture transport is through its effect on infiltration and drainage. When a soil layer has high ice content, on one hand, it will be nearly saturate to the runoff calculations, but on the other hand there is little moisture (unfrozen) to be allowed to drain to the lower layer.
The frozen soil model also has an option to simulate excess ground ice, a common feature of permafrost. The user specifies the amount of excess ground ice as an optional soil parameter and then VIC computes new effective densities and porosities. As this ice melts, the effective porosities and densities approach the non-excess-ice values (and the melt water is added to the soil; any excess runs off as necessary)

Temperature hetereogenity "Spatial Frost": Based on linear (uniform) distribution of soil temperature around a mean. It allows some moisture movement in soil when the average temperature is below freezing.

LAKE AND WETLAND MODEL

In the VIC model, the effects of lakes and wetlands are simulated by creating a lake/wetland tile that can be added to the grid cell mosaic, in addition to the vegetation and bare soil tiles.
The lake/wetland tile represents seasonally flooded ground as well as permanent water bodies. The tile contains a body of open water (lake) whose areal extent is allowed to change in response to the lake water balance. The wetland portion of the tile is the (time-varying) remaining portion of the lake/wetland tile not covered by the lake. Water and energy components of the combined lake and wetland are resolved at each model time step.

There are a few limitations with the lake and wetland model:

-First, the vegetation in the wetland portion is prescribed to be shrubs that are typical of tundra vegetation.
-Second, the model only simulates lakes that receive all of their inflows from within the same grid cell, i.e. no channel inflows from other grid cells. This restricts the lakes to just those small lakes whose drainage basins are contained within the current grid cell.

-Third, the wetlands in the current version are essentially uplands that could potentially be flooded by lake expansion, with no special wetland processes considered. Only wetlands formed by seasonal flooding due to local precipitation and snowmelt and poor drainage are modeled.

Lake algorithm: Evaporation from the water surface is calculated in each time step by solving a surface energy balance using the formulations. The energy exchange with the atmosphere occurs within the surface water layer, which is limited to a user-specified depth (z_{surf}), typically around 0.6 m. The absorption of solar radiation by the surface water layer is assumed to follow Beer's law. The radiation intensity at the depth *h* is assumed to be a two-band system and expressed as:

$$I(h) = I_o\left[A_v \cdot \exp(-\lambda_v h) + A_{NIR} \cdot \exp(-\lambda_{NIR} h)\right] \text{ where:}$$

I_o = net shortwave radiation at the water surface (Wm^{-2}),
A_v, A_{NIR} = fractions of total radiation in the visible and near-infrared bands, respectively, A_v and A_{NIR} are set to 0.7 and 0.3, respectively.
λ_v, λ_{NIR} = attenuation coefficients of the two bands.

In deeper lakes, the average temperature for additional water layers is resolved by solving a set of simultaneous equations. Included in these equations are the effects of radiation absorption by each water layer, the eddy diffusion of heat from adjacent layers by molecular diffusion, wind-induced turbulent mixing, and convective mixing due to temperature instabilities.
The bottom boundary has a no flux condition, meaning that energy is not exchanged with the sub-lake soils (this condition could be relaxed in the future).

The lake layer thickness is recalculated in each time step in response to variations in total lake liquid water depth, as follows:

$$\begin{aligned}
&d_{zsurf} = z; d_z = 0; l = 1 && z < z_{surf} \\
&d_{zsurf} = z/2; d_z = z/2; l = 2 && z_{surf} \le z < 2z_{surf} \\
&d_{zsurf} = z_{surf}; d_z = \left(z - z_{surf}\right)/\left(l-1\right); l = \left(\text{int}\right) z/z_{surf} && 2z_{surf} \le z < N_{nodes} z_{surf} \\
&d_{zsurf} = z_{surf}; d_z = \left(z - z_{surf}\right)/\left(N_{nodes}-1\right); l = N_{nodes} && z \ge N_{nodes} z_{surf}
\end{aligned}$$

Where:
z = current lake depth (m).
l = current number of solution layers.
d_z= Thickness of all solution layers (m) excluding the surface layer.
d_{zsurf} = current thickness of the surface solution layer, m
z_{surf} = maximum allowable thickness of the surface solution layer (m). The maximum number of computational layers in the lake,
N_{nodes},= maximum number of computational layers in the lake, is a user-specified parameter.

Snow accumulation and melt over the frozen surface is solved using the VIC two-layer energy balance snow model. In this case, heat flux out of the lake takes the place of the ground heat flux. A two-band solar radiation absorption model similar to the equation for the unfrozen lake case is applied to the snow and ice layers. Heat flux through the ice is driven by the temperature gradient, and must balance the heat flux from the lake and the energy of ice formation at the ice/water interface.
In the VIC model, the water equivalent of lake ice is a state variable, and the available liquid water volume is checked before new ice can form (which is important in shallow wetland systems). For stability, lake ice must exceed a user-specified minimum thickness (usually taken to be 10 cm). As ice melts, the area of lake ice is adjusted to maintain this minimum thickness, resulting in fractional ice coverage if ice area is less than the surface area of liquid water.

Lake/wetland dynamics: unique features of the VIC lakes and wetland algorithm include the interaction of the simulated lake within the VIC model grid cell and the ability to represent wetlands of varying size. The algorithm can be summarized as follows:
- All open water areas within a VIC model grid cell are simulated together as an effective grid cell lake.
- A user-defined fraction of runoff from vegetated areas within the grid cell is diverted to the lake. This represents the storage retardation effect of lakes on seasonal streamflow.
- Once the new lake level is calculated, runoff is released from the lake as a function of the lake level. Base flow is calculated from below the lake as a function of the liquid water content of saturated wetland soils.
- Specification of a variable depth-area relationship allows for the representation of the reduction in surface water extent and the emergence of wetland vegetation following drainage of seasonally flooded wetlands.

In surface hydrology, the term wetland specifically means areas that are saturated or covered by water for some portion of the year. The tendency of a region to flood periodically can be represented within the VIC model by a user-input depth-area relationship, *A(z)*, for the maximum inundated fraction of the grid cell. For clarity of the subsequent discussion, wetland fraction, C_{wet}, will be used to refer to the maximum fraction of the VIC model grid cell that can be flooded, while lake fraction, f_{lake}, refers to the fraction of C_{wet} that is inundated for a given time step. In this context, therefore, the lake fraction does not distinguish between the pelagic open water zone and the benthic zone that may contain emergent wetland vegetation.
As the stage of the simulated lake drops, the open water area is recalculated and additional wetland area is exposed. The energy and water balance of the newly exposed wetland is solved as an additional vegetation tile. The water balance of the wetland fraction (C_{wet}) can be represented as follows:

$$\Delta S = P + D_{veg} - \left[E_w \cdot f_{lake} + E_v \cdot (1 - f_{lake})\right] - D_{lake} \quad \text{where:}$$

ΔS = change in soil moisture, lake water and ice and snow storage (mm)
P is precipitation (mm).

E_w and E_v are evaporation from the open water and wetland vegetation (mm) respectively.
D_{veg} is the discharge (runoff and baseflow) entering into the lake from the non-wetland portion of the grid cell (mm)
D_{lake} is the discharge out of the lake (mm).

All of the runoff and baseflow generated by the exposed wetland area is assumed to enter the grid cell lake, so this internal transfer is not needed in the wetland water balance.
The soil column under the lake is assumed to be saturated. As the lake area is reduced, the soil moisture of the non-lake area is updated to include the newly exposed fraction of saturated soil.
Likewise, as the lake area expands, some of the lake volume must go to saturating the newly inundated soil. The average soil moisture for the wetland fraction is therefore updated as follows:

$$\overline{W} = (1 - f_{lake}) \cdot W_v + f_{lake} \cdot W_{\max} \quad f'_{lake} \le f_{lake}$$
$$\overline{W} = (1 - f'_{lake}) \cdot W_v + f'_{lake} \cdot W_{\max} \quad f'_{lake} > f_{lake}$$

where

f'_{lake} and f_{lake} = new and old lake fractions, respectively.
W_v = wetland soil moisture for the current time step (mm)
W_{max} = total soil moisture storage capacity of the soil column (mm).

The volume of water (as mm per unit area) from the expanding lake used to recharge the wetland soil moisture is calculated as follows:

$$Recharge = (f'_{lake} - f_{lake})(W_{\max} - W_v) \quad f'_{lake} > f_{lake}$$

Changes in lake stage are calculated via a water balance for the saturated lake area. Runoff into the lake is composed of all of the runoff and baseflow from the exposed wetland and a fraction of the runoff and baseflow from all other grid cell vegetation tiles. To avoid complications due to the variation of lake area with depth, lake volume is the state variable used for the water balance. Lake depth is updated each time step by piecewise integration of the derived depth volume curve. Subsurface outflow from the lake is calculated using the VIC model Arno baseflow curve. Since the sub-lake soil thermal regime is not resolved, the maximum moisture storage in the bottom soil layer is reduced by the ice content of the exposed wetland soil profile in order to calculate the baseflow.Surface outflow from the lake is calculated as a function of the new depth, based on the equation for flow over a broad-crested weir, assuming that the velocity head is negligible:

$$Q = c_d b \sqrt{g} \left(\frac{2}{3}(z - z_{\min})^{\frac{3}{2}}\right) \quad \text{Where}$$

Q is the discharge ($m^3\ s^{-1}$)
b is the flow width (m)
g is the acceleration due to gravity
z is the current lake depth (m)

z_{min} is the elevation above the lake bottom of the weir or lake outlet (m).
c_d= coefficient of discharge, is used to account for the velocity of approach, non-parallel streamlines over the crest, and energy losses. c_d varies between about 0.8 and 1.2 and frequently has a value of about 0.94)

Surface runoff out of the lake (m) becomes:

$$R_{lake}(z) = \frac{1.6b(z - z_{\min})^{\frac{3}{2}} \cdot dt}{A(z)}$$ Where

dt = time step length in seconds
A(z)= lake surface area (m^2) at depth *z* (m).
For natural lakes and wetlands the width of the reservoir outlet is also likely to vary with water level. Assuming a roughly circular lake, the flow width, *b*, can be expressed as a fraction of the lake circumference:

$$b = 2f\sqrt{\pi \cdot A(z)}$$ where:

f = fraction of the lake circumference.
Surface runoff out of the lake becomes:

$$R_{lake} = \begin{cases} 0 & z \le z_{\min} \\ \dfrac{5.67 f (z - z_{\min})^{3/2} dt}{\sqrt{A(z)}} & z > z_{\min} \end{cases}$$

Lake depth, *z*, is calculated as the depth of both liquid water and lake ice water equivalent when liquid water exceeds the lake ice water equivalent, to account for the displacement of water by floating ice. When the mass of ice exceeds the mass of liquid water, *z* is the depth of liquid water alone. The depth-area curve (*A(z)*), width fraction (*f*); and minimum allowable depth of the lake (z_{min})are input parameters to the lake model. The width fraction, *f*, can take on values from 0 - 0.5, and is typically adjusted during the calibration.

VIC MODEL PARAMETERS AND FORCINGS

Land surface characteristics required by the VIC model include soil data, topography, and vegetation characteristics. These parameters as well as the model forcing data are described with detail in the **anexe 5: VIC input files** and **anexe 6: VIC output files**. The locations of these parameters and forcings, as well as the modes of operation are described by a global parameter file.

CALIBRATION

Like most physically based hydrologic models, the VIC model has many parameters that must be specified (about 20, depending on how the term "parameter" is defined). However, most of the parameters can be derived from in situ measurement and remote sensing observation. The usual implementation approach involves calibration of six parameters:

a) The infiltration parameter (b_i), which controls the partitioning of rainfall (or snowmelt) into infiltration and direct runoff (a higher value of b_i gives lower infiltration and yields higher surface runoff);
b) D_2 and D_3, which are the second and third soil layer thicknesses (D_1, the top soil layer depth, is usually specified *a priori*) and affect the water available for transpiration and baseflow respectively (thicker soil depths have slower runoff response — baseflow dominated —with higher evapotranspiration, but result in longer retention of soil moisture and higher baseflow in wet seasons);
c) Ds_{max}, Ds, and Ws, which are baseflow parameters and also are estimated via calibration. Ds_{max} is the maximum baseflow velocity, Ds is the fraction of maximum baseflow velocity, and Ws is the fraction of maximum soil moisture content of the third soil layer at which non-linear baseflow occurs. These three baseflow parameters determine how quickly the water stored in the third soil layer is evacuated as baseflow. The three baseflow parameters and the third soil layer depth (d_3) are used with only minor adjustment during the calibration, while the infiltration parameter (b_i) and the second soil depth (d_2) are targeted for intensive calibration. Parameters b_i and d_2 are calibrated independently.

The calibration of these parameters is conducted via a trial and error procedure that leads to an acceptable match of model-predicted discharge with observations. Besides visual comparison of monthly simulated and observed hydrographs, two objective functions are often used:

- **Nash-Sutcliffe efficiency (E_f)** which describes the prediction skill of the modeled streamflow as compared to the observed value.
- **The relative error (*Er*)** between simulated and observed mean annual runoff. E_f and Er are calculated as:

$$E_f = 1 - \frac{\sum_{i=1}^{N}(Q_{\mathrm{mod},i} - Q_{obs,i})^2}{\sum_{i=1}^{N}(Q_{obs,i} - \overline{Q_{obs}})^2}$$

$$E_r = (\overline{Q_{\mathrm{mod}}} - \overline{Q_{obs}}) / \overline{Q_{obs}}$$

$Q_{mod,i}$ =monthly modeled streamflow for month i,
Q_{obs} = monthly observed streamflow for month i,
N =the number of months, and
$\overline{Q_{\mathrm{mod}}}$ and $\overline{Q_{obs}}$ = mean of the monthly modeled and observed streamflows,

respectively. When E_f equals 1.0 it means that the model perfectly predicts the observations.

VALIDATION AND APPLICATIONS

Since its existence, VIC has been well calibrated in a number of large river basins over the continental US and the globe. The procedure of matching the simulated and observed streamflows through calibration ensures that evapotranspiration is realistically estimated over a sufficiently long enough time. This is because the change in surface storage is relatively small compared to other accumulated variables in the water balance system. On this basis, and given the physically based model parameterizations of the soil moisture and energy fluxes calculation, the other surface fluxes and state variables such as soil moisture should represent observations reasonably well, at least in the aggregate.

9 basins across the globe were selected to calibrate, with each basin representing a unique climate zone (and there is at least one basin on each continent). The calibration was successful in the arctic and temperate climate zones, although it did not work as well in the tropical climate zone. Partitioning the pan-Arctic drainage basin system into 12 regions and calibrated 9 of them, the VIC model did a good job of reproducing observed streamflow in the coldest areas of the domain that were mostly underlain by permafrost, while problems remained in areas of discontinuous permafrost where simulated streamflow was mostly overestimated.

14 comparatively small basins (less than 10 000 km^2) were selected over the whole Mexico to calibrate (with the basins representing different climate zones). Generally, VIC did a good job of capturing the peak time and temporal pattern of streamflow for both arid and wet regions. The obvious problem is the great overestimation or underestimation of peak flows in some years especially for arid basins.

Throughout its existence, the VIC model has been used in many research areas, such as meteorology and atmospheric sciences, water resources, geosciences, environmental sciences, remote sensing, etc. So far VIC has been cited about 1700 times from all over the world.

A table A.3.1 lists a selected number of papers directly using the VIC model or VIC model results is given at the end of the project.

Authors	**Studied region**	**Specific topic**
Adam et. (2007)	Eurasian arctic	Reservoir influence on streamflow
Andreadis and Lettenmaier (2006a)	United States	Drought analysis
Arora and Boer (2006)	Global	Temporal variability of soil moisture
Arora (2001)	Russian lowlands	Water balance
Berbery et al (2003)	Mississippi basin	Hydrological cycle
Cherkauer and Lettenmaier (2003)	Minnesota River	Snow and frozen soil
Cosgrove et al. (2003)	North America	Model spin-up behavior
Crow et al. (2003)	Southern Great Plains	Model calibration
Demaria et al. (2007)	Selected US basins	Model parameter sensitivity
Feng et al. (2008)	Colorado	Snow simulation
Gao et al. (2006)	North America	Surface soil moisture remote sensing
Gao et al. (2007)	Southern Great Plains	Data assimilation
Gao et al. (2004)	Southern Great Plains	Surface soil moisture remote sensing
Huang et al. (2003)	Selected US basins	Model parameter transfer
Li et al. (2007)	Rio Grande	Water cycle
Liang et al. (2003)	Pennsylvania	Surface and ground water interaction
Liang et al. (1994)	Kansas	VIC model
Lucas-Picher et al. (2003)	North America	Routing scheme validation
Luo et al. (2005)	Columbia and Colorado basin	Water cycle
Luo and Wood (2007)	United States	Drought analysis
Maurer et al. (2001)	Mississippi river basin	Water budget evaluation
Meng and Quiring (2008)	Texas and Maryland	Soil moisture modeling
Miguez-Macho et al. (2008)	North America	Water table and Soil moisture modeling
Mo (2008)	United States	Drought indices
Nijssen et al. (2001a)	Global basins	Hydrologic sensitivity of rivers
Nijssen et al. (2001b)	Global	Soil moisture modeling
O'Donnell et al. (2000)	Ohio river basin	Water and energy balance
Pan and Wood (2006)	Southern Great Plains	Data assimilation
Pan et al. (2003)	North America	Snow modeling
Pan et al. (2008)	Arkansas-Red river basin	Data assimilation
Parada and Liang (2008)	Southern Great Plains	Data assimilation

Rhoads et al. (2001)	Arkansas-Red river basin	Surface temperature modeling
Sheffield and Wood (2007)	Global	Drought analysis
Sheffield et al. (2004a)	United States	Drought analysis
Sheffield et al. (2004b)	Global	Precipitation correction
Sheffield et al. (2003)	North America	Snow modeling
Stamm et al. (1994)	Global	Global climate sensitivity
Su et al. (2006)	pan-Arctic	Surface water flux
Su et al. (2005)	Arctic	Streamflow
Wang et al. (2008)	Global	Integration to climate model
Warrach-Sagi et al. (2008)	Germany	Streamflow
Wojcik et al. (2008)	Colorado	Snow modeling
Wood et al. (2002)	United States	Hydrologic forcasting
Wood et al. (1992)	North Carolina	VIC model
Wu et al. (2007)	China	Soil moisture modeling
Xie et al. (2007)	China	Parameter estimation
Zhou et al. (2006)	Baohe river, China	Hydrological cycle
Zhu and Lettenmair (2007)	Mexico	Surface hydrology and energy flux
Abdulla and Lettenmaier (1997a)	Arkansas-Red river basin	Parameter estimation
Abdulla and Lettenmaier (1997b)	Arkansas-Red river basin	Water balance
Andreadis and Lettenmaier (2006b)	Snake river basin	Data assimilation
Guo et al. (2004)	Illinois river watershed	Precipitation impact on water budget
Huang and Liang (2006)	Selected watersheds in US	Parameter estimation
Hurkmans et al. (2008)	Rhine river basin	River discharge
Lakshmi and Wood (1998)	King's creak catchment	evaporation
Liang et al. (2004)	Blue river watershed	Water flux
Liang and Xie (2003)	Pennsylvania	Runoff
Lobmeyr et al. (1999)	Elbe river, Germany	Water balance
Lohmann et al. (1998b)	West river, Germany	Streamflow
Matheussen et al. (2000)	Columbia river basin	Streamflow
Mengelkamp et al. (1999)	Netherland, Arkansas	Surface energy and water balance
Nijssen et al. (1997)	Major rivers in US	Streamflow
Shaman et al. (2002)	Sleepers river and Black Rock catchment	Storm flow
Silberstein et al. (2002)	Western Australia	Water logging and ground water
Sivapalan et al. (1997)	Australia	Runoff
Sivapalan and Woods	Australia	Water balance fluxes

(1995)		
Su and Xie (2003)	China	Runoff
te Linde et al. (2008)	Rhine river basin	Discharge
Troy et al. (2008)	United states	Parameter estimation
VanShaar et al. (2002)	Columbia river basin	Runoff
Wooldridge SA, Kalma (2001)	Eastern Australia	Streamflow
Yang and Xie (2003)	China	Groundwater table
Yuan et al. (2004)	Hanjiang river basin (China)	Streamflow
Liang et al. (1996)	PILPS sites	VIC model
Slater et al. (2007)	pan-Arctic	Hydrologic processes
Han and Li (2008)	California	Data assimilation
Hillard et al. (2003)	Upper Mississippi river basin, central Canada	Snow modeling

Table A.3.1: List of research papers using VIC model directly

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ANNEXE 4: HOW TO RUN VIC

The VIC model has been developed for use on LINUX and UNIX platforms. To use VIC on a windows platform, a UNIX emulator such as Cywin to compile/run this model is needed.

Download Source Code

To download the latest VIC source code, is necessary to proceed to the download page. The code is packaged in a compressed tar archive. Extract the contents via:

tar -xvzf filename where
filename = name of the file you downloaded, e.g. VIC_code_4.1.1.tar.gz

Compile VIC

Change directory, cd, to the source code directory (extracted from the compressed tar archive above)
At the command prompt type:

make

If this completes without errors, you will now see a file called vicNl in this directory. vicNl is the executable file for the model.

Run VIC

At the command prompt, type:

vicNl -g global_parameter_filename where:
global_parameter_filename = name of the global parameter file corresponding to your project.

If you'd like to capture VIC's screen output in a log file, you can do (in C-shell):

vicNl -g global_parameter_filename >& log.txt, where
global_parameter_filename = name of the global parameter file corresponding to the project.
log.txt = name of a log file to contain VIC's screen output.

Other Command Line Options

VIC has a few other command line options:

- vicNl -v: says which version of VIC this is
- vicNl -h: prints a list of all the VIC command-line options

- vicNl -o: prints a list of all of the current compile-time settings in this executable; to change thses settings, you must edit user_def.h and recompile using "make clean; make"

Model Results

The contents of the results files can be controlled by the user, by options/instructions in the global parameter file. If no output file instructions are given in the global parameter file, VIC will create the same 2 or 3 output files as in earlier versions, by default.

Output to the Screen

VIC sends messages to the screen regarding status of the simulation, warnings, and errors. The amount of verbage sent to the screen can be controlled by the appropriate setting of VERBOSE in the file user_def.h.
To capture VIC's screen output in a log file, it is possible (in C-shell):

vicNl -g global_parameter_filename >& log.txt where

global_parameter_filename = name of the global parameter file corresponding to your project.

log.txt = name of a log file to contain VIC's screen output.

When VERBOSE is TRUE, VIC prints the following output to the screen:

- List of parameter files that are opened for reading
- List of the values of compile-time and run-time options for this simulation (this is important for diagnosing the causes of model behavior)
- For each grid cell, lists:
    - Cell ID, latitude, and longitude
    - Forcing file opened for reading
    - Output files opened for writing
    - Warnings and error messages encountered during the simulation
    - Final total moisture and energy balance residual errors

State File (optional)

VIC can save the hydrologic state from any point in the simulation (usually the final state) to a file for the purpose of re-starting the simulation later (as an initial state file). This is useful for simulations that require lengthy spin-up periods or ensemble methods. The point at which the hydrologic state is saved, and the name/location of the state file, can be specified by the user in the global parameter file

ANNEXE 5: INPUT FILES

A.GLOBAL PARAMETER FILE

This is the main input file for VIC. It points VIC to the locations of the other input/output files and sets parameters that govern the simulation (e.g., start/end dates, modes of operation).

VIC Run-Time Options - Global Parameter File

The global parameter file serves two main purposes:

1. Tells VIC the names, locations, and formats of input and output files
2. Defines some global parameters of the simulation, known as *run-time* options.

Other global parameters are defined in the file user_def.h in the source code. Those parameters are therefore *compile-time* options, since they are defined when compiling the model from source code. The order of the options in the global parameter file is not important, but the complete option name must be followed by the required option type information.

MAIN SECTIONS OF GLOBAL PARAMETER FILE	OTHER SECTIONS OF GLOBAL PARAMETER FILE
Define Main Simulation Parameters Define State Files Define Meteorological Forcing Files Define Parameter Files Define Lake Parameters Define Output Files Example Global Parameter File	Simulation Parameters That Rarely Need to be Changed: Soil Temperature Parameters Precipitation Parameters Turbulent Flux Parameters Met. Forcing Disaggregation Parameters Miscellaneous Parameters Obsolete Options from Earlier Versions Note about compatibility with previous versions of VIC

Define Main Simulation Parameters

The following options determine the type of simulation that will be performed.

Name	Type	Units	Description
NLAYER	Integer	N/A	Number of moisture layers used by the model
NODES	Integer	N/A	Number of thermal solution nodes in the soil column
TIME_STEP	Integer	hours	Simulation time step length (must divide 24 evenly). NOTE: TIME_STEP should be < 24 for FULL_ENERGY=TRUE FROZEN_SOIL=TRUE.
SNOW_STEP	Integer	hours	Length of time step used to solve the snow model,must divide 24 evenly. if TIME_STEP < 24, SNOW_STEP should = TIME_STEP)
STARTYEAR	Integer	year	Year model simulation starts
STARTMONTH	Integer	month	Month model simulation starts
STARTDAY	Integer	day	Day model simulation starts
STARTHOUR	Integer	hour	Hour model simulation starts
EITHER:			Note: **either** *NRECS* **or** *ENDYEAR*, *ENDMONTH*, and *ENDDAY* must be specified, but **not both**
NRECS	Integer	N/A	Number of time steps over which to run model. NOTE: The number of records must be defined such that the model completes the last day.
OR:			Note: **either** *NRECS* **or** *ENDYEAR*, *ENDMONTH*, and *ENDDAY* must be specified, but **not both**
ENDYEAR	Integer	year	Year model simulation ends
ENDMONTH	Integer	month	Month model simulation ends
ENDDAY	Integer	day	Day model simulation ends
FULL_ENERGY	String	TRUE or FALSE	Option for computing land surface temperature (soil or snowpack surface) • **TRUE** = compute (via iteration) the

			temperature that balances the surface energy budget • **FALSE** = set surface temperature equal to air temperature
FROZEN_SOIL	string	TRUE or FALSE	Option for handling the water/ice phase change in frozen soils • **TRUE** = account for water/ice phase change (including latent heat) • **FALSE** = soil moisture always remains liquid, even when below 0 C; no latent heat effects and ice content is always 0. Note: to activate this option, the user must **also** set the **FS_ACTIVE** flag to 1 in the soil parameter file for each grid cell where this option is desired. In other words, the user can choose for some grid cells (e.g. cold ones) to compute ice contents and for others (e.g. warm ones) to skip the extra computation.

NLAYER: NLAYER is the number of soil moisture layers to be used by the model. Typically the number of layers is 2 or 3. The model cannot be run in energy balance mode with fewer than 3 layers (the top layer is thin 5-15cm), but the water balance model used to have only 2 layers. The model has not been tested with more than 3 layers, so problems may develop.

NODES: NODES defines the number of soil thermal nodes used by the model to explicitly solve soil thermal fluxes. At this time the explicit solution of the soil thermal fluxes occurs only when the model is run with the frozen soil algorithm activated. The model uses a node at the surface, a node at the bottom of the thin (5-15cm) top layer, and a node at the damping depth. If more nodes are defined they are distributed evenly between the bottom of the top layer and the damping depth. More nodes improve the accuracy of the soil heat flux solution, but also increases the computational time. I recommend at least 5 nodes.

Simulation Parameters That Rarely Need to be Changed

The following sections describe options for which VIC will select the appropriate default values. The user may override these values but should do so with care.

Define Soil Temperature Parameters

The following options determine the type of simulation that will be performed.

Name	Type	Units	Description
QUICK_FLUX	String	TRUE or FALSE	Option for computing the soil vertical temperature profile • **TRUE** = use the approximate method described to compute soil temperatures and ground heat flux; this method ignores water/ice phase changes • **FALSE** = use the finite element method described to compute soil temperatures and ground heat flux; this method is appropriate for accounting for water/ice phase changes Default = FALSE when running FROZEN_SOIL; and TRUE in all other cases.
IMPLICIT	String	TRUE or FALSE	If TRUE the model will use an implicit solution for the soil heat flux equation (QUICK_FLUX is FALSE), otherwise uses original explicit solution. When QUICK_FLUX is TRUE the implicit solution has no effect. The user can override this option by setting IMPLICIT to FALSE in the global parameter file. The implicit solution is guaranteed to be stable for all combinations of time step and thermal node spacing; the explicit solution is only stable for some combinations. If the user sets IMPLICIT to FALSE, VIC will check the time step, node spacing, and soil thermal properties to confirm stability. If the explicit solution will not be stable, VIC will exit with an error message. Default = TRUE.
QUICK_SOLVE	String	TRUE or FALSE	This option is a hybrid of QUICK_FLUX TRUE and FALSE. Default = FALSE.

NOFLUX	string	TRUE or FALSE	If TRUE model will use a no flux bottom boundary with the finite difference soil thermal solution (i.e. QUICK_FLUX = FALSE or FULL_ENERGY = TRUE or FROZEN_SOIL = TRUE). Default = FALSE (i.e., use a constant temperature bottom boundary condition).
EXP_TRANS	string	TRUE or FALSE	If TRUE the model will exponentially distributes the thermal nodes in the finite difference algorithm, otherwise uses linear distribution. (This is only used if FROZEN_SOIL = TRUE). Default = FALSE.
GRND_FLUX_TYPE	string	N/A	Options for handling ground flux: • **GF_406** = use (flawed) formulas for ground flux, deltaH, and fusion as in VIC 4.0.6 and earlier • **GF_410** = use formulas from VIC 4.1.0 NOTE: this option exists for backwards compatibility with earlier releases and likely will be removed in later releases. Default = GF_410.
TFALLBACK	string	TRUE or FALSE	Options for handling failures of T iterations to converge: • **FALSE** = if T iteration fails to converge, report an error • **TRUE** = if T iteration fails to converge, use the previous time step's T value This option affects the temperatures of canopy air, canopy snow, ground snow pack, ground surface, and soil T nodes. If TFALLBACK is TRUE, VIC will report the total number of instances in which the previous step's T was used, at the end of each grid cell's simulation. In addition, a time series of when these instances occurred (averaged across all veg tile/snow band combinations) can be written to the output files,

			using the following output variables: • **OUT_TFOL_FBFLAG** = time series of T fallbacks in canopy snow T solution • **OUT_TCAN_FBFLAG** = time series of T fallbacks in canopy air T solution • **OUT_SNOWT_FBFLAG** = time series of T fallbacks in snow pack surface T solution • **OUT_SURFT_FBFLAG** = time series of T fallbacks in ground surface T solution • **OUT_SOILT_FBFLAG** = time series of T fallbacks in soil node T solution (one time series per node) Default = TRUE.

Precipitation (Rain and Snow) Parameters

Generally these default values do not need to be overridden.

Name	Type	Units	Description
SNOW_ALBEDO	string	N/A	Options for computing snow albedo: • **USACE** = Use traditional VIC algorithm based on US Army Corps of Engineers empirical snow albedo decay curves, using hard-coded dates for transitions from snow accumulation to melting. • **SUN1999** = Use algorithm of Sun et al 1999, in which albedo decay depends on snow cold content (more appropriate for simulations outside the US). Default = USACE.
SNOW_DENSITY	string	N/A	Options for computing snow density: • **DENS_BRAS** = Use traditional VIC algorithm taken from Bras, 1990. • **DENS_SNTHRM** = Use algorithm taken from SNTHRM model. Default = DENS_BRAS.
BLOWING	string	TRUE or FALSE	If TRUE, compute evaporative fluxes due to blowing snow Default = FALSE.
COMPUTE_TREELINE	string or integer	FALSE or veg class id	Options for handling above-treeline vegetation: • **FALSE** = Do not compute treeline or replace vegetation above the treeline. • ***CLASS_ID*** = Compute the treeline elevation based on average July temperatures; for those elevation bands with elevations above the treeline (or the entire grid cell if

			SNOW_BAND == 1 and the grid cell elevation is above the tree line), if they contain vegetation tiles having overstory, replace that vegetation with the vegetation having id *CLASS_ID* in the vegetation library. NOTE: If LAKES=TRUE, COMPUTE_TREELINE **MUST** be FALSE. Default = FALSE.
DIST_PRCP	string	TRUE or FALSE	If TRUE use distributed precipitation Default = FALSE.
PREC_EXPT	float	N/A	Exponent used to determine the fraction of a grid cell that receives precipitation. Used only if DIST_PREC option is set to TRUE. Default = 0.6.
CORRPREC	string	TRUE or FALSE	If TRUE correct precipitation for gauge undercatch NOTE: This option is not supported when using snow/elevation bands. Default = FALSE.
MAX_SNOW_TEMP	float	deg C	Maximum temperature at which snow can fall Default = 0.5 C.
MIN_RAIN_TEMP	float	deg C	Minimum temperature at which rain can fall Default = -0.5 C.

Distributed Precipitation Formulation

VIC includes consideration for sub-grid scale variability in various properties, including precipitation. Precipitation is distributed throughout all or a portion of a grid cell, as a function of the intensity of the precipitation event.

The fractional coverage of a grid cell by a precipitation event is determined based on a relationship of the form:

$$\mu = (1 - e^{-aI})$$

where I represents the grid cell averaged precipitation intensity.

As the intensity of the precipitation event changes during a storm, this approach allows the adjustment of the fractional coverage accordingly. As storm intensity increases, the fractional coverage of the grid cell by the storm increases; with decreasing storm intensity the coverage decreases. Before a new storm event, the soil water content throughout the grid cell is set to the average value for the grid cell. The "a" coefficient includes the effects of grid cell size, as well as geographic and other variations. Using values for I in millimeters per hour (mm/hr), the VIC model sets the value for "a" to 0.6. This value can be set to a specific value by the model user. In the instance of precipitation occurring as snow, an exception is made to the above formulation. If there is snow on the ground in the grid cell, or if the precipitation for an event is snow, the fractional coverage for the grid cell is set to 1.0.

Turbulent Flux Parameters

Generally these default values do not need to be overridden.

Name	Type	Units	Description
MIN_WIND_SPEED	float	m/s	Minimum allowable wind speed. Default = 0.1 m/s.
AERO_RESIST_CANSNOW	string	N/A	Options for aerodynamic resistance in snow-filled canopy: • **AR_406** = Multiply by 10 for latent heat, but do NOT multiply by 10 for sensible heat. When no snow in canopy, use surface aero_resist instead of overstory aero_resist. (As in VIC 4.0.6). • **AR_406_LS** = Multiply by 10 for both latent and sensible heat. When no snow in canopy, use surface aero_resist instead of overstory aero_resist. • **AR_406_FULL** = Multiply by 10 for both latent and sensible heat. Always use overstory aero_resist (snow or bare). • **AR_410** = Apply stability correction, instead of multiplying by 10, for both latent and sensible heat. Always use overstory aero_resist (snow or bare). NOTE: this option exists for backwards compatibility with earlier releases and likely will be removed in later releases. Default = AR_406_FULL.

MIN_WIND_SPEED parameter defines the minimum observable wind speed, which is then used to correct the model forcing data. Anemometers typically have a minimum observable wind speed on the order of 0.5 m/s. When forcing the VIC model with hourly wind speeds, the model's surface flux estimates have been observed to "hiccup" (especially in dry climates), while this does not impact the long term energy balance, it will be very noticable when looking at daily fluxes. Therefore, VIC will use MIN_WIND_SPEED to restrict the minimum value of wind speed used to force the model. Default value is set to 0 m/s, which works well when the model is forced with daily or monthly winds.

Meteorological Forcing Disaggregation Parameters

Generally these default values do not need to be overridden.

Name	Type	Units	Description
PLAPSE	string	TRUE or FALSE	Options for computing grid cell average surface atmospheric pressure (and density) when it is not explicitly supplied as a meteorological forcing: • **FALSE** = Set surface atmospheric pressure to constant 95.5 kPa (as in earlier releases). • **TRUE** = Lapse surface atmospheric pressure (and density) from sea level to the grid cell average elevation. NOTE: air pressure is already lapsed to grid cell or band elevation when computing latent heat; this option only affects computation of sensible heat. NOTE: this option exists for backwards compatibility with earlier releases and likely will be removed in later releases (the TRUE option will become the standard behavior). Default = TRUE.
SW_PREC_THRESH	float	mm	Minimum daily precipitation, above which incoming shortwave is dimmed by 25%, when shortwave is not supplied as a forcing but instead is estimated from daily temperature range. This option's purpose is to avoid erroneous dimming of estimated shortwave when using forcings that have been aggregated or re-sampled from a different resolution. Re-sampling can sometimes smear small

			amounts of precipitation from neighboring cells into cells that originally had no precipitation. The appropriate value of SW_PREC_THRESH must be found through examination of the forcings. Default = 0 mm (any precipitation causes dimming)
MTCLIM_SWE_CORR	string	TRUE or FALSE	This controls VIC's estimates of incoming shortwave (when shortwave is not supplied as a forcing) in the presence of snow. When shortwave is supplied as a forcing, this option is ignored. • **TRUE** = Adjust incoming shortwave for snow albedo effect. • **FALSE** = Do not adjust shortwave (as in earlier releases). Default = TRUE.
VP_ITER	string	N/A	This controls VIC's iteration between estimates of shortwave and vapor pressure: • **VP_ITER_NEVER** = Never iterate; make estimates separately. • **VP_ITER_ALWAYS** = Always iterate once (as in previous releases). • **VP_ITER_ANNUAL** = Iterate once for arid climates (based on annual Precip/PET ratio) and never for humid climates. • **VP_ITER_CONVERGE** = Always iterate until shortwave and vp stabilize. Default = VP_ITER_ALWAYS.
VP_INTERP	string	TRUE or	This controls sub-daily humidity

		FALSE	estimates: • **TRUE** = Interpolate daily VP estimates linearly between sunrise of one day to the next. • **FALSE** = Hold VP constant for entire day (as in previous releases). Default = TRUE.
LW_TYPE	string	N/A	This controls the algorithm used to estimate clear-sky longwave radiation: • **LW_TVA** = Tennessee Valley Authority algorithm (1972) (this option is what previous releases used) • **LW_ANDERSON** = Algorithm of Anderson (1964) • **LW_BRUTSAERT** = Algorithm of Brutsaert (1975) • **LW_SATTERLUND** = Algorithm of Satterlund (1979) • **LW_IDSO** = Algorithm of Idso (1981) • **LW_PRATA** = Algorithm of Prata (1996) Default = LW_TVA.
LW_CLOUD	string	N/A	This controls the algorithm used to estimate the influence of clouds on total longwave: • **LW_CLOUD_BRAS** = Method from Bras textbook (this option is what previous releases used) • **LW_CLOUD_DEARDORFF** = Algorithm of Deardorff (1978) Default = LW_CLOUD_DEARDORFF.

Miscellaneous Parameters

Generally these default values do not need to be overridden.

Name	Type	Units	Description
CONTINUEONERROR	string	TRUE or FALSE	Options for handling fatal errors: • **FALSE** = if simulation of a grid cell encounters an error, exit VIC • **TRUE** = if simulation of a grid cell encounters an error, move to next grid cell NOTE: in either case, if a grid cell encounters a fatal error, the output files for that grid cell will likely be incomplete. But since most fatal errors are the result of failure of the temperature iteration to converge, seting the **TFALLBACK** option to TRUE should eliminate most fatal errors.. Default = TRUE.

Define State Files

The following options control input and output of state files.

Name	Type	Units	Description
INIT_STATE	string	path/filename	Full path and filename of initial state file. NOTE: if INIT_STATE is not specified, VIC will take initial soil moistures from the soil parameter file and set all other state variables to a default state.
STATENAME	string	path/filename	Path and file prefix of the state file to be created on the specified date. The date within the simulation at which the state is saved will be appended to the file prefix to form a complete file name. NOTE: if STATENAME is not specified, VIC will not save its state in a statefile.
STATEYEAR	integer	year	Year at which model simulation state should be saved. NOTE: if STATENAME is not specified, STATEYEAR will be ignored.
STATEMONTH	integer	month	Month at which model simulation state should be saved. NOTE: if STATENAME is not specified, STATEMONTH will be ignored.
STATEDAY	integer	day	Day at which model simulation state should be saved. State will be saved at the **end** of the final timestep on this day. NOTE: if STATENAME is not specified, STATEDAY will be ignored.
BINARY_STATE_FILE	string	TRUE or FALSE	If FALSE, VIC reads/writes the intial/output state files in ASCII format. If TRUE, VIC reads/writes intial/output state files in binary format. NOTE: if INIT_STATE or STATENAME are not specified, BINARY_STATE_FILE will be ignored.

Define Meteorological Forcing Files

This section describes how to define the forcing files needed by the VIC model.
Unlike model parameters, for which 1 file contains data for all grid cells, the meteorological forcings are stored as a separate time series for each grid cell. If the input forcings are daily and VIC is running with a sub-daily model timestep, it will disaggregate the daily forcings to sub-daily, using the "mtclim" algorithm of Thornton and Running. However, VIC will not disaggregate sub-daily forcings from one time step length to another. If the input forcings are sub-daily, and VIC is running with a different sub-daily model time step, VIC will exit. Input files can be ASCII or Binary (signed or unsigned short ints) column formatted. Columns in the file must be in the same order as they are defined in the global control file.VIC will allow forcing data to be stored in two different files per grid cell (e.g., precip and wind speed in one file, tmin and tmax in another file). Note that if you are using two forcing files per grid cell, the parameters for the first file must be defined before those for the second. **Bold** numbers indicate the order in which these values should be defined, after each forcing file (FORCING1 or FORCING2). Options that do not have a bold number apply to both forcing file types and should appear after the numbered options.All FORCING filenames are actually the pathname, and prefix for gridded data types: ex. DATA/forcing_YY.YYY_XX.XXX. Latitude and longitude index suffix is added by VIC based on GRID_DECIMAL parameter defined above, and the latitude and longitude values defined in the soil parameter file.

Name	Type	Units	Description
(1*) FORCING1	string	pathname and file prefix	First forcing file name, always required. This must precede all other forcing parameters used to define the first forcing file.
(1*) FORCING2	string	pathname and file prefix	Second forcing file name, or FALSE if only one file used. This must precede all other forcing parameters used to define the second forcing file, and follow those used to define the first forcing file.
(2) FORCE_FORMAT	string	BINARY or ASCII	Defines the format type for the forcing files.
(3)FORCE_ENDIAN	string	BIG or LITTLE	Identifies the architecture of the machine on which the binary forcing files were created: • BIG = big-endian (*e.g.* SUN) • LITTLE = little-endian (*e.g.* PC/linux)

			Model will identify the endian of the current machine, and swap bytes if necessary. Required for binary forcing file, not used for ASCII forcing file.
(4) N_TYPES	int	N/A	Number of columns in the current data file.
(5) **FORCE_TYPE**	string string float	VarName (un)signed multiplier	Defines what forcing types are read from the file, and in what order. For ASCII file only the forcing type needs to be defined, but for Binary file each line must also define whether the column is SIGNED or UNSIGNED short int and by what factor values are multiplied before being written to output.
(6) FORCE_DT	integer	hours	Time step length of the current input files in hours
(7) FORCEYEAR	integer	year	Year meteorological forcing files start
(8) FORCEMONTH	integer	month	Month meteorological forcing files start
(9) FORCEDAY	integer	day	Day meteorological forcing files start
(10) FORCEHOUR	integer	hour	Hour meteorological forcing files start
GRID_DECIMAL	integer	N/A	Number of decimals to use in gridded file name extensions
WIND_H	float	m	Height of wind speed measurement over bare soil and snow cover. Wind measurement height over vegetation is now read from the vegetation library file for all types, the value in the global file only controls the wind height over bare soil and over the snow pack when a vegetation canopy is not defined.
MEASURE_H	float	m	Height of humidity measurement
ALMA_INPUT	string	TRUE or FALSE	This option tells VIC the units to expect for the input variables (default is **FALSE**): • FALSE = Use standard VIC units: for moisture fluxes, use cumulative mm over the time step; for temperature, use degrees C; • TRUE = Use the units of the ALMA

			convention: for moisture fluxes, use the average rate in mm/s (or kg/m^2s) over the time step; for temperature, use degrees K;

* If using one forcing file, use only FORCING1, if using two forcing files, define all parameters for FORCING1, and then define all forcing parameters for FORCING2. All parameters need to be defined for both forcing files when a second file is used.

FORCE_TYPE parameter defines which forcing variables are in the forcing file, and the order in which they appear. These lines must follow either FORCING1 or FORCING2, and N_TYPES so that the model knows which file to associate the columns with and how any columns are present. If the forcing file is in binary format, FORCE_TYPE must also define whether each value is a SIGNED or UNSIGNED short int and the factor by which it needs to be multiplied.

Possible forcing file data types are:

AIR_TEMP - sub-daily air temperature (C)

ALBEDO - surface albedo (fraction)

DENSITY - atmospheric density (kg/m^3)

PREC - precipitation (mm)

PRESSURE - atmospheric pressure (kPa)

SHORTWAVE - shortwave radiation (W/m^2)

TMAX - daily maximum temperature (C)

TMIN - daily minimum temperature (C)

VP - atmospheric vapor pressure (kPa)

WIND - wind speed (m/s)

SKIP - used to indicate a data column which is not read into the model

EXAMPLES: a standard four column daily forcing data file will be defined as:

ASCII File

```
FORCING1       FORCING_DATA/LDAS_ONE_DEGREE/data_
N_TYPES        4
FORCE_TYPE     PREC
FORCE_TYPE     TMAX
FORCE_TYPE     TMIN
FORCE_TYPE     WIND
FORCE_FORMAT   ASCII
FORCE_DT       24
```

Binary File

```
FORCING1       FORCING_DATA/LDAS_ONE_DEGREE/data_
N_TYPES        4
FORCE_TYPE     PREC   UNSIGNED     40
FORCE_TYPE     TMAX   SIGNED       100
FORCE_TYPE     TMIN   SIGNED       100
FORCE_TYPE     WIND   SIGNED       100
FORCE_FORMAT   BINARY
FORCE_ENDIAN   LITTLE
FORCE_DT       24
```

Define Parameter Files

The following options describe the input parameter files.

Name	Type	Units	Description
SOIL	string	path/filename	either the Soil parameter file or the ARC/INFO Soil Parameter File List name, depending on the setting of ARC_SOIL.
ARC_SOIL	string	TRUE or FALSE	if TRUE read soil parameters from ARC/INFO ASCII gridded files. Default = FALSE.
SOIL_DIR	string	directory name	The directory in which to look for all ARC/INFO ASCII gridded parameter files. Used only if ARC_SOIL is TRUE.
BASEFLOW	string	N/A	This option describes the form of the baseflow parameters in the soil parameter file: • ARNO = fields 5-8 of the soil parameter file are the standard VIC baseflow parameters • NIJSSEN2001 = fields 5-8 of the soil parameter file are the baseflow parameters from Nijssen et al (2001) Default = ARNO.
JULY_TAVG_SUPPLIED	string	TRUE or FALSE	If TRUE then VIC will look in the last column of the soil file for the average July temperature. Default = FALSE.
ORGANIC_FRACT	string	TRUE or FALSE	(release 4.1.2 and later) TRUE = the soil parameter file contains 3*Nlayer extra columns, listing, for each layer: the organic fraction, and the bulk density and soil particle density of the organic matter in the soil layer. FALSE = the soil parameter file does not

			contain any information about organic soil, and organic fraction should be assumed to be 0. Default = FALSE.
VEGLIB	String	path/filename	Vegetation library file name
VEGPARAM	String	path/filename	Vegetation parameter file name
ROOT_ZONES	Integer	N/A	Number of defined root zones defined for root distribution.
VEGPARAM_LAI	String	TRUE or FALSE	If TRUE the vegetation parameter file contains an extra line for each vegetation type that defines monthly LAI values for each vegetation type for each grid cell. Default = FALSE.
LAI_SRC	String	N/A	This option tells VIC where to look for LAI values: • LAI_FROM_VEGLIB = Use the LAI values listed in the vegetation library file. • LAI_FROM_VEGPARAM = Use the LAI values listed in the vegetation parameter file. Note: for this to work, **VEGPARAM_LAI** must be TRUE. Default = LAI_FROM_VEGLIB.
SNOW_BAND	integer string	N/A path/filename	Maximum number of snow elevation bands to use, and the name (with path) of the snow elevation band file. For example: • SNOW_BAND 5 path/filename To turn off this feature, set the number of snow bands to 1 and do not follow this with a snow elevation band file name. Default = 1.

ROOT_ZONES is the number of root zones used in the vegetation parameter file to define the root distribution. This allows the rooting distribution to be defined independently of both vegetation type and soil layer depth. When soil moisture layer depths are changed during calibration, the model uses linear distribution based on the defined root zones to redistribute root fractions.No default value is set, this parameter must be defined in the model control file.

Lake Parameters

The following options only take effect when the lake model is running.

Name	Type	Units	Description
LAKES	String	FALSE or path/filename	Options for handling lakes: • FALSE = do not simulate lakes • *lake parameter path/filename* = simulate lakes and read the given file for lake model parameters Default = FALSE.
LAKE_PROFILE	String	TRUE or FALSE	Options for describing lake profile: • FALSE = VIC computes a parabolic depth-area profile for the lake basin • TRUE = VIC reads user-specified depth-area profile from the lake parameter file Default = FALSE.
EQUAL_AREA	String	TRUE or FALSE	Options for computing grid cell areas: • **FALSE** = Grid cell boundaries and centers fall on a regular lat-lon grid, i.e. grid cells appear as squares when plotted in geographic projection; this means that the grid cells do not have

			equal areas. • **TRUE** = Grid cells have equal area, i.e. they appear as squares when plotted in an equal-area projection; this means that their boundaries do not fall on a regular lat-lon grid and the cell centers are not equally-spaced in latitude and longitude. Default = FALSE.
RESOLUTION	Float	decimal degrees of latitude or area in km^2	Options for grid cell resolution: • If **EQUAL_AREA** = **FALSE**: width of grid cells, in decimal degrees latitude or longitude. • If **EQUAL_AREA** = **TRUE**: area of grid cells, in km^2. Default = none; this MUST be set by the user to match the grid cell size if the lake model is running.

Define Output Files

The following options describe the output files.

Name	**Type**	**Units**	**Description**
RESULT_DIR	String	path name	Name of directory where model results are written
OUT_STEP	Integer	hours	Output time step length
SKIPYEAR	Integer	years	Number of years to skip before starting to write output file. Used to reduce output by not including spin-up years.
COMPRESS	String	TRUE or FALSE	if TRUE compress input and output files when done (uses gzip)

BINARY_OUTPUT	string	TRUE or FALSE	If TRUE write output files in binary (default is ASCII).
ALMA_OUTPUT	string	TRUE or FALSE	Options for output units (default is **FALSE**): • FALSE = standard VIC units. Moisture fluxes are in cumulative mm over the time step; temperatures are in degrees C • TRUE = units follow the ALMA convention. Moisture fluxes are in average mm/s (kg/m^2s) over the time step; temperatures are in degrees K Click here for more information.
MOISTFRACT	string	TRUE or FALSE	Options for output soil moisture units (default is **FALSE**): • FALSE = Standard VIC units. Soil moisture is in mm over the grid cell area • TRUE = Soil moisture is volume fraction
PRT_HEADER	string	TRUE or FALSE	Options for output file headers (default is **FALSE**): • FALSE = output files contain no headers • TRUE = headers are inserted into the beginning of each output file, listing the names of the variables in each field of the file (if ASCII) and/or the variable data types (if BINARY)
PRT_SNOW_BAND	string	TRUE or FALSE	if TRUE then print snow variables for each snow band in a separate output file (snow_band_*). NOTE: this option is ignored if output file contents are specified.
			N_OUTFILES, OUTFILE, and OUTVAR are

			optional; if omitted, traditional output files are produced.
N_OUTFILES	Integer	N/A	Number of output files per grid cell.
OUTFILE	string integer	prefix nvars	Information about this output file: 1. Prefix of the output file (to which the lat and lon will be appended) 2. Number of variables in the output file This should be specified once for each output file.
OUTVAR	string string string integer	name format type multiplier	Information about this output variable: 1. Name (must match a name listed in vicNl_def.h) 2. Output format (C fprintf-style format code) 3. Data type (one of: OUT_TYPE_DEFAULT, OUT_TYPE_CHAR, OUT_TYPE_SINT, OUT_TYPE_USINT, OUT_TYPE_INT, OUT_TYPE_FLOAT,OUT_TYPE_DOUBLE) 4. Multiplier - number to multiply the data with in order to recover the original values (only valid with BINARY_OUTPUT=TRUE) This should be specified once for each output variable. Click here for more information.

B. VIC Compile-Time Options - user_def.h File

While this is not technically an "input" file because it is a header file in the model source code, it is worth mentioning because some simulation options are set in this file.

The header file user_def.h defines some global parameters of the simulation (known as *compile-time* options, since changing their values requires recompiling the model). Other global parameters, known as *run-time* options, are defined in the global parameter file and take effect as soon as the model reads the global parameter file.

The order of the parameters in the file is not important, but the complete option name must be followed by the required option type information.

Define Simulation Parameters

The following options determine the type of simulation that will be performed

Name	Type	Description
VERBOSE	TRUE or FALSE	Option for controlling messages sent to the screen: • FALSE = Only print minimum information: errors, etc. • TRUE = Print much more information: file opening/closing, warnings, etc.
CLOSE_ENERGY	TRUE or FALSE	Option for handling energy fluxes between components of the land surface (canopy, snow pack, ground): • FALSE = Estimate energy balance of each component individually, using incoming fluxes from the other components from the previous time step. • TRUE = Take interactions among the components by iterating: solve each component separately and update the outgoing fluxes from each component, then solve each component again using the updated incoming fluxes from the other components, and repeat until

		desired exit condition reached. Note: both methods generally give similar results, but while setting CLOSE_ENERGY to FALSE improves speed, it results in energy balance errors.
QUICK_FS	TRUE or FALSE	Option for speeding up frozen soil calculations: • FALSE = use full equations for estimating maximum unfrozen water content. • TRUE = use linearized version of maximum unfrozen water content equations, defined in global.h. These equations significantly improve speed when simulating frozen soil. Note: this method is not fully tested.
QUICK_FS_TEMPS	Integer	Number of terms to use in linearized maximum unfrozen water calcuation. This is only used if QUICK_FS is TRUE; otherwise it is ignored.
LOW_RES_MOIST	TRUE or FALSE	Option for improving accuracy of soil moisture drainage calculations: • FALSE = assume uniform matric potential within each soil layer (this tends to drain the soil too quickly when used with 2-4 soil layers). • TRUE = use linear interpolation of logarithm of the matric potential from the two adjacent layers to estimate drainage across the layer boundary (Boone and Wetzel, 1996). This allows a model with fewer (2-4) layers to retain more soil moisture near the top of the soil column, as a model with more layers would. Note: this method is not fully tested.

NO_REWIND	TRUE or FALSE	Option for controlling reading of parameter files: • FALSE = Rewinds (goes back to the beginning of) parameter files before reading the data for each cell. • TRUE = Does not rewind parameter files before reading the data for each cell. This saves time but requires that the order of grid cells in all files is the same.
OUTPUT_FORCE	TRUE or FALSE	Option to save VIC's internal, disaggregated forcings: • FALSE = Run a simulation (including disaggregating the forcings). • TRUE = Do not run a simulation; simply disaggregate the forcings and write them to output files. This allows us to use VIC as a meteorological forcing disaggregator. Note that in this mode of operation, VIC should be executed the same way as normal: VIC still must read a global parameter file that tells it the locations of the forcings and soil parameter file, and sets the model time step (this is the time step the forcings will be disaggregated to), the output time step (usually the same as the model time step in this case), and start/end dates.
OUTPUT_FORCE_STATS	TRUE or FALSE	Option to compute the statistics of the forcings: • FALSE = Run a simulation (including disaggregating the forcings). • TRUE = Do not run a simulation; simply compute the mean, standard deviation, and min and max values of the forcing variables and write

		them to stdout.
SPATIAL_FROST	TRUE or FALSE	Option to allow spatial heterogeneity in soil temperature: • FALSE = Assume soil temperature is horizontally constant (only varies with depth) • TRUE = Assume soil temperatures at each given depth are distributed horizontally with a uniform (linear) distribution, so that even when the mean temperature is below freezing, some portion of the soil within the grid cell at that depth is above freezing. This requires specifying a *frost slope* value as an extra field in the soil parameter file, so that the minimum/maximum temperatures can be computed from the mean value.
FROST_SUBAREAS	Integre	Number of discrete values in the soil temperature distribution. This is only used if SPATIAL_FROST is TRUE; otherwise it is ignored.
SPATIAL_SNOW	TRUE or FALSE	Option to allow spatial heterogeneity in snow water equivalent (yielding partial snow coverage) when the snowpack is melting: • FALSE = Assume snow water equivalent is constant across grid cell • TRUE = Assume snow water equivalent is distributed horizontally with a uniform (linear) distribution, so that some portion of the grid cell has 0 snow pack. This requires specifying the *max_snow_distrib_slope* value as an extra field in the soil parameter file. NOTE: *max_snow_distrib_slope* should be

		set to twice the desired minimum spatial average snow pack depth [m]. I.e., if we define *depth_thresh* to be the minimum spatial average snow depth below which coverage < 1.0, then max_snow_distrib_slope = 2*depth_thresh. NOTE: Partial snow coverage is **only** computed when the snow pack has started **melting** and the spatial average snow pack depth <= max_snow_distrib_slope/2. During the accumulation season, coverage is 1.0. Even after the pack has started melting and depth <= max_snow_distrib_slope/2, new snowfall resets coverage to 1.0, and the previous partial coverage is stored. Coverage remains at 1.0 until the new snow has melted away, at which point the previous partial coverage is recovered.
EXCESS_ICE	TRUE or FALSE	Optional permafrost behavior: • FALSE = No excess ice in the soil; porosities, densities, etc are exactly as described in the soil parameter file. • TRUE = Excess ground ice in the soil. This requires user to specify the *initial volumetric ice content* of the soil as an additional parameter in the soil parameter file. VIC computes *effective* porosities, densities, etc. based on presence of excess ground ice. As the excess ice melts, these effective porosities and densities approach their ice-free values. Excess soil moisture resulting from the melt is expelled as runoff or baseflow.
MAXIT_FE	integre	Maximum number of iterations to use in solving the surface energy balance
LAI_WATER_FACTOR	float	Coefficient multiplied by the LAI to determine the amount of water that can be

		stored in the canopy.
LWAVE_COR	Float	Longwave correction factor, used to correct estimated incoming longwave radiation (use 1, unless measured longwave available for calibration)

Define Data Dimensions

The following parameters define the dimensions of some of the data structures in the model. Note: these dimensions are simply maximum sizes, rather than the actual sizes that will be used in your simulations. This is used for certain memory allocation requirements. Therefore, the optimal values of these parameters should be equal to or slightly larger than the numbers that you think you will need.

Name	**Type**	**Description**
MAX_VEG	Int	Maximum number of vegetation tiles that can be defined within a grid cell (a good rule of thumb is to set this to the number of vegetation classes in your vegetation library file).
MAX_LAYERS	Int	Maximum number of soil layers that can be defined within a grid cell.
MAX_NODES	Int	Maximum number of soil thermal nodes that can be defined within a grid cell.
MAX_BANDS	Int	Maximum number of snow elevation bands that can be defined within a grid cell.
MAX_FRONTS	Int	Maximum number of soil freeze/thaw fronts that can be defined within a grid cell.
MAX_LAKE_NODES	Int	Maximum number of lake solution nodes that can be defined within a grid cell.

C.VIC METEOROLOGICAL FORCINGS FILE

VIC can take daily or sub-daily timeseries of meteorological variables as inputs. These can be gridded or point station data or reanalysis fields.

Forcing Data Files

VIC can take either daily (Precip, Tmax, Tmin, Windspeed) or sub-daily meteorological data as inputs (or a combination of daily and sub-daily inputs). VIC has some flexibility in which variables and combinations of variables it can use. The contents and formats of the meteorological data files must be described in the global parameter file.

There is a List of possible input variables described in another section of this project**.**

Because VIC allows the user to supply any combination of the necessary met variables, there is no single format for these files. For this reason, the user must give VIC all of the relevant details necessary to read the forcing files (e.g., file type - ascii or binary, file "endian-ness", which variables are in the file and in what order, the units of the variables, and start date of the file). This must be done by inserting this information into the forcings section of the global parameter file.

VIC needs the following meteorological variables, at the model timestep, to run: precipitation, air temperature, wind speed, atmospheric pressure and density, vapor pressure (or vapor pressure deficit or relative humidity or specific humidity), incoming shortwave (solar) radiation, and incoming longwave (or thermal) radiation. However, VIC can estimate some of these quantities internally, so that the user need not supply all of them.

The minimum set of variables that VIC requires the user to supply are: daily total precipitation (rain and/or snow), daily max and min temperature, and daily average wind speed. In this case, VIC uses the MTCLIM algorithms (Kimball et al., 1997; Thornton and Running, 1999) to convert daily min and max temperature to humidity and incoming shortwave radiation. VIC then deduces incoming longwave radiation from humidity and temperature. VIC also computes atmospheric pressure and density from grid cell elevation and global mean pressure lapse rate. Finally, VIC converts these daily quantities into sub-daily.

1. Making some assumptions about what time of day the min and max air temperatures occur
2. Interpolating the time series of min and max air temperature with a spline
3. Distributing the shortwave (solar) radiation throughout the day according to solar zenith angle

4. Assuming vapor pressure, atmospheric pressure and density, and wind speed are Constant throughout the day
5. Computing sub-daily longwave from sub-daily temperature and constant vapor pressure
6. Computing sub-daily vapor pressure deficit as sub-daily saturation pressure (at sub-daily air temperature) - sub-daily (constant) vapor pressure
7. Dividing daily total precipitation into equal sub-daily amounts

VIC also accepts more than these minimum 4 variables. If the user wishes to supply more than the minimum set of variables, for example sub-daily {precip, air temp, pressure, humidity, wind speed, and sw/lw radiation} terms from a reanalysis product, or sub-daily observations from a meteorological station, this is also OK. In fact, most combinations of variables are acceptable, as long as the user supplies VIC with at least the minimum 4 variables mentioned above. For example, the user could supply daily {precip, tmin, tmax, wind} in one forcing file and sub-daily sw and lw radiation in another file (i.e. the two files need not have the same time step - as long as the sub-daily file is at the same timestep as the model timestep).

NOTE: Important Information Regarding the Time Zone of Sub-Daily Forcing Inputs

As of release 4.1.2, we have fixed inconsistencies (present in all previous releases) in timing of sub-daily forcings computed by VIC and sub-daily forcings supplied by the user. Now, we have adopted the following convention:

- The parameter **off_gmt** (from the soil parameter file) determines how VIC interprets sub-daily time steps relative to the model start date and time.
- An **off_gmt** value of **0** indicates that the model start date/time is relative to **Greenwich Mean Time (GMT)**.
- An **off_gmt** value of **(grid_cell_longitude*24/360)** indicates that the model start date/time is relative to **local time**.
- When outputting sub-daily results, VIC's output files are referenced to the model start date/time; therefore they are controlled by **off_gmt** (off_gmt=0 means VIC results are referenced to GMT; off_gmt=(grid_cell_longitude*24/360) means VIC results are referenced to local time).
- **Daily** supplied forcings are assumed to start/end at midnight in **local time**; the forcing start date/time is thus in **local time**. When VIC disaggregates daily forcings into sub-daily forcings, **off_gmt** will be used to determine the time lag between the start of the forcing's diurnal cycle and the start of the VIC simulation.

- **Sub-daily** supplied forcings are assumed to occur relative to **the time zone indicated by off_gmt**. Therefore, if VIC outputs these sub-daily forcings, they will occur at the exact same time of day as in the input files.

Therefore, if mixing daily and sub-daily forcing inputs, it is important that any sub-daily forcing inputs be shifted as necessary to be in the time zone indicated by off_gmt.

In all cases, the user must list the variables contained in the forcing files, by their names and in the exact order in which they appear in the forcing files. **This is done in the global parameter file using the FORCE_TYPE parameter**. Possible forcing file data types and units are:

Variable Name	**Definition**	**Default Units**	**ALMA units**
AIR_TEMP	sub-daily air temperature	deg C	K
ALBEDO	surface albedo	fraction	fraction
CRAINF	convective rainfall	mm per step	mm/s == $kg/m^2/s$
CSNOWF	convective snowfall	mm per step	mm/s == $kg/m^2/s$
DENSITY	atmospheric density	kg/m^3	kg/m^2
LONGWAVE	incoming longwave (thermal infrared) radiation	W/m^2	W/m^2
LSRAINF	large-scale rainfall	mm per step	mm/s == $kg/m^2/s$
LSSNOWF	large-scale snowfall	mm per step	mm/s == $kg/m^2/s$
PREC	total precipitation	mm per step	mm/s == $kg/m^2/s$
PRESSURE	atmospheric pressure	kPa	Pa
QAIR	specific humidity	kg/kg	kg/kg
RAINF	total rainfall	mm per step	mm/s == $kg/m^2/s$
REL_HUMID	relative humidity	fraction	fraction
SHORTWAVE	incoming shortwave (solar) radiation	W/m^2	W/m^2
SNOWF	total snowfall	mm per step	mm/s == $kg/m^2/s$

TMAX	daily maximum temperature	deg C	K
TMIN	daily minimum temperature	deg C	K
TSKC	cloud cover	fraction	fraction
VP	atmospheric vapor pressure	kPa	Pa
WIND	wind speed	m/s	m/s
WIND_E	East component of wind speed	m/s	m/s
WIND_N	North component of wind speed	m/s	m/s
SKIP	indicates a data column which is ignored, e.g., year, month, and day columns if they are present		

By default, the variables are assumed to have units described in column 3 of the table above. To use the units in column 4 (ALMA), the user must set ALMA_INPUT TRUE in the global parameter file. ALMA units correspond more closely to the units used by reanalysis products or GCMs.

Forcing data files can be in short-int Binary or ASCII column formats. Details are below. Three examples of file type definitions are provided below using a standard daily input file containing precipitation, daily maximum and minimum air temperature and wind speed:

ASCII Column Format

Below is an example of a 4 column daily forcing file:

```
0.000 -10.00 -2.00 2.00
0.000 -8.50 -1.10 2.00
5.000 -7.90 0.10 2.00
10.000 -8.20 -3.10 2.00
...
```

To read this file the global control file must have the following lines

```
FORCING1
  FORCING_DATA/LDAS_ONE_DEGREE/data_
N_TYPES          4
FORCE_TYPE       PREC
FORCE_TYPE       TMAX
FORCE_TYPE       TMIN
```

```
FORCE_TYPE        WIND
FORCE_FORMAT      ASCII
FORCE_DT  24
FORCEYEAR 1950
FORCEMONTH        1
FORCEDAY  1
FORCEHOUR 0
FORCING2  FALSE
```

Binary short int Format

Short integer binary files are significantly smaller than an equivalent ASCII column file. However, floating point data values must be converted by a multiplication factor in order to be stored in a single short int value. If a forcing value is always positive (such as precipitation), then using UNSIGNED short int values means that a larger range of positive values can be stored. To properly extract the data stored in the forcing file, both the multiplication factor, and whether the data is SIGNED or UNSIGNED must be included in the global control file.

One further piece of information must be provided to make sure that VIC reads the binary file correctly even if the file was created on a diffrent machine than the one which runs the simulation. There are two different architectures present on our systems. Most of the workstations store data in big-endian format (most significant byte first), while the PC based systems (including all of the FreeBSD systems) store data in little-endian format (least significant byte first). VIC can determine the endian of the simulation machine, but the global control file must tell it the format of the machine on which the binary files were created.

Below is an example of what would be in the global control file in order to read the previous example if it had been encoded in short int binary form:

```
FORCING1     FORCING_DATA/LDAS_ONE_DEGREE/data_
                 N_TYPES        4
                 FORCE_TYPE     PREC   UNSIGNED
                   40
                 FORCE_TYPE     TMAX   SIGNED
                   100
                 FORCE_TYPE     TMIN   SIGNED
                   100
```

```
FORCE_TYPE     WIND   SIGNED
  100
FORCE_FORMAT   BINARY
FORCE_ENDIAN   LITTLE
FORCE_DT24
FORCEYEAR      1950
FORCEMONTH     1
FORCEDAY1
FORCEHOUR      0
FORCING2       FALSE
```

Using two forcing files

As the final example, assume that you have daily precipitation, and minimum and maximum air temperature, but you also have hourly wind speed. To save space, it makes the most sense to save the data sets separately (otherwise the daily data must be converted to hourly, or the hourly to daily). VIC is capable of reading forcing data from two sources with two different time steps. Below is an example of what the global control file would look like:

```
FORCING1
  FORCING_DATA/LDAS_ONE_DEGREE/data
_
N_TYPES        4
FORCE_TYPE     PREC
FORCE_TYPE     TMAX
FORCE_TYPE     TMIN
FORCE_TYPE     SKIP
FORCE_FORMAT   ASCII
FORCE_DT24
FORCEYEAR      1950
FORCEMONTH     1
FORCEDAY1
FORCEHOUR      0
FORCING2
  FORCING_DATA/LDAS_ONE_DEGREE/data
_
N_TYPES        2
FORCE_TYPE     SKIP
```

```
FORCE_TYPE     WIND
FORCE_FORMAT   ASCII
FORCE_DT1
FORCEYEAR      1950
FORCEMONTH     1
FORCEDAY1
FORCEHOUR      0
```

D. SOIL PARAMETER FILE

The soil parameter file serves three main purposes:

- Define the cell ID number of each grid cell. This ID number is essentially a database key that links a grid cell to its parameters in the various parameter files.
- Define the grid cell soil parameters, as well as geographic information such as grid cell center latitude and longitude.
- Define initial soil moisture conditions, to be used in the absence of an initial state file.

The soil parameters can be supplied to VIC in two alternate formats:

- A single ASCII file, with a separate row for each grid cell, with each field containing a different parameter value (description of this file is below).
- A set of ASCII Arc/Info grid files, each one containing a map of the values of a single parameter for all the grid cells in the domain

Soil hydrologic and thermal parameters needed for the different VIC model set-ups are listed below. All columns of the input file must be filled, but certain parameters need only be defined if the full energy or frozen soil models are activated. Header lines can be added by starting the line with a '#'.

In previous versions certain parameters were read as average values for the entire soil column. In version 4.0 all soil parameter values are now read for all layers. Converting the soil parameter file from older model versions, should simply require copying column average values to separate columns for each soil moisture layer.

Column	Variable Name	Units	Number of Values	Description
1	run_cell	N/A	1	1 = Run Grid Cell, 0 = Do Not Run
2	gridcel	N/A	1	Grid cell number
3	Lat	degrees	1	Latitude of grid cell
4	Lon	degrees	1	Longitude of grid cell
5	infilt	N/A	1	Variable infiltration curve parameter (b_{infilt})
6	Ds	fraction	1	Fraction of Dsmax where non-linear baseflow

				begins
7	Dsmax	mm/day	1	Maximum velocity of baseflow
8	Ws	fraction	1	Fraction of maximum soil moisture where non-linear baseflow occurs
9	c	N/A	1	Exponent used in baseflow curve, normally set to 2
10 : (Nlayer+9)	expt	N/A	Nlayer	Exponent *n* (=3+2/lambda) in Campbell's eqn for hydraulic conductivity Values should be > 3.0.
(Nlayer+10) :(2*Nlayer+9)	Ksat	mm/day	Nlayer	Saturated hydrologic conductivity
(2*Nlayer+10):(3*Nlayer+9)	phi_s	mm/mm	Nlayer	Soil moisture diffusion parameter
(3*Nlayer+10):(4*Nlayer+9)	init_moist	mm	Nlayer	Initial layer moisture content
(4*Nlayer+10)	elev	m	1	Average elevation of grid cell
(4*Nlayer+11):(5*Nlayer+10)	depth	m	Nlayer	Thickness of each soil moisture layer
(5*Nlayer+11)	avg_T	C	1	Average soil temperature, used as the bottom boundary for soil heat flux solutions
(5*Nlayer+12)	dp	m	1	Soil thermal damping depth (depth at which soil temperature remains constant through the year, ~4 m)
(5*Nlayer+13):(6*Nlayer+12)	bubble	cm	Nlayer	Bubbling pressure of soil Values should be > 0.0

(6*Nlayer+13):(7*Nlayer+12)	quartz	fraction	Nlayer	Quartz content of soil
(7*Nlayer+13):(8*Nlayer+12)	bulk_density	kg/m^3	Nlayer	Bulk density of soil layer
(8*Nlayer+13):(9*Nlayer+12)	soil_density	kg/m^3	Nlayer	Soil particle density, normally 2685 kg/m^3
(Optional)	organic	fraction	Nlayer	Fraction of soil layer that is organic If ORGANIC_FRACT is TRUE in the global parameter file, this variable must be included in the soil parameter file. If ORGANIC_FRACT is FALSE then this variable must not appear in the soil parameter file.
(Optional)	bulk_dens_org	kg/m^3	Nlayer	Bulk density of organic portion of soil If ORGANIC_FRACT is TRUE in the global parameter file, this variable must be included in the soil parameter file. If ORGANIC_FRACT is FALSE then this variable must not appear in the soil parameter file.
(Optional)	soil_dens_org	kg/m^3	Nlayer	Soil particle density of organic portion of soil, normally 1300 kg/m^3 If ORGANIC_FRACT is TRUE in the global parameter file, this variable must be included in the soil

				parameter file. If ORGANIC_FRACT is FALSE then this variable must not appear in the soil parameter file.
(9*Nlayer+13)	off_gmt	hours	1	Time zone offset from GMT. This parameter determines how VIC interprets sub-daily time steps relative to the model start date and time. NOTE: Important update in VIC 4.1.2: We have adopted the following convention for off_gmt: An off_gmt value of 0 indicates that the model start date/time is relative to Greenwich Mean Time (GMT). An off_gmt value of (grid_cell_longitude*24/360) indicates that the model start date/time is relative to local time. When outputting sub-daily results, VIC's output files are referenced to the model start date/time; therefore they are controlled by off_gmt (off_gmt=0 means VIC results are referenced to GMT; off_gmt=(grid_cell_longitude*24/360) means VIC results are referenced to

				local time). Daily supplied forcings are assumed to start/end at midnight in local time; the forcing start date/time is thus in local time. When VIC disaggregates daily forcings into sub-daily forcings, off_gmt will be used to determine the time lag between the start of the forcing's diurnal cycle and the start of the VIC simulation. Sub-daily supplied forcings are assumed to occur relative to the time zone indicated by off_gmt. Therefore, if VIC outputs these sub-daily forcings, they will occur at the exact same time of day as in the input files. Therefore, if mixing daily and sub-daily forcing inputs, it is important that any sub-daily forcing inputs be shifted as necessary to be in the time zone indicated by off_gmt.
(9*Nlayer+14):(10*Nlayer+13)	Wcr_FRACT	fraction	Nlayer	Fractional soil moisture content at the critical point (~70% of field capacity) (fraction of maximum moisture)
(10*Nlayer+14):(11*Nlayers+13)	Wpwp_FRACT	fraction	Nlayer	Fractional soil moisture content at the wilting point (fraction of

				maximum moisture)
(11*Nlayer+14)	rough	m	1	Surface roughness of bare soil
(11*Nlayer+15)	snow_rough	m	1	Surface roughness of snowpack
(11*Nlayer+16)	annual_prec	mm	1	Average annual precipitation.
(11*Nlayer+17):(12* Nlayer+16)	resid_moist	fraction	Nlayer	Soil moisture layer residual moisture.
(12*Nlayer+17)	fs_active	1 or 0	1	If set to 1, then frozen soil algorithm is activated for the grid cell. A 0 indicates that frozen soils are not computed even if soil temperatures fall below 0C.
(Optional)	frost_slope	C	1	Slope of uniform distribution of soil temperature (if SPATIAL_FROST == TRUE in the user_def.h file).
(Optional)	max_snow_distrib_slope	m	1	Maximum slope of the snow depth distribution. This is only used if SPATIAL_SNOW == TRUE in the user_def.h file. This parameter should be set to twice the spatial average snow depth at which coverage == 1.0. In other words, if we define *depth_thresh* to be the minimum spatial average snow depth below which coverage < 1.0, then max_snow_distrib_slope = 2*depth_thresh.

				NOTE: Partial snow coverage is only computed when the snow pack has started melting and the spatial average snow pack depth <= max_snow_distrib_slope /2. During the accumulation season, coverage is 1.0. Even after the pack has started melting and depth <= max_snow_distrib_slope /2, new snowfall resets coverage to 1.0, and the previous partial coverage is stored. Coverage remains at 1.0 until the new snow has melted away, at which point the previous partial coverage is recovered.
(Optional)	initial_ice_content	N/A	1	Initial volumetric ice content in soil (if EXCESS_ICE == TRUE in the user_def.h file).
(Optional)	July_Tavg	C	1	Average July air temperature, used for treeline computations (if JULY_TAVG_SUPPLIED == TRUE in the global parameter file).

VARIABLES

Cellnum Parameter

Cell numbers are assigned to each grid cell beginning with 1 at the upper left corner of the basin, and numbering consecutively by rows. Cell numbers will be referenced in soil files, as well as in the vegetation parameter file.

b_infilt Parameter

The b_infilt parameter is the parameter used to describe the Variable Infiltration Curve. This is typically a value that is adjusted during the calibration of the VIC model. Parameter values range from 10^{-5} to 0.4. Higher values will produce more runoff. 0.2 is often used as a starting value.

Ds Parameter

The soil parameter Ds represents the fraction of the Dsmax parameter at which non-linear base-flow occurs. This is typically a parameter that is adjusted during the calibration of the VIC model. An initial value of 0.001 may be used. Typically this value is small (less than 1).

Dsmax Parameter

The parameter Dsmax is the maximum velocity of baseflow for each grid cell. This can be estimated using the saturated hydraulic conductivity, Ksat, for each grid cell multiplied by the slope of the grid cell. The values for Ksat can be averaged for the layers for which baseflow will be included. When working in decimal degrees, the elevation data for the basin should be projected to an equal area map projection, in order to have horizontal dimensions in the same units as the vertical dimensions so that the slopes computed in Arc/Info are meaningful values.

Ws Parameter

The parameter Ws is the fraction of maximum soil moisture where non-linear baseflow occurs. As with the Ds parameter, this is generally adjusted during the calibration phase of applying the VIC model. Values for Ws are typically greater than 0.5. An initial value of 0.9 can be used.

expt Parameter

The Exponent (expt) parameter is the exponent, n, from the Brooks-Corey relationship. Values can be estimated from the table of soil hydraulic properties indexed by soil texture. Values should be > 3.0.

Ksat Parameter

The parameter Ksat is the saturated hydraulic conductivity for each layer used in a VIC model. Ksat is approximated using data onsoil textures available for the basin.

Soil textures are from the STATSGO database (USDA NRCS), which has been compiled from a state-by-state format into a U.S. database, available through Penn State University at:
http://dbwww.essc.psu.edu/dbndx/tree/amer_n/us_48/data/soilprop/statsgo_geo.html
This reports 16 different soil texture classes for 11 layers, which cover a depth of 2.5 meters. The majority of data does not extend beyond 1.5 meters, which includes the first 9 of their 11 layers. The Penn State data is available in gridded form at a resolution of 30 arc-seconds.
The soil texture data is then imported into Arc/Info, where it is indexed to values of Ksat according to an index table soil hydraulic properties. The data in this table are placed into an INFO file in Arc/Info, and the individual relates are then created to be used in an Arc/Info macro to create the Ksat grid for each layer.

phi_s Parameter

The parameter phi_s is the unitless soil moisture diffusion coefficient. This parameter is designed for the future inclusion of soil moisture diffusion in the VIC model moisture trasport equations. Currently this feature has not been implemented so a value of -999 can be used as a placeholder.

Init_moist Parameter

Initial moisture content of each layer can be set at any reasonable value. One approach is to use fractional soil moisture content (expressed as a fraction of the maximum soil moisture; max. soil moisture = porosity * layer depth) at the critical point, Wcr, which can be computed for each layer as a depth in millimeters by multiplying Wcr by the thickness of the layer in meters, and then multiplying by 1000.

Depth Parameter

Depth is the depth of each layer in meters. Though this can be changed in the calibration process, initially it can be set to the breakdown of layer depths selected by combining the 11 individual soil layers of the Penn State University STATSGO data (for example, the Ksat data).

Avg_T Parameter

This parameter is the temperature of the soil at the damping depth. This temperature is often assumed to be the same as the average annual air temperature. This temperature is used as the bottom boundary of all thermal flux calculations made for the soil column.

Dp Parameter

This is the soil thermal damping depth. It is defined as the depth in the soil column at which the soil temperature remains nearly constant annually. This is the depth to which soil thermal flux calculations will be made, and is often set to 4m. The constant temperature at this boundary is defined with the parameter avg_T.

Bubble Parameter

The bubble parameter is the bubbling pressure, h, for the soil texture type (see, e.g., Table 5.3.2 in Rawls, et al (Handbook of Hydrology)). This parameter is necessary for running the VIC model with FULL_ENERGY==TRUE or FROZEN_SOIL==TRUE. Values must be > 0.0.

If you have a VIC soil parameter file created for water-balance mode runs, in which bubbling pressure has been set to a "nodata" value such as -99, you will not be able to use this soil parameter file for FULL_ENERGY==TRUE or FROZEN_SOIL==TRUE. However, a quick way to estimate bubbling pressure from the existing soil parameters (namely the *expt* parameter) is:

bubble = 0.32*expt + 4.3

bulk_density Parameter

The bulk density in layers used in the VIC model can be compiled from data available through Penn State University at
http://dbwww.essc.psu.edu/dbndx/tree/amer_n/us_48/data/soilprop/statsgo_geo.html
This reports bulk density for each of 11 individual layers, which cover a depth of 2.5 meters. The majority of data does not extend beyond 1.5 meters, which includes the first 9 of their 11 layers. The Penn State data is available in gridded form at a resolution of 30 arc-seconds.

Off_gmt Parameter

off_gmt is the number of hours difference from GMT. These are the number of hours to be added to GMT/UTC to obtain local time for each grid cell. Sample offsets are listed in the table below. Since UTC does not use any daylight savings adjustment, the gmt offset will decrease by one hour for those areas using daylight savings. For example, Eastern Standard Time (EST) changes from GMT-5 hours to Eastern Daylight Time (EDT) at GMT-4 hours.

Table of GMT Offsets in hours

Zone	**City or Area Zone Crosses**
GMT-12	Eniwetok
GMT-11	Samoa
GMT-10	Hawaii
GMT-9	Alaska
GMT-8	PST, Pacific US
GMT-7	MST, Mountain US
GMT-6	CST, Central US
GMT-5	EST, Eastern US
GMT-4	Atlantic, Canada
GMT-3	Brazilia, Buenos Aries
GMT-2	Mid-Atlantic
GMT-1	Cape Verdes

GMT	Greenwich Mean Time, Dublin
GMT+1	Berlin, Rome
GMT+2	Israel, Cairo
GMT+3	Moscow, Kuwait
GMT+4	Abu Dhabi, Muscat
GMT+5	Islamabad, Karachi
GMT+6	Almaty, Dhaka
GMT+7	Bangkok, Jakarta
GMT+8	Hong Kong, Beijing
GMT+9	Tokyo, Osaka
GMT+10	Sydney, Melbourne, Guam
GMT+11	Magadan, Soloman Is.
GMT+12	Fiji, Wellington, Auckland

Wcr_FRACT (Wcr) Parameter

The parameter Wcr_FRACT is the fractional soil moisture (expressed as a fraction of the maximum soil moisture; max. soil moisture = porosity * layer depth) at the critical point, which is the water content below which hydraulic conductivity begins to fall below saturated values, as does transpiration. This is set at 70% of the field capacity, in accordance with the different soil textures. Field Capacity is defined as the water content at a tension of -33kPa.

Wpwp_FRACT (Wp) Parameter

The parameter Wpwp_FRACT is the fractional soil moisture (expressed as a fraction of the maximum soil moisture; max. soil moisture = porosity * layer depth) at the wilting point.

Wilting Point is set at the water content at a tension of 1500 kPa, and is approximated for the different soil textures.

Rough Parameter

Surface roughness of bare soil, expressed in meters, can be set to a value 0.001, and adjusted according to local data.

Snow_rough Parameter

The surface roughness of the snowpack, expressed in meters, can be set to an initial value of 0.0005, and can then be adjusted according to local data.

Annual_prec Parameter

VIC uses the regression published by Kimball *et. al.* to improve the estimation of the dew point temperature in dry regions. This regression requires the average annual precipitation in mm for each grid cell. If the value of annual_prec is negative, the

model will use the daily minimum temperature without modification for the dew point temperature.

Resid_moist Parameter

Residual moisture content is the amount of soil moisture that cannot be removed from the soil by drainage or evapotranspiration. Values are provided to the model as soil moisture contents (volume of residual soil moisture content / total volume of soil) [mm/mm].

E.VIC VEGETATION LIBRARY FILE

Descriptions of the available land cover types are described on this section.

Vegetation parameters needed for each vegetation type used in the VIC model are provided in a column format ASCII file as described in this document. Parameters are given for different vegetation types, and are referenced by the vegetation parameter file, which provides information about the number of vegetation types per grid cell, and their fractional coverage. A header may be added to the top of the file if the first column contains a '#'. Comments can also be added to the end of each line in the vegetation library file.

Vegetation Library File Format

Column	Variable Name	Units	Number of Values	Description
1	veg_class	N/A	1	Vegetation class identification number (reference index for library table)
2	overstory	N/A	1	Flag to indicate whether or not the current vegetation type has an overstory (TRUE for overstory present [*e.g.* trees], FALSE for overstory not present [*e.g.* grass])

3	Rarc	s/m	1	Architectural resistance of vegetation type (~2 s/m)
4	Rmin	s/m	1	Minimum stomatal resistance of vegetation type (~100 s/m)
5 : 16	LAI		12	Leaf-area index of vegetation type
17 : 28	Albedo	fraction	12	Shortwave albedo for vegetation type
29 : 40	Rough	m	12	Vegetation roughness length (typically 0.123 * vegetation height)
41 : 52	displacement	m	12	Vegetation displacement height (typically 0.67 * vegetation height)
53	**wind_h**	m	1	Height at which wind speed is measured.
54	RGL	W/m^2	1	Minimum incoming shortwave radiation at which there will be transpiration. For trees this is about 30 W/m^2, for crops about 100 W/m^2.
55	rad_atten	fract	1	Radiation attenuation factor. Normally set to 0.5, though may need to be adjusted for high latitudes.

56	wind_atten	fract	1	Wind speed attenuation through the overstory. The default value has been 0.5.
57	trunk_ratio	fract	1	Ratio of total tree height that is trunk (no branches). The default value has been 0.2.
58	comment	N/A	1	Comment block for vegetation type. Model skips end of line so spaces are valid entrys.

wind_h Parameter

The measurement wind height is the height above the ground at which wind observations were recorded. Typically wind observations are taken at a height of 2 m in clearings. However, the VIC model assumes wind observations are made above the vegetation cover in each grid cell and that wind speeds through and below the canopy can be found using exponential and logarithmic wind profiles.

For short vegetation types (grasses, shrubs, etc.), the wind measurment height should be ~2 m above the top of the vegetation. For tall vegetation types (trees), especially those defined with an overstory, the wind measurement height should be set much higher than the vegetation. This is physically justified because a forest canopy impacts atmospheric stability to a much higher elevation, than shorter vegetation. If the model is required to run with an overstory defined, and the wind height set to just above the vegetation (for example the tree height + 2m) large negative evaporations and sublimations may be found during the winter months, as the snow interception algorithm is forced to use unrealistically strong wind speeds.

When defining a vegetation type with overstory, it is strongly reccommended that wind_h be defined at least 10 m higher than the height of the vegetation.

F.VIC VEGETATION PARAMETER FILE

Landcover types, fractional areas, rooting depths, and seasonal LAIs of the various land cover tiles within each grid cell.

Vegetation parameters needed for the different VIC model set-ups are listed below. Number of vegetation tiles and fraction of grid cell covered must be defined for each grid cell.

Vegetation Parameter File Format

Variable Name	Units	Description
gridcel	N/A	Grid cell number
Nveg	N/A	Number of vegetation tiles in the grid cell

Repeats for each vegetation tile in the grid cell:

Variable Name	Units	Description
veg_class	N/A	Vegetation class identification number (reference index to vegetation library) NOTE 1: it is common practice to define only one tile for each vegetation class in the grid cell. But this is not strictly necessary. It is OK to define multiple tiles having the same vegetation class. NOTE 2: As of VIC 4.1.1, if you are simulating lakes, you MUST designate one of the tiles from each grid cell as the tile that contains the lake(s). This designation happens in the lake parameter file. You can either choose an existing tile to host the lakes, or insert a new tile (just make sure that the sum of the tile areas in the grid cell = 1.0). This extra lake/wetland tile may have the same vegetation

		class as one of the other existing tiles (see NOTE 1). For advice on how to prepare your vegparam and lakeparam files, click here.
Cv	fraction	Fraction of grid cell covered by vegetation tile

Gridcel parameter are assigned to each grid cell beginning with 1 at the upper left corner of the basin, and numbering consecutively by rows. Cell numbers will be referenced in soil files, as well as in the vegetation parameter file.

For each vegetation tile, repeats for each defined root zone:

Variable Name	Units	Description
root_depth	M	Root zone thickness (sum of depths is total depth of root penetration)
root_fract	fraction	Fraction of root in the current root zone.

OPTIONAL - If BLOWING_SNOW is TRUE in global parameter file, then for each vegetation tile, the following parameters must appear after the list of root depth/fract parameters:

Variable Name	Units	Description
sigma_slope	N/A	Standard deviation of terrain slopes within vegetation tile
lag_one	N/A	Lag-one autocorrelation of terrain slope within vegetation tile
fetch	m	Average fetch (distance the wind blows without obstructions) within vegetation tile

OPTIONAL - If GLOBAL_LAI is TRUE in global parameter file, then for each vegetation tile, there must be a line containing the following parameters:

Variable Name	*Units*	*Description*
LAI	N/A	Leaf Area Index, one per month

G.ELEVATION BAND (OPTIONAL)

This is a file summarizing the distribution of elevations in each grid cell.

By default, VIC assumes grid cells are flat. This assumption can lead to inaccuracies in snow pack estimates in mountainous grid cells. For this reason, the option exists to have VIC break each grid cell up into a number of *elevation bands* (also called *snow bands*) and simulate them separately. Each band's mean elevation is used to lapse the grid cell average temperature, pressure, and precipitation to a more accurate local estimate. This file contains information needed to define the properties of each elevation band used by the snow model. Snow elevation bands are used to improve the model's performance in areas with pronounced topography, especially mountainous regions, where the effects of elevation on snow pack accumulation and ablation might be lost in a large grid cell.The number of snow elevation bands (*option.SNOW_BAND*) to be used with the model is defined in the global parameter file. The elevation band (or snow band) file is only read if the number of snow elevation bands is greater than 1.It is not necessary that all grid cells in a basin have the same number of elevation bands. *SNOW_BAND* is simply the maximum number of elevation bands anywhere in the basin. For relatively flat grid cells, some of the elevation bands will have *AreaFract* values of 0. For these zero-area bands, a value of 0 may be supplied for *elevation* and *Pfactor*.

Elevation Band File Format

Column	**Variable Name**	**Units**	**Number of Values**	**Description**
1	Cellnum	N/A	1	Grid cell number (should match numbers assigned in soil parameter file)
2 : (SNOW_BAND+1)	AreaFract	fraction	SNOW_BAND	Fraction of grid cell covered by each elevation

				band. Sum of the fractions must equal 1.
(SNOW_BAND+2) : (2*SNOW_BAND+1)	elevation	m	SNOW_BAND	Mean (or median) elevation of elevation band. This is used to compute the change in air temperature from the grid cell mean elevation.
(2*SNOW_BAND+2) : (3*SNOW_BAND+1)	Pfactor	fraction	SNOW_BAND	Fraction of cell precipitation that falls on each elevation band. Total must equal 1. To ignore effects of elevation on precipitation, set these fractions equal to the area fractions.

H. INITIAL STATE FILE (OPTIONAL)

Moisture storages (soil moisture, snow pack, etc…),energy storages (soil temperatures, etc) and other information describing the current state of the system. A state file saved from a previous VIC simulation may be used as the initial state for another run. VIC can save the hydrologic state from any point in the simulation (usually the final state) to a file for the purpose of re-starting the simulation later (as an initial state file). This is useful for simulations that require lengthy spin-up periods or ensemble methods. The initial state file is not required; if it is not specified, VIC will use a default starting condition, and will take initial soil moisture contents from the values specified in the Soil Parameter File. An Initial State File may be prepared simply by running VIC with the necessary state file options in the global parameter file. The model state file contains all information needed by the VIC model to "warm"-start a simulation (i.e. start from "realistic" conditions, or re-start a simulation exactly where the model previously stopped). To read an initial state file, or to save a "final" state file, the appropriate options should be set in the global parameter file.

The state file has two header lines used by the VIC model to verify that the model is set-up correctly. Following the header there are repeating blocks of lines which define all variables for each grid cell. Each block starts with a line defining variables held constant across the grid cell and is then followed by lines for all vegetation types (including bare soil) and all snow bands [(number of vegetation types) * (number of snow bands) = (number of lines)].

- File Header

- Grid Cell Information
- Vegetation and Snow Band Information
- Lake Information

File Header

The file header appears once at the top of the state file and is used by the VIC model to verify the parameters initialized with the model control file match those for the data stored in the state file. An error is reported if the model state file cannot be used to initialize the current state.

Define date of state file, always saved at hour 0 of the defined day.

Column	Name	Type	Description
1	STATEYEAR	int	Year of the model state file
2	STATEMONTH	int	Month of the model state file
3	STATEDAY	int	Day of the model state file

Define global soil limits.

Column	Name	Type	Description
1	Nlayer	int	Number of soil moisture layers
2	Nnodes	int	Number of soil thermal nodes

Grid Cell Information

This line is used to define the parameters that are constant for the entire grid cell. It first appears after the file header lines and must be defined for each grid cell.

Column	Name	Type	Description
1	cellnum	int	Current cell number
2	Nveg	int	Number of vegetation types in the grid cell
3	Nbands	int	Number of snow elevation bands in the grid cell
4:(3+Nnodes)	dz_node	double	Distances between soil thermal nodes [m]

(4+Nnodes):(3+2*Nnodes)	node_depth	double	Depth from surface of each soil thermal node (first node should have a depth of 0m indicating it is at the surface) [m]

Vegetation and Snow Band Information

Each grid cell information line must be followed with lines for all defined vegetation types (plus bare soil) and snow bands ([Nveg+1]*Nbands = number of lines required). These lines contain information about the storage of moisture within each fractional coverage type. If the model is being run with distributed precipitation, the wet and dry fractions are averaged before the model state is stored and the model is always initialized with a mu value of 1.

Column	Name	Type	Description
1	veg	int	Current vegetation number as defined in the vegetation parameter file
2	band	int	Current snow band number
3:(2+Nlayer)	moist	double	Soil layer total moisture contents including ice [mm]
(3+Nlayer):(2+2*Nlayer)	ice	double	Soil layer ice contents [mm]
(3+2*Nlayer)	Wdew	double	Amount of dew stored in the vegetation [mm]. Not defined for bare soil (veg = Nveg)
(4+2*Nlayer)	last_snow	int	Number of model time steps since the

			last new snow
(5+2*Nlayer)	MELTING	char	Flag to indicate whether snowpack is in accumulation or melting phase
(6+2*Nlayer)	coverage	double	Fraction of grid cell area covered by snow
(7+2*Nlayer)	swq	double	Snow water equivalence of the pack [m]
(8+2*Nlayer)	surf_temp	double	Temperature of the surface layer in the snow algorithm [C]
(9+2*Nlayer)	surf_water	double	Liquid water content of the surface layer [m]
(10+2*Nlayer)	pack_temp	double	Temperature of the pack layer in the snow algorithm [C]
(11+2*Nlayer)	pack_water	double	Liquid water content of the surface layer [m]
(12+2*Nlayer)	density	double	Density of the snowpack [kg/m^3]
(13+2*Nlayer)	coldcontent	double	Cold content of snow pack [J/m^2]
(14+2*Nlayer)	snow_canopy	double	Snow water equivalence stored in the canopy [m]
(15+2*Nlayer):(15+2*Nlayer+Nnodes)	node_T	double	Soil

			temperature at each of the defined soil thermal nodes [C]

I.VIC LAKE/WETLAND PARAMETER FILE

File containing lake model parameters. By default, VIC does not simulate lakes or other impoundment of surface water.If desired, VIC can simulate lakes and seasonal inundation of wetlands. These lakes and wetlands are fed by runoff from within the current grid cell, and optionally (as of VIC release 4.1.2) by channel inputs from other grid cells upstream. Simulation of lakes and wetlands can be enabled by setting the **LAKES** option in the global parameter file to the name of a lake parameter file.

The lake/wetland model consists of a landcover tile in which some (time-varying) portion of the land surface is covered by water. The portion of the tile covered by standing water is called the ***lake***, and the portion of the tile where soil and vegetation are exposed is called the ***wetland***. Thus, the lake can represent either a "permanent" lake or seasonal flooding of vegetated land. The size of the lake as a function of time depends on the hydrologic budget and on the underlying lake bathymetry (or topography of the land being flooded), which is supplied by the user. The vegetation covering the exposed wetland portion of the tile must be defined in the vegetation parameter file; i.e. if you wish to simulate a lake/wetland in a given grid cell, you must either choose an existing landcover tile to associate with the lake/wetland, or define a new tile to contain the lake/wetland. The index number of the landcover tile that contains the lake/wetland must be indicated in the lake parameter file (see the table below). NOTE: when running VIC over multiple grid cells (which is true of almost all applications), inevitably some grid cells will not contain lakes and the user will not want to run the lake model in those cells. **To denote a cell that does not contain a lake, you should set the landcover tile index to -1 in the lake parameter file**.

By default, the lake/wetland tile will receive some fraction of the runoff from the other landcover tiles within the grid cell as inputs; this fraction is the parameter ***rpercent***. However, larger lakes often require water inputs from a larger area than just the current grid cell in order to balance evaporation and outflow. This is especially true in arid regions. To allow for this, we created a new forcing input variable, **CHANNEL_IN**, that can be included in the meteorologic forcing file or as a

separate forcing file (VIC can read two separate forcing files per grid cell). For more information, see the documentation on forcing files for more information.

The lake/wetland parameters mentioned above, plus all other necessary lake parameters, are described in the table below.

NOTE: all depths are measured from the water/air surface to the lake bottom, at the lake's deepest point (approximately the geographic center of the lake). This is similar to using the word "height" to refer to the elevation of a mountain's peak.

Lake/Wetland Parameter File Format

Variable Name	**Units**	**Description**
gridcel	N/A	Grid cell number
lake_idx	N/A	Index of the veg tile containing the lake/wetland, with respect to the list of veg tiles given in the veg param file for the current grid cell. Numbering starts at 0 for the grid cell's first veg tile, up to (Nveg-1) for the grid cell's final veg tile. For example, if the lake/wetland is contained in the 2nd landcover tile in the list of landcover tiles for this grid cell, then lake_idx = 1 (=2-1). **NOTE: To denote a grid cell that does not contain any lakes or seasonal flooding, set lake_idx to -1.** NOTE: this may require changing your veg param file (if it already exists) or preparing it in a special way.
numnod	N/A	Number of lake layers (or "nodes")
min_depth	m	Lake depth below which channel outflow is 0.
wfrac	N/A	Width of lake outlet, as a fraction of the lake perimeter
depth_in	m	Initial lake depth

rpercent	fraction	Fraction of grid cell runoff that enters lake (instead of going directly to channel network)

If LAKE_PROFILE is FALSE in the global parameter file, then the lake depth-area profile will be computed assuming that the lake basin has a circular cross-section at all depths, with a radius that depends on depth to the power BETA, which is set in LAKE.h. In this case, the 2nd line of parameters for the grid cell are as follows:

Variable Name	**Units**	**Description**
basin_depth	m	Maximum allowable depth of lake
basin_area	fraction	Fraction of the grid cell covered by lake when its depth is at its maximum value

If LAKE_PROFILE is TRUE in the global parameter file, then the 2nd line of parameters for the grid cell consists of *numnod* (depth, area) pairs describing the profile of the lake basin, starting from the maximum depth and area and descending to the minimum depth and area:

Variable Name	**Units**	**Description**
basin_depth	m	Depth of lake
basin_area	fraction	Fraction of the grid cell covered by lake when its depth is *depth*

Example Global Parameter File

```
################################################################
#############
# VIC Model Parameters - 4.1.x
################################################################
#############
# $Id: global.param.sample,v 5.7.2.25 2012/02/05 00:15:44
vicadmin Exp $
################################################################
#############
# Simulation Parameters
################################################################
#############
NLAYER       3      # number of soil layers
NODES        10     # number of soil thermal nodes
TIME_STEP    3      # model time step in hours (set to 24
if FULL_ENERGY = FALSE, set to < 24 if FULL_ENERGY = TRUE)
SNOW_STEP    3      # time step in hours for which to solve
the snow model (should = TIME_STEP if TIME_STEP < 24)
STARTYEAR    2000   # year model simulation starts
STARTMONTH   01     # month model simulation starts
STARTDAY     01     # day model simulation starts
STARTHOUR    00     # hour model simulation starts
ENDYEAR      2000   # year model simulation ends
ENDMONTH     12     # month model simulation ends
ENDDAY       31     # day model simulation ends
FULL_ENERGY  TRUE   # TRUE = calculate full energy balance;
FALSE = compute water balance only
FROZEN_SOIL  TRUE   # TRUE = calculate frozen soils

################################################################
#############
# Soil Temperature Parameters
# VIC will choose appropriate values for QUICK_FLUX and
IMPLICIT depending on values of FULL_ENERGY and
FROZEN_SOIL; the user should only need to override VIC's
choices in special cases.
# The other options in this section are only applicable
when FROZEN_SOIL is TRUE and their values depend on the
application.
################################################################
#############
#QUICK_FLUX  FALSE  # TRUE = use simplified ground heat
flux method of Liang et al (1999); FALSE = use finite
element method of Cherkauer et al (1999)
#IMPLICIT    TRUE   # TRUE = use implicit solution for soil
heat flux equation of Cherkauer et al (1999), otherwise
uses original explicit solution.
```

```
#QUICK_SOLVE FALSE  # TRUE = Use Liang et al., 1999
formulation for iteration, but explicit finite difference
method for final step.
#NO_FLUX           FALSE  # TRUE = use no flux lower
boundary for ground heat flux computation; FALSE = use
constant flux lower boundary condition.  If NO_FLUX = TRUE,
QUICK_FLUX MUST = FALSE
#EXP_TRANS   FALSE  # TRUE = exponentially distributes the
thermal nodes in the Cherkauer et al. (1999) finite
difference algorithm, otherwise uses linear distribution
#GRND_FLUX_TYPE    GF_410 # Options for ground flux:
#                  # GF_406 = use (flawed) formulas for
ground flux, deltaH, and fusion from VIC 4.0.6 and earlier;
#                  # GF_410 = use formulas from VIC 4.1.0
(ground flux, deltaH, and fusion are correct; deltaH and
fusion ignore surf_atten);
#                  # Default = GF_410

################################################################
#############
# Precip (Rain and Snow) Parameters
# Generally these default values do not need to be
overridden
################################################################
#############
#SNOW_ALBEDO USACE  # USACE = use traditional VIC algorithm
based on US Army Corps of Engineers empirical snow albedo
decay curves, using hard-coded dates for transitions from
snow accumulation to melting; SUN1999 = use algorithm of
Sun et al 1999, in which albedo decay depends on snow cold
content (more appropriate for simulations outside the US).
#SNOW_DENSITY      DENS_BRAS    # DENS_BRAS = use
traditional VIC algorithm taken from Bras, 1990;
DENS_SNTHRM = use algorithm taken from SNTHRM model.
#BLOWING           FALSE  # TRUE = compute evaporative
fluxes due to blowing snow
#COMPUTE_TREELINE  FALSE  # Can be either FALSE or the id
number of an understory veg class; FALSE = turn treeline
computation off; VEG_CLASS_ID = replace any overstory veg
types with the this understory veg type in all snow bands
for which the average July Temperature <= 10 C (e.g.
"COMPUTE_TREELINE 10" replaces any overstory veg cover with
class 10)
#DIST_PRCP   FALSE  # TRUE = use distributed precipitation
#PREC_EXPT   0.6    # exponent for use in distributed
precipitation eqn (only used if DIST_PRCP is TRUE)
#CORRPREC    FALSE  # TRUE = correct precipitation for
gauge undercatch
#MAX_SNOW_TEMP     0.5    # maximum temperature (C) at
which snow can fall
```

```
#MIN_RAIN_TEMP     -0.5   # minimum temperature (C) at
which rain can fall

##############################################################
############
# Miscellaneous Simulation Parameters
# Generally these default values do not need to be
overridden
##############################################################
############
#CONTINUEONERROR   TRUE   # TRUE = if simulation aborts on
one grid cell, continue to next grid cell
#TFALLBACK   TRUE   # TRUE = when temperature iteration
fails to converge, use previous time step's T value

##############################################################
############
# Turbulent Flux Parameters
# Generally these default values do not need to be
overridden
##############################################################
############
#MIN_WIND_SPEED    0.1    # minimum allowable wind speed
(m/s)
#AERO_RESIST_CANSNOW     AR_406_FULL  # Options for
aerodynamic resistance in snow-filled canopy:
#                   # AR_406     = multiply by 10 for latent
heat but do NOT multiply by 10 for sensible heat and do NOT
apply stability correction (as in VIC 4.0.6); when no snow
in canopy, use surface aero_resist for ET.
#                   # AR_406_LS  = multiply by 10 for latent
heat AND sensible heat and do NOT apply stability
correction; when no snow in canopy, use surface aero_resist
for ET.
#                   # AR_406_FULL      = multiply by 10 for
latent heat AND sensible heat and do NOT apply stability
correction; additionally, always use overstory aero_resist
for ET (as in 4.1.0).
#                   # AR_410     = apply stability
correction but do NOT multiply by 10 (as in VIC 4.1.0);
additionally, always use overstory aero_resist for ET (as
in 4.1.0).
#                   # Default    = AR_406_FULL

##############################################################
############
# Meteorological Forcing Disaggregation Parameters
# Generally these default values do not need to be
overridden
##############################################################
############
```

```
#PLAPSE            TRUE   # This controls how VIC computes
air pressure when air pressure is not supplied as an input
forcing: TRUE = set air pressure to sea level pressure,
lapsed to grid cell average elevation; FALSE = set air
pressure to constant 95.5 kPa (as in all versions of VIC
pre-4.1.1)
#SW_PREC_THRESH          0     # Minimum daily precip [mm]
that can cause dimming of incoming shortwave; default = 0.
#MTCLIM_SWE_CORR   TRUE    # This controls VIC's estimates
of incoming shortwave in the presence of snow; TRUE =
adjust incoming shortwave for snow albedo effect; FALSE =
do not adjust shortwave; default = TRUE
#VP_ITER           VP_ITER_ALWAYS     # This controls
VIC's iteration between estimates of shortwave and vapor
pressure:
#                  # VP_ITER_NEVER = never iterate; make
estimates separately
#                  # VP_ITER_ALWAYS = always iterate once
#                  # VP_ITER_ANNUAL = iterate once for
arid climates based on annual Precip/PET ratio
#                  # VP_ITER_CONVERGE = iterate until
shortwave and vp stabilize
#                  # default = VP_ITER_ALWAYS
#VP_INTERP   TRUE   # This controls sub-daily humidity
estimates; TRUE = interpolate daily VP estimates linearly
between sunrise of one day to the next; FALSE = hold VP
constant for entire day
#LW_TYPE           LW_TVA # This controls the algorithm
used to estimate clear-sky longwave radiation:
#                  # LW_TVA = Tennessee Valley Authority
algorithm (1972)
#                  # other options listed in vicNl_def.h
#                  # default = LW_TVA (this was also the
traditional VIC algorithm)
#LW_CLOUD    LW_CLOUD_DEARDORFF # This controls the
algorithm used to estimate the influence of clouds on total
longwave:
#                  # LW_CLOUD_BRAS = method from Bras
textbook (this was the traditional VIC algorithm)
#                  # LW_CLOUD_DEARDORFF = method of
Deardorff (1978)
#                  # default = LW_CLOUD_DEARDORFF

##############################################################
############
# State Files and Parameters
##############################################################
############
#INIT_STATE  (put the initial state path/filename here)   #
Initial state path/file
```

```
#STATENAME   (put the path/prefix of output state file
here)  # Output state file path/prefix.  The date
(STATEYEAR,STATEMONTH,STATEDAY) will be appended to the
prefix automatically in the format yyyymmdd.
#STATEYEAR   2000   # year to save model state
#STATEMONTH  12     # month to save model state
#STATEDAY    31     # day to save model state
#BINARY_STATE_FILE       FALSE  # TRUE if state file should
be binary format; FALSE if ascii

##############################################################
############
# Forcing Files and Parameters
#
#       All FORCING filenames are actually the pathname,
and prefix
#               for gridded data types: ex. DATA/forcing_
#               Latitude and longitude index suffix is
added by VIC
#
#     There must be 1 FORCE_TYPE entry for each variable
(column) in the forcing file
#
#     If FORCE_TYPE is BINARY, each FORCE_TYPE must be
followed by:
#                   SIGNED/UNSIGNED    SCALE_FACTOR
#            For example (BINARY):
#                   FORCE_TYPE   PREC   UNSIGNED     40
#            or (ASCII):
#                   FORCE_TYPE   PREC
##############################################################
############
FORCING1     (put the forcing path/prefix here)     #
Forcing file path and prefix, ending in "_"
FORCE_FORMAT BINARY# BINARY or ASCII
FORCE_ENDIAN LITTLE# LITTLE (PC/Linux) or BIG (SUN)
N_TYPES             4      # Number of variables (columns)
FORCE_TYPE   PREC   UNSIGNED     40
FORCE_TYPE   TMAX   SIGNED 100
FORCE_TYPE   TMIN   SIGNED 100
FORCE_TYPE   WIND   SIGNED 100
FORCE_DT     24     # Forcing time step length (hours)
FORCEYEAR    2000   # Year of first forcing record
FORCEMONTH   01     # Month of first forcing record
FORCEDAY     01     # Day of first forcing record
FORCEHOUR    00     # Hour of first forcing record
GRID_DECIMAL 4      # Number of digits after decimal point
in forcing file names
WIND_H           10.0    # height of wind speed measurement
(m)
```

```
MEASURE_H       2.0     # height of humidity measurement
(m)
ALMA_INPUT   FALSE  # TRUE = ALMA-compliant input variable
units; FALSE = standard VIC units

##############################################################
############
# Land Surface Files and Parameters
##############################################################
############
SOIL            (put the soil parameter path/file here)   #
Soil parameter path/file
ARC_SOIL        FALSE   # TRUE = read soil parameters from
ARC/INFO ASCII grids
#SOIL_DIR        (soil param directory)   # Directory
containing ARC/INFO ASCII grids of soil parameters - only
valid if ARC_SOIL is TRUE
BASEFLOW    ARNO   # ARNO = columns 5-8 are the standard
VIC baseflow parameters; NIJSSEN2001 = columns 5-8 of soil
file are baseflow parameters from Nijssen et al (2001)
JULY_TAVG_SUPPLIED FALSE  # TRUE = final column of the soil
parameter file will contain average July air temperature,
for computing treeline; this will be ignored if
COMPUTE_TREELINE is FALSE; FALSE = compute the treeline
based on the average July air temperature of the forcings
over the simulation period
ORGANIC_FRACT      FALSE  # TRUE = simulate organic soils;
soil param file contains 3*Nlayer extra columns, listing
for each layer the organic fraction, and the bulk density
and soil particle density of the organic matter in the soil
layer; FALSE = soil param file does not contain any
information about organic soil, and organic fraction should
be assumed to be 0
VEGLIB        (put the veg library path/file here) # Veg
library path/file
VEGPARAM        (put the veg parameter path/file here)    #
Veg parameter path/file
ROOT_ZONES      3  # Number of root zones (must match
format of veg param file)
VEGPARAM_LAI       TRUE    # TRUE = veg param file
contains LAI information; FALSE = veg param file does NOT
contain LAI information
LAI_SRC      LAI_FROM_VEGLIB    # LAI_FROM_VEGPARAM = read
LAI from veg param file; LAI_FROM_VEGLIB = read LAI from
veg library file
SNOW_BAND    1      # Number of snow bands; if number of
snow bands > 1, you must insert the snow band path/file
after the number of bands (e.g. SNOW_BAND 5
my_path/my_snow_band_file)
```

```
################################################################
############
# Lake Simulation Parameters
# These need to be un-commented and set to correct values
only when running lake model (LAKES is not FALSE)
################################################################
############
#LAKES       (put lake parameter path/file here)    # Lake
parameter path/file
#LAKE_PROFILE      FALSE  # TRUE = User-specified depth-
area parameters in lake parameter file; FALSE = VIC
computes a parabolic depth-area profile
#EQUAL_AREA  FALSE  # TRUE = grid cells are from an equal-
area projection; FALSE = grid cells are on a regular lat-
lon grid
#RESOLUTION  0.125  # Grid cell resolution (degrees if
EQUAL_AREA is FALSE, km^2 if EQUAL_AREA is TRUE); ignored
if LAKES is FALSE

################################################################
############
# Output Files and Parameters
################################################################
############
RESULT_DIR      (put the result directory path here)     #
Results directory path
OUT_STEP        0       # Output interval (hours); if 0,
OUT_STEP = TIME_STEP
SKIPYEAR     0      # Number of years of output to omit
from the output files
COMPRESS     FALSE  # TRUE = compress input and output
files when done
BINARY_OUTPUT      FALSE  # TRUE = binary output files
ALMA_OUTPUT  FALSE  # TRUE = ALMA-format output files;
FALSE = standard VIC units
MOISTFRACT   FALSE  # TRUE = output soil moisture as
volumetric fraction; FALSE = standard VIC units
PRT_HEADER   FALSE   # TRUE = insert a header at the
beginning of each output file; FALSE = no header
PRT_SNOW_BAND   FALSE   # TRUE = write a "snowband" output
file, containing band-specific values of snow variables;
NOTE: this is ignored if N_OUTFILES is specified below.

################################################################
############
#
# Output File Contents
#
# As of VIC 4.0.6 and 4.1.0, you can specify your output
file names and
```

```
# contents # in the global param file (see the README.txt
file for more
# information).
#
# If you do not specify file names and contents in the
global param
# file, VIC will produce the same set of output files that
it has
# produced in earlier versions, namely "fluxes" and "snow"
files, plus
# "fdepth" files if FROZEN_SOIL is TRUE and "snowband"
files if
# PRT_SNOW_BAND is TRUE.  These files will have the same
contents and
# format as in earlier versions.
#
# The OPTIMIZE and LDAS_OUTPUT options have been removed.
These
# output configurations can be selected with the proper set
of
# instructions in the global param file.  (see the
output.*.template
# files included in this distribution for more
information.)
#
# If you do specify the file names and contents in the
global param file,
# PRT_SNOW_BAND will have no effect.
#
# Format:
#
#   N_OUTFILES
#
#   OUTFILE
#   OUTVAR               [          ]
#   OUTVAR               [          ]
#   OUTVAR               [          ]
#
#   OUTFILE
#   OUTVAR               [          ]
#   OUTVAR               [          ]
#   OUTVAR               [          ]
#
#
# where
#    = number of output files
#        = name of the output file, NOT including latitude
#                  and longitude
#          = number of variables in the output file
#       = name of the variable (this must be one of the
```

```
#                   output variable names listed in
vicNl_def.h.)
#         = (for ascii output files) fprintf format string,
#                   e.g.
#                     %.4f = floating point with 4 decimal
places
#                     %.7e = scientific notation w/ 7
decimal places
#                     *    = use the default format for this
variable
#
#   , , and  are optional.  For a given
#   variable, you can specify either NONE of these, or ALL
of
#   these.  If these are omitted, the default values will
be used.
#
#          = (for binary output files) data type code.
#                   Must be one of:
#                     OUT_TYPE_DOUBLE = double-precision
floating point
#                     OUT_TYPE_FLOAT  = single-precision
floating point
#                     OUT_TYPE_INT    = integer
#                     OUT_TYPE_USINT  = unsigned short
integer
#                     OUT_TYPE_SINT   = short integer
#                     OUT_TYPE_CHAR   = char
#                     *               = use the default type
#    = (for binary output files) factor to multiply
#                   the data by before writing, to increase
precision.
#                     *    = use the default multiplier for
this variable
#
##############################################################
#############
```

Example user_def.h File

```
/**************************************************************
************
  This header file contains model parameters that can be
modified by
  the user to control model performance.  When this file is
modified
  the model needs to be recompiled for the changes to take
effect.
**************************************************************
***********/

/***** If TRUE include frozen soil algorithm in compiled
code *****/
#define FROZEN TRUE

/***** If TRUE include all model messages to stdout, and
stderr *****/
#define VERBOSE TRUE

/***** If TRUE limit output data to runoff and baseflow for
optimization *****/
#define OPTIMIZE FALSE

/***** If TRUE include all debugging code - debugging
options still
       have to be activated to get extra output.  When set
to FALSE
       all debugging if-then statements are removed from
the compiled
       code *****/
#define LINK_DEBUG TRUE

/***** If TRUE output will be in LDAS binary format, which
is a single
       file with limited variables, most of which are
truncated to
       conserve disk space *****/
#define LDAS_OUTPUT FALSE

/***** If TRUE VIC uses a system of linear equations
defined in global.h
       to estimate the maximum unfrozen water content
equation.  This
       significantly reduces the run time with frozen soil,
but may
       introduce new errors (STILL UNDER TESTING) *****/
#define QUICK_FS FALSE
#define QUICK_FS_TEMPS 7
```

```
/***** If TRUE VIC uses the linear interpolation of the
logarithm of the
       matric potential from the two surrounding layers to
estimate the
       soil moisture drainage from each layer (Boone and
Wetzel, 1996).
       This should improve the soil moisture drainage
predicted by the
       low resolution solution computed by VIC. *****/
#define LOW_RES_MOIST FALSE

/***** If TRUE VIC code to save the model state is included
in the
       compiled code.  If STATEYEAR, STATEMONTH and
STATEDAY are
       defined in the global control file the model state
will
       be written to a file. *****/
#define SAVE_STATE FALSE

/***** If TRUE VIC does not rewind the vegetation, state,
and snow
       band files before read data for each cell.  This
saves time
       but requires that all grid cells are listed in the
same
       order as the soil parameter file *****/
#define NO_REWIND TRUE

/***** If TRUE VIC reads the model forcing files, and
creates the full
       internal forcing dataset (longwave, shortwave,
humidity, etc.)
       which is then written to a series of gridded output
files for
       later use.  Gridded forcing files are written to the
RESULTS
       directory defined in the global control file, and
are binary
       or ASCII based on the BINARY_OUTPUT flag. *****/
#define OUTPUT_FORCE FALSE

/***** Define maximum array sizes for model source code
*****/
#define MAX_VEG      8          /* maximum number of
vegetation types per
                              cell */
#define MAX_LAYERS   3          /* maximum number of soil
moisture layers */
```

```
#define MAX_NODES    18         /* maximum number of soil
thermal nodes */
#define MAX_BANDS    2          /* maximum number of snow
bands */
#define MAX_FRONTS   3          /* maximum number of
freezing and thawing
                            front depths to store */

/***** Number of iterations to use in solving the surface
energy balance.
       The original VIC model uses only 1 iteration for
speed.  Increasing
       the number of iterations improves precision, and is
recommended
       for single point comparisons with frozen soils
*****/
#define MAXIT_FE        25

/***** Coefficient multiplied by the LAI to determine the
amount of
       water that can be stored in the canopy *****/
#define LAI_WATER_FACTOR 0.2


/***** Offset of shortwave measurement from model hour,
used for
       computation of longwave radiation from hourly
shortwave
       measurements *****/
#define SOLARTIMEOFFSET  0.0

/***** Longwave correction factor, used to correct
estimated incoming
       longwave radiation (use 1, unless measured longwave
available for
       calibration) *****/
#define LWAVE_COR  1.

/***** Snow albedo curve parameters.  Defaults are from
Bras p263.
       Should not be changed except for serious problems
with snow melt *****/
#define NEW_SNOW_ALB            0.85
#define SNOW_ALB_ACCUM_A  0.94
#define SNOW_ALB_ACCUM_B  0.58
#define SNOW_ALB_THAW_A         0.82
#define SNOW_ALB_THAW_B         0.46
```

Example Vegetation Parameter File:

```
###  Two vegetation tiles with three root zones in the
seventh grid cell
###  with LAI included.


7 2

    8 0.102679 0.10 0.10 1.00 0.65 0.50 0.25

      0.312 0.413 0.413 0.413 0.413 0.488 0.975 1.150 0.625
0.312 0.312 0.312

   10 0.897321 0.10 0.10 1.00 0.70 0.50 0.20

      0.212 0.262 0.275 0.338 0.750 1.275 0.950 0.650 0.450
0.288 0.237 0.212
```

ANNEXE 6: OUTPUT FILES

VIC OUTPUT FORMATING

In this annexe how to control the contents of VIC output files is detailed. These instructions apply to VIC model versions 4.0.6 and later. In earlier versions of VIC, the user has little control over the contents of VIC output files without changing the VIC source code.

Contents

- Specifying Output Files and Variables
- Specifying Units
- Specifying Output Time Step
- Optional Output File Headers

SPECIFYING OUTPUT FILES AND VARIABLES

In earlier versions of VIC, the set of output files and their contents were hard-coded. A few settings in user_def.h (OPTIMIZE and LDAS_OUTPUT) allowed the user to change the contents of the output files, but this has not been enough to accomodate the various needs of users. Users inevitably have had to modify write_data.c to produce the type of output they want, and when VIC is updated, they must merge their changes into the new version of the code.

VIC 4.0.6 (and later) now allows the user to specify exactly which output files to create and which variables to store in each file. This way, users can save space by only writing those variables that are useful, and will be less likely to need to maintain a private version of the code to do this.

Main points:

Output file names and contents can be specified in the global parameter file as is explained. If you do not specify file names and contents in the global parameter file, VIC will produce the same set of output files that it has produced in earlier versions, namely "fluxes" and "snow" files, plus "fdepth" files if FROZEN_SOIL is TRUE and "snowband" files if PRT_SNOW_BAND is TRUE. These files will have the same contents and format as in earlier versions.

The OPTIMIZE and LDAS_OUTPUT options have been removed. These output configurations can be selected with the proper set of instructions in the global

parameter file. If you do specify the file names and contents in the global parameter file, PRT_SNOW_BAND will have no effect.

To specify file names and contents in the global parameter file: Find the names of the desired variables in the output variable list. Decide how many output files you would like, what to name them, and which output variables will appear in each of these output files.Add this information to the global parameter file in the following format:

```
(typical global parameter file contents here...)

 # Output File Contents
N_OUTFILES   n_outfiles
OUTFILE            prefix nvars
OUTVAR varname     [format     type   multiplier]
OUTVAR varname     [format     type   multiplier]
OUTVAR varname     [format     type   multiplier]
OUTFILE            prefix <NVARS< i>
OUTVAR varname     [format     type   multiplier]
OUTVAR varname     [format     type   multiplier]
OUTVAR varname     [format     type   multiplier]
```

where

n_outfiles = number of output files
prefix = name of the output file, NOT including latitud and longitude
nvars = number of variables in the output file
varname = name of the variable (this must be one of the output variable names listed in vicNl_def.h.)

format, *type*, and *multiplier* are optional. For a given variable, you can specify either NONE of these, or ALL of these. If these are omitted, the default values will be used.

format = (for ascii output files) fprintf format string,e.g.
%.4f = floating point with 4 decimal places
%.7e = scientific notation w/ 7 decimal places

```
*    = use the default format for this variable
type       = (for binary output files) data type code.
Must be one of:
OUT_TYPE_DOUBLE = double-precision floating point
OUT_TYPE_FLOAT = single-precision floating point
OUT_TYPE_INT    = integer
OUT_TYPE_USINT = unsigned short integer
OUT_TYPE_SINT   = short integer
OUT_TYPE_CHAR   = char
*  = use the default type
multiplier = (for binary output files) factor to multiply
the data by before writing, to increase precision.
*    = use the default multiplier for this variable
```

Here's an example. To specify 2 output files, named "wbal" and "ebal", and containing water balance and energy balance terms, respectively, you could do something like this:

```
N_OUTFILES   2

OUTFILE      wbal   6
OUTVAR OUT_PREC
OUTVAR OUT_EVAP
OUTVAR OUT_RUNOFF
OUTVAR OUT_BASEFLOW
OUTVAR OUT_SWE
OUTVAR OUT_SOIL_MOIST

OUTFILE      ebal   7
OUTVAR OUT_NET_SHORT
OUTVAR OUT_NET_LONG
OUTVAR OUT_LATENT
OUTVAR OUT_SENSIBLE
OUTVAR OUT_GRND_FLUX
OUTVAR OUT_SNOW_FLUX
OUTVAR OUT_ALBEDO
```

Since no format, type, or multiplier were specified for any variables, VIC will use the default format, type, and multiplier for the variables. If you wanted scientific notation with 10 significant digits for ALBEDO, you could do the following:

```
OUTVAR OUT_ALBEDO    %.9e   *       *
```

Note that even if you only want to specify the format, you must supply a value in the type and multiplier columns as well. This can be "*" to indicate the default value. Similarly, if you only want to specify the type (e.g. as a double), you would need to do something like:

```
OUTVAR OUT_ALBEDO    *
OUT_TYPE_DOUBLE      *
```

Date variables: For typical output files, the date is always written at the beginning of each record. This will consist of the following columns:

```
year month day hour
```

For daily output timestep, "hour" is not written.
If BINARY_OUTPUT is TRUE, these will all be written as type int (OUT_TYPE_INT).
If OUTPUT_FORCE is TRUE, the date will NOT be written.

Multiple-valued variables: Since variables like SOIL_MOIST have 1 value per soil layer, these variables will be written to multiple columns in the output file, one column per soil layer. Other multiple-valued variables are treated similarly.

Snow band output: To specify writing the values of variables in each snow band, append "_BAND" to the variable name though this only works for some variables (see the list in vicNl_def.h). If you specify these variables, the value of the variable in each band will be written, one band per column. For example, for a cell having 2 snow bands:

```
OUTVAR OUT_SWE_BAND
OUTVAR OUT_ALBEDO_BAND
```

will result in an output file containing

```
year month day (hour) swe[0] swe[1] albedo[0] albedo[1]
```

SPECIFYING UNITS

The user now has some control over the units of the input and output variables. The standard VIC units for moisture fluxes are total mm over the output time interval, and

degrees C for temperatures. However, other land surface schemes and circulation or climate models tend to use mm/s for moisture fluxes and degrees K for temperatures.

Now there are options in the global parameter file that allow you to specify whether to use traditional VIC units or the mm/s and K convention for input or output variables. The option names are "ALMA_INPUT" and "ALMA_OUTPUT".

Alma input: VIC now accepts the following new ALMA-compliant input forcings in addition to the forcings that it already accepts:

```
SNOWF     snowfall rate (kg/m^2s)
RAINF     rainfall rate (kg/m^2s)
CRAINF    convective rainfall rate (kg/m^2s)
LSRAINF   large scale rainfall rate (kg/m^2s)
QAIR      specific humidity (kg/kg)
WIND_E    zonal wind speed (m/s)
WIND_N    meridional wind speed (m/s)
TAIR      air temperature per time step (K)
PSURF     atmospheric pressure (Pa)
```

When giving VIC ALMA-compliant input files, you must be sure to use the names given above in the forcing section of your global parameter file.

Instead of the existing PREC (precipitation per timestep in mm), you can now specify SNOWF and RAINF (snowfall and rainfall rates, both in mm/s). VIC will simply add these two quantities together, multiply by the forcing interval, and treat their sum the same way it treats PREC.

An alternative to supplying RAINF is to supply CRAINF (convective rainfall rate, mm/s) and LSRAINF (large-scale rainfall rate, mm/s). VIC will add these two quantities together to get RAINF.

Instead of the existing WIND, alternatively you can specify WIND_E and WIND_N (zonal and meridional wind speed, m/s). VIC will simply compute WIND = sqrt(WIND_E**2+WIND_N**2).

TAIR has units of K, while the existing AIR_TEMP is in C. Similarly, PSURF is in Pa, while PRESSURE is in kPa. VIC will convert these to AIR_TEMP and PRESSURE after reading them in.

Alma output: if the user sets ALMA_OUTPUT=TRUE in the global parameter file, then VIC will convert its output variables to ALMA-compliant forms. The majority of the changes are changes of units. Moisture fluxes are changed from VIC's standard (mm accumulated over the time step) to the average flux rate (mm/s). Temperatures are converted from C to K.

In addition, several more variables have been added to the list of available output variables. See vicNl_def.h for the complete list of available output variables.

SPECIFYING OUTPUT TIME STEP

VIC can now aggregate the output variables to a user-defined output interval, via the OUT_STEP setting in the global parameter file. Currently, the largest output interval allowed is 24 hours, so this option is only useful for simulations running at sub-daily time steps.

OPTIONAL OUTPUT FILE HEADER

Now VIC provides an option to insert descriptive headers into its output files, via the PRT_HEADER option in the global parameter file. If this is set to TRUE, VIC will insert a short header into its output files, describing the time step, start date/time, variables and units included in the file.

For ascii files, the output header has the following format:

```
# NRECS: (nrecs)
# DT: (dt)
# STARTDATE: yyyy-mm-dd hh:00:00
# ALMA_OUTPUT: (0 or 1)
# NVARS: (Nvars)
# VARNAME    VARNAME   VARNAME   ...
```

where

```
nrecs       = Number of records in the file
dt          = Time step length in hours
start date  = Date and time of first record of file
ALMA_OUTPUT = Indicates units of the variables; 0 =
standard VIC units; 1 = ALMA units
Nvars  = Number of variables in the file, including date
fields
```

For binary files, the output header has the following format:

```
// Data        Stored As           Comment

 //
  /  Identifier   (unsigned short)*4   0xFFFF, repeated 4
times
    // Nbytes       (unsigned short)*1  Number of bytes in
the header,
    //                                       INCLUDING THE
IDENTIFIER
    //
    // Part 1: Global Attributes
    // Nbytes1      (unsigned short)*1  Number of bytes in
part 1
    // nrecs       (int)*1             Number of records in
the file
    // dt          (int)*1              Time step length in
hours
    // startyear   (int)*1             Year of first record
    // startmonth   (int)*1                 Month of first
record
    // startday    (int)*1             Day of first record
    // starthour   (int)*1             Hour of first record
    // ALMA_OUTPUT (char)*1               0 = standard VIC
units; 1 = ALMA

units
    // Nvars       (char)*1             Number of variables
in the file,
    // including date fields
    //
    // Part 2: Variables
    // Nbytes2      (unsigned short)*1  Number of bytes in
part 2
    //  For  each  variable,  the  following  fields:  {  len
varname type mult }
    //   len       (char)*1            Number of characters
in varname
```

```
    //   varname    (char)*len          Variable name
    //    type        (char)*1              Code identifying
variable type
    //    mult        (float)*1             Multiplier for
variable
```

To accomodate input forcing files that might have been produced via VIC's OUTPUT_FORCE option, and therefore could contain a header, read_atmos_data.c has been modified to detect and skip headers that follow the formats outlined above.

OUTPUT TABLE VARIABLES

Water Balance Terms (state variables)		
Variable	**Description**	**Units**
OUT_ASAT	Saturated Area Fraction (of exposed land, i.e. non-lake; the total fraction of the grid cell that is completely full of water would be OUT_ASAT plus OUT_LAKE_AREA_FRAC)	fraction
OUT_LAKE_AREA_FRACT	(release 4.1.2 and later) Lake surface area as fraction of grid cell area	fraction
OUT_LAKE_DEPTH	Lake depth (distance between surface and deepest point)	M
OUT_LAKE_ICE	Moisture stored as lake ice	mm over lake ice area
OUT_LAKE_ICE_FRACT	Fractional coverage of lake ice	fraction
OUT_LAKE_ICE_HEIGHT	Thickness of lake ice	Cm
OUT_LAKE_MOIST	Liquid water and ice stored in lake	mm over grid cell
OUT_LAKE_SURF_AREA	Lake surface area	m^2
OUT_LAKE_SWE	(release 4.1.2 and later) Liquid water equivalent of snow on top of lake ice	m over lake ice area

OUT_LAKE_SWE_V	(release 4.1.2 and later) Volumetric liquid water equivalent of snow on top of lake ice	m^3
OUT_LAKE_VOLUME	Lake volume	m^3
OUT_ROOTMOIST	Root zone soil moisture	Mm
OUT_SMFROZFRAC	Fraction of soil moisture (by mass) that is ice, for each soil layer	fraction
OUT_SMLIQFRAC	Fraction of soil moisture (by mass) that is liquid, for each soil layer	fraction
OUT_SNOW_CANOPY	Snow interception storage in canopy	Mm
OUT_SNOW_COVER	Fractional area of snow cover	fraction
OUT_SNOW_DEPTH	Depth of snow pack	Cm
OUT_SOIL_ICE	Soil ice content for each soil layer	Mm
OUT_SOIL_LIQ	Soil liquid content for each soil layer	Mm
OUT_SOIL_MOIST	Total soil moisture content for each soil layer	Mm
OUT_SOIL_WET	Vertical average of (soil moisture - wilting point)/(maximum soil moisture - wilting point)	mm/mm
OUT_SURFSTOR	Storage of liquid water and ice (not snow) on surface (ponding)	Mm
OUT_SURF_FROST_FRAC	Fraction of soil surface that is frozen	fraction
OUT_SWE	Snow water equivalent in snow pack (including vegetation-intercepted snow)	Mm
OUT_WDEW	Total moisture interception storage in canopy	Mm
OUT_ZWT	Water table position, using lowest unsaturated soil layer	cm (positive upwards, i.e. negative values indicate below soil surface; 0 = at soil surface)
OUT_ZWT_LUMPED	Water table position, lumping all layers'	cm (positive

	moistures together	upwards, i.e. negative values indicate below soil surface; 0 = at soil surface)
Water Balance Terms (fluxes)		
Variable	**Description**	**Units**
OUT_BASEFLOW	Baseflow out of the bottom layer	mm (ALMA_OUTPUT: mm/s)
OUT_DELINTERCEPT	Change in canopy interception storage	Mm
OUT_DELSOILMOIST	Change in soil water content	Mm
OUT_DELSURFSTOR	Change in surface liquid water storage	Mm
OUT_DELSWE	Change in snow water equivalent	Mm
OUT_EVAP	Total net evaporation	mm (ALMA_OUTPUT: mm/s)
OUT_EVAP_BARE	Net evaporation from bare soil	mm (ALMA_OUTPUT: mm/s)
OUT_EVAP_CANOP	Net evaporation from canopy interception	mm (ALMA_OUTPUT: mm/s)
OUT_INFLOW	Moisture that reaches top of soil column	mm (ALMA_OUTPUT: mm/s)
OUT_LAKE_BF_IN	(release 4.1.2 and later) Incoming baseflow from lake catchment	mm (ALMA_OUTPUT: mm/s)
OUT_LAKE_BF_IN_V	(release 4.1.2 and later) Incoming volumetric baseflow from lake catchment	m^3 (ALMA_OUTPUT: m^3/s)

OUT_LAKE_BF_OUT	(release 4.1.2 and later) Outgoing baseflow from lake to channel network	mm (ALMA_OUTPUT: mm/s)
OUT_LAKE_BF_OUT_V	(release 4.1.2 and later) Outgoing volumetric baseflow from lake to channel network	m^3 (ALMA_OUTPUT: m^3/s)
OUT_LAKE_CHANNEL_IN	(release 4.1.2 and later) Channel inflow from upstream	mm (ALMA_OUTPUT: mm/s)
OUT_LAKE_CHANNEL_IN_V	(release 4.1.2 and later) Volumetric channel inflow from upstream	m^3 (ALMA_OUTPUT: m^3/s)
OUT_LAKE_CHANNEL_OUT	(release 4.1.2 and later) Channel outflow from lake to channel network	mm (ALMA_OUTPUT: mm/s)
OUT_LAKE_CHANNEL_OUT_V	(release 4.1.2 and later) Volumetric channel outflow from lake to channel network	m^3 (ALMA_OUTPUT: m^3/s)
OUT_LAKE_DSTOR	(release 4.1.2 and later) Change in lake moisture storage (liquid plus ice cover)	mm (ALMA_OUTPUT: mm/s)
OUT_LAKE_DSTOR_V	(release 4.1.2 and later) Volumetric change in lake moisture storage (liquid plus ice cover)	m^3 (ALMA_OUTPUT: m^3/s)

OUT_LAKE_DSWE	(release 4.1.2 and later) Change in swe on top of lake ice	mm (ALMA_OUTPUT: mm/s)
OUT_LAKE_DSWE_V	(release 4.1.2 and later) Volumetric change in swe on top of lake ice	m^3 (ALMA_OUTPUT: m^3/s)
OUT_LAKE_EVAP	(release 4.1.2 and later) Net evaporation from lake surface	mm (ALMA_OUTPUT: mm/s)
OUT_LAKE_EVAP_V	(release 4.1.2 and later) Net volumetric evaporation from lake surface	m^3 (ALMA_OUTPUT: m^3/s)
OUT_LAKE_PREC_V	(release 4.1.2 and later) Volumetric precipitation over lake surface	m^3 (ALMA_OUTPUT: m^3/s)
OUT_LAKE_RCHRG	(release 4.1.2 and later) Recharge from lake to surrounding wetland	mm (ALMA_OUTPUT: mm/s)
OUT_LAKE_RCHRG_V	(release 4.1.2 and later) Volumetric recharge from lake to surrounding wetland	m^3 (ALMA_OUTPUT: m^3/s)
OUT_LAKE_RO_IN	(release 4.1.2 and later) Incoming runoff from lake catchment	mm (ALMA_OUTPUT: mm/s)
OUT_LAKE_RO_IN_V	(release 4.1.2 and later) Incoming volumetric runoff from lake	m^3 (ALMA_OUTPUT: m^3/s)

	catchment	
OUT_LAKE_VAPFLX	(release 4.1.2 and later) Outgoing sublimation from snow on top of lake ice	mm (ALMA_OUTPUT: mm/s)
OUT_LAKE_VAPFLX_V	(release 4.1.2 and later) Outgoing volumetric sublimation from snow on top of lake ice	m^3 (ALMA_OUTPUT: m^3/s)
OUT_PET_SATSOIL	Potential evap from saturated bare soil	mm (ALMA_OUTPUT: mm/s)
OUT_PET_H2OSURF	Potential evap from open water	mm (ALMA_OUTPUT: mm/s)
OUT_PET_SHORT	Potential evap (transpiration only) from short reference crop (grass)	mm (ALMA_OUTPUT: mm/s)
OUT_PET_TALL	Potential evap (transpiration only) from tall reference crop (alfalfa)	mm (ALMA_OUTPUT: mm/s)
OUT_PET_NATVEG	Potential evap (transpiration only) from current vegetation and current canopy resistance	mm (ALMA_OUTPUT: mm/s)
OUT_PET_VEGNOCR	Potential evap (transpiration only) from current vegetation and 0 canopy resistance	mm (ALMA_OUTPUT: mm/s)
OUT_PREC	Incoming precipitation	mm (ALMA_OUTPUT: mm/s)
OUT_RAINF	Rainfall	mm (ALMA_OUTPUT: mm/s)
OUT_REFREEZE	Refreezing of water in the snow	mm (ALMA_OUTPUT: mm/s)

OUT_RUNOFF	Surface runoff	mm (ALMA_OUTPUT: mm/s)
OUT_SNOW_MELT	Snow melt	mm (ALMA_OUTPUT: mm/s)
OUT_SNOWF	Snowfall	mm (ALMA_OUTPUT: mm/s)
OUT_SUB_BLOWING	Net sublimation of blowing snow	mm (ALMA_OUTPUT: mm/s)
OUT_SUB_CANOP	Net sublimation from snow stored in canopy	mm (ALMA_OUTPUT: mm/s)
OUT_SUB_SNOW	Total net sublimation from snow pack (surface and blowing)	mm (ALMA_OUTPUT: mm/s)
OUT_SUB_SURFACE	Net sublimation from snow pack surface	mm (ALMA_OUTPUT: mm/s)
OUT_TRANSP_VEG	Net transpiration from vegetation	mm (ALMA_OUTPUT: mm/s)
OUT_WATER_ERROR	Water budget error	Mm
Energy Balance Terms (state variables)		
Variable	**Description**	**Units**
OUT_ALBEDO	Average surface albedo	fraction
OUT_BARESOILT	Bare soil surface temperature	C (ALMA_OUTPUT: K)
OUT_FDEPTH	Depth of freezing fronts for each freezing front	cm (ALMA_OUTPUT: m)
OUT_LAKE_ICE_TEMP	Temperature of lake ice	K
OUT_LAKE_SURF_TEMP	Lake surface temperature	K

OUT_RAD_TEMP	Average radiative surface temperature	K
OUT_SALBEDO	Snow pack albedo	fraction
OUT_SNOW_PACK_TEMP	Snow pack temperature	C (ALMA_OUTPUT: K)
OUT_SNOW_SURF_TEMP	Snow surface temperature	C (ALMA_OUTPUT: K)
OUT_SNOWT_FBFLAG	Snow surface temperature fallback flag	0 or 1
OUT_SOIL_TEMP	Soil temperature for each soil layer	C (ALMA_OUTPUT: K)
OUT_SOIL_TNODE	Soil temperature for each soil thermal node	C (ALMA_OUTPUT: K)
OUT_SOIL_TNODE_WL	Soil temperature for each soil thermal node in the wetland	C (ALMA_OUTPUT: K)
OUT_SOILT_FBFLAG	Soil temperature flag for each soil thermal node	0 or 1
OUT_SURF_TEMP	Average surface temperature	C (ALMA_OUTPUT: K)
OUT_SURFT_FBFLAG	Surface temperature fallback flag	0 or 1
OUT_TCAN_FBFLAG	Tcanopy fallback flag	0 or 1
OUT_TDEPTH	Depth of thawing fronts for each thawing front	cm (ALMA_OUTPUT: m)
OUT_TFOL_FBFLAG	Tfoliage fallback flag	0 or 1
OUT_VEGT	Average vegetation canopy temperature	C (ALMA_OUTPUT: K)
Energy Balance Terms (fluxes)		
Variable	**Description**	**Units**
OUT_ADV_SENS	Net sensible flux advected to snow pack	W/m^2

OUT_ADVECTION	Advected energy	W/m^2
OUT_DELTACC	Rate of change in cold content in snow pack	W/m^2 (ALMA_OUTPUT: J/m^2)
OUT_DELTAH	Rate of change in heat storage	W/m^2 (ALMA_OUTPUT: J/m^2)
OUT_ENERGY_ERROR	Energy budget error	W/m^2
OUT_FUSION	Net energy used to melt/freeze soil moisture	W/m^2
OUT_GRND_FLUX	Net heat flux into ground	W/m^2
OUT_IN_LONG	Incoming longwave at ground surface (under veg)	W/m^2
OUT_LATENT	Net upward latent heat flux	W/m^2
OUT_LATENT_SUB	Net upward latent heat flux from sublimation	W/m^2
OUT_MELT_ENERGY	Energy of fusion (melting) in snowpack	W/m^2
OUT_NET_LONG	Net downward longwave flux	W/m^2
OUT_NET_SHORT	Net downward shortwave flux	W/m^2
OUT_R_NET	Net downward radiation flux	W/m^2
OUT_RFRZ_ENERGY	Net energy used to refreeze liquid water in snowpack	W/m^2
OUT_SENSIBLE	Net upward sensible heat flux	W/m^2
OUT_SNOW_FLUX	Energy flux through snow pack	W/m^2
Miscellaneous Terms		
Variable	**Description**	**Units**
OUT_AERO_COND	"Scene" aerodynamic conductance (tiles with overstory contribute overstory conductance; others contribute surface conductance)	m/s
OUT_AERO_COND1	Surface aerodynamic conductance	m/s
OUT_AERO_COND2	Overstory aerodynamic conductance	m/s

OUT_AERO_RESIST	"Scene"canopy aerodynamic resistance (tiles with overstory contribute over story resistance; others contribute surface resistance)	s/m
OUT_AERO_RESIST1	Surface aerodynamic resistance	s/m
OUT_AERO_RESIST2	Overstory aerodynamic resistance	s/m
OUT_AIR_TEMP	Air temperature	C (ALMA_OUTPUT: K)
OUT_DENSITY	Near-surface atmospheric density	kg/m^3
OUT_LONGWAVE	Incoming longwave	W/m^2
OUT_PRESSURE	Near surface atmospheric pressure	kPa (ALMA_OUTPUT: Pa)
OUT_QAIR	Specific humidity	kg/kg
OUT_REL_HUMID	Relative humidity	fraction
OUT_SHORTWAVE	Incoming shortwave	W/m^2
OUT_SURF_COND	Surface conductance	m/s
OUT_TSKC	(release 4.1.2 and later) Cloud fraction	fraction
OUT_VP	Near surface vapor pressure	kPa (ALMA_OUTPUT: Pa)
OUT_VPD	Near surface vapor pressure deficit	kPa (ALMA_OUTPUT: Pa)
OUT_WIND	Near surface wind speed	m/s
Band-specific quantities		
Variable	**Description**	**Units**
OUT_ADV_SENS_BAND	Net sensible heat flux advected to snow pack	W/m^2
OUT_ADVECTION_BAND	Advected energy	W/m^2

OUT_ALBEDO_BAND	Average surface albedo	fraction
OUT_DELTACC_BAND	Change in cold content in snow pack	W/m^2
OUT_GRND_FLUX_BAND	Net heat flux into ground	W/m^2
OUT_IN_LONG_BAND	Incoming longwave at ground surface (under veg)	W/m^2
OUT_LATENT_BAND	Net upward latent heat flux	W/m^2
OUT_LATENT_SUB_BAND	Net upward latent heat flux due to sublimation	W/m^2
OUT_MELT_ENERGY_BAND	Energy of fusion (melting) in snowpack	W/m^2
OUT_NET_LONG_BAND	Net downward longwave flux	W/m^2
OUT_NET_SHORT_BAND	Net downward shortwave flux	W/m^2
OUT_RFRZ_ENERGY_BAND	Net energy used to refreeze liquid water in snowpack	W/m^2
OUT_SENSIBLE_BAND	Net upward sensible heat flux	W/m^2
OUT_SNOW_CANOPY_BAND	Snow interception storage in canopy	Mm
OUT_SNOW_COVER_BAND	Fractional area of snow cover	fraction
OUT_SNOW_DEPTH_BAND	Depth of snow pack	Cm
OUT_SNOW_FLUX_BAND	Energy flux through snow pack	W/m^2
OUT_MELT_BAND	Snow melt	Mm
OUT_SNOW_PACKT_BAND	Snow pack temperature	C (ALMA_OUTPUT: K)
OUT_SNOW_SURFT_BAND	Snow surface temperature	C (ALMA_OUTPUT: K)
OUT_SWE_BAND	Snow water equivalent in snow pack	Mm
Dynamic Soil Property Terms (EXCESS_ICE option in user_def.h)		
Variable	**Description**	**Units**
OUT_SOIL_DEPTH	Soil moisture layer depths	M
OUT_SUBSIDENCE	Subsidence of soil layer	Mm
OUT_POROSITY	Porosity	mm/mm

OUT_ZSUM_NODE	Depths of thermal nodes	M

DEFAULT OUTPUT FILES

If the user does not give explicit output file instructions in the global parameter file, then VIC will produce a set of default output files, one per grid cell. The exact set of output files, and which variables they contain, is determined by model settings, as follows:

- If OUTPUT_FORCE is TRUE in user_def.h (and the model has been re-compiled), VIC will produce 1 output file per grid cell, containing: PREC, AIR_TEMP, SHORTWAVE, LONGWAVE, DENSITY, PRESSURE, VP, and WIND. Units of these variables will depend on whether ALMA_OUTPUT is set to TRUE or FALSE in the global parameter file. These files will be named "full_data_lat_lon", where "lat" and "lon" are the latitude and longitude of the grid cell.
- If OUTPUT_FORCE is FALSE in user_def.h, the set of output files, and the variables they contain, will depend on which operation mode VIC is being run in (e.g. FULL_ENERGY, FROZEN_SOIL, etc...in the global parameter file).

VIC can also be explicitly instructed to output these default files by pasting the contents of the file output.TRADITIONAL.410.template, which is included with the VIC source code, into the bottom of your global parameter file. Of course, this is not necessary, since omitting any output file format information will cause VIC to make these files by default. But if you wish to have output that is similar to the default output files, but with fewer or additional variables, it is easiest to paste the contents into the global parameter file and then edit them to your liking. NOTE: to have output files exactly similar to those of 4.0.6 and earlier, use output TRADITIONAL template, instead of output.TRADITIONAL.410.template.

Flux Files

The primary output file type for the VIC-NL model is the flux file, which contains information about moisture and energy fluxes for each time step. The number of variables in this file depends on the values of FULL_ENERGY and FROZEN_SOIL in the global parameter file; when either FULL_ENERGY or FROZEN_SOIL are true, the file will contain the same number of columns. Flux files are always written, regardless of the mode of operation. Flux files begin with the prefix "fluxes_".

Snow Files

The snow file contains information about the snowpack, averaged across all elevation bands and vegetation tiles. The set of variables in this file depends on the values of FULL_ENERGY and FROZEN_SOIL in the global parameter file. Snow files are always written, regardless of the mode of operation. Snow files begin with the prefix "snow_".

Frozen Soil Files

When the model is run with FROZEN_SOIL set to TRUE in the global parameter file, a third output file is produced which contains soil thermal output parameters. Frozen soil files begin with the prefix "fdepth_".

Snow Band Files

When the model is run with snow elevation bands, and PRT_SNOW_BAND is turned on in the global parameter file, snow pack information for each elevation band will be output to files in the results directory with the prefix "snow_band_". Energy fluxes are output only for the full energy balance model, so there are file descriptions for both full energy and water balance model output files.

Lake Files

The lake file contains information about the lake fraction of the grid cell. Lake files are only written when LAKES is set equal to a valid lake parameter file, in the global parameter file. Lake files begin with the prefix "lake_".

ANEXE 7: VIC MODES OF OPERATION

A large number of options exist for tailoring VIC simulations to your application. Most of these are set in the global parameter file (run-time options), while others are set in the file user_def.h and require re-compiling VIC to take effect (compile-time options). The most commonly used options are FULL_ENERGY (which determines whether VIC will iterate to find the surface temperature that balances the energy budget) and FROZEN_SOIL (which determines whether VIC simulates the phase change of water in the soil). The notes below show some comparisons of the effects of the different options on model performance, in terms of both results and speed.

Some of the modes of operation are accessed simply by changing the options in the global parameter file, while others require that pre-processor options are defined prior to compiling the model.

Possible model options are located in table A.7.1:

MODEL OPTIONS				
Water balance	**Energy balance** • Quick flux • Finite Difference • No flux boundary	**Frozen soil** • Quick frozen soil • No flux boundary	**Special cases** • Low resolution moisture • Optimize Output • Model State • Debug Code	**Simulation time**

Table A.7.1: VIC modes of operation

WATER BALANCE

Model Control File Options	
FULL_ENERGY	FALSE
FROZEN_SOIL	FALSE
GRND_FLUX	FALSE

The water balance model does not solve the surface energy balance. Instead it assumes that the soil surface temperature is equal to the air temperature for the current time step. The exception to this is that the snow algorithm still solves the surface energy balance to determine the fluxes needed to drive accumulation and ablation processes. By eliminating the ground heat flux solution and the iterative processes required to close the surface energy balance, the water balance model requires significantly less computational time than other model modes (see table A.7.II below).

It should be noted that the daily water balance model while significantly faster than sub-daily simulations is essentially a different model. The parameterizations required for daily solutions are different from those used for sub-daily solutions. While the daily water balance model can be used to simulate discharge from a basin it should be understood that calibration parameters for the daily water balance model are unlikely to be transferable to any model run with a sub-daily time step.

ENERGY BALANCE

Model Control File Options	
FULL_ENERGY	TRUE
FROZEN_SOIL	FALSE
GRND_FLUX	TRUE

Energy balance mode solves the complete water balance but also minimizes the surface energy balance error. The surface energy balance is closed through an iterative process which tries finds a surface temperature which adjusts surface energy fluxes (sensible heat, ground heat, ground heat storage, outgoing longwave and indirectly latent heat) so that they compensate for incoming solar and longwave radiation fluxes. This mode requires more computational time than water balance mode as well as requiring a sub-daily simulation time step. However, it simulates the surface energy fluxes, which are important to understanding the hydrologic cycle and land surface-atmosphere interactions in a basin.

Quick Flux

Model Control File Options : QUICK_FLUXTRUE

The default setting for the energy balance model is to use a simplified method for estimating the ground heat flux. This method estimates ground heat flux by assuming an exponential temperature profile between a near surface thermal node (5 to 15 cm deep) and the thermal damping depth (at which depth soil temperature is unaffected by daily and annual changes in surface temperature. The solution uses a constant soil temperature at the damping depth.

Finite Difference

Model Control File Options	
QUICK_FLUX	FALSE
NOFLUX	FALSE

The finite difference method makes no assumptions about the temperature profiles, instead it solves heat fluxes at nodes through the soil column using a finite difference solution to the heat flux equations. Soil nodes are set at the surface, between the first and second soil layers, at twice the depth of the second node, and at the thermal damping depth. Other nodes are either spaced equally between the third node and the damping depth, or at user defined depths in the same space. The solution uses a constant soil temperature at the damping depth.

No Flux Boundary

Model Control File Options	
QUICK_FLUX	FALSE
NOFLUX	TRUE

When the no flux boundary is selected the VIC model solves ground heat flux using the finite difference method. However, instead of using a constant temperature boundary at the damping depth, the model uses a no flux boundary. This means that the soil temperature at the damping depth can change, but there is no loss or gain of heat energy through the boundary. This method adds slightly to the computation time but is especially useful for very long simulations, climate change studies and permafrost simulations.

FROZEN SOIL

Model Control File Options	
FULL_ENERGY	TRUE
FROZEN_SOIL	TRUE

GRND_FLUX	TRUE
NOFLUX	FALSE

Frozen soil adds the effects of soil ice content to both moisture and energy fluxes. It solve thermal fluxes at nodes through the soil column using the finite difference method previous described. In addition it computes the maximum unfrozen water content at each soil node based on the nodal temperature. Ice content for each soil moisture layer is then computed from the nodal values and is used to restrict infiltration and soil moisture drainage. The nodal ice contents are also used to derive the soil thermal conductivity and volumetric heat capacity for the next model time step.The frozen soil algorithm is computationally intensive (Table A.7.II) but may play a major role in both the energy and water balance of cold regions (through seasonally frozen soil and permafrost).

Quick Frozen Soil

Model Pre-processor Options	
QUICK_FS	TRUE
QUICK_FS_TEMPS	*Ntemp*

Model Control File Options	
FULL_ENERGY	TRUE
FROZEN_SOIL	TRUE
GRND_FLUX	TRUE
NOFLUX	FALSE

The time required to solve the frozen soil algorithm can be reduced significantly by compiling the VIC model the QUICK_FS pre-processor option activated. This creates a set of *Ntemp* linear equations which represent the more complex maximum unfrozen water (UFWC) equation. The new set of equations reduces the accuracy of the solution of the UFWC equation but by removing the complex power function, which is solved often for each iteration, it saves a lot of computational time **(Table A.7.II).**

No Flux Boundary

Model Control File Options	
FULL_ENERGY	TRUE
FROZEN_SOIL	TRUE
GRND_FLUX	TRUE
NOFLUX	TRUE

The finite difference ground heat flux solution used with the frozen soil algorithm can, like that for the energy balance, be solved using a no flux bottom boundary condition. Plots of discharge and cell fluxes of the hourly energy balance with frozen soil and no bottom flux (1hr EWB FSq NF) can be found in Figures A.7.7 and A.7.8 respectively.

SPECIAL CASES

The following model modes are special cases which can be applied to any of the above modes but modify them in the described fashion. These options are controlled by pre-processor commands in user_def.h and need to be set before the source code is compiled.

Low Resolution Moisture

Model Pre-processor Options	
LOW_RES_MOIST	TRUE

This mode changes how the VIC model computes soil moisture drainage. In the original model drainage is a straight function of the unsaturated hydraulic conductivity. However, it is showed that when this method is used with a small number of soil layers (2-4) it drains the soil too quickly. They proposed a different method which uses the average soil matrix potential of the current layer and the one below it to find a better value for the unsaturated hydraulic conductivity. They showed that soil moisture storage simulated using this new method compared favorably to a model with many soil moisture layers, allowing the model with fewer layers to retain more soil moisture near the top of the soil column.

Optimize Output

Model Pre-processor Options	
OPTIMIZE	TRUE

This modifies the model so that it outputs daily runoff and baseflow only. This reduces simulation time slightly (Table A.7.II) but can significantly reduce post-processing time for sub-daily model simulations. This mode was designed for use with the model optimization code though it may also be of use for calibration by hand since it eliminates some post-processing steps.

Model State

Model Pre-processor Options	
SAVE_STATE	TRUE

When SAVE_STATE is active and the STATE file variables have been set in the global parameter file, VIC will create a state file at hour 0 of the selected day. Subsequently the VIC model can be restarted at the start of that day using the same state file (INIT_STATE option in the global parameter file). Users can also create their own state file to start the VIC model with observed properties (*i.e.* for a field site simulation).

Debug Code

Model Pre-processor Options	
LINK_DEBUG	TRUE

The LINK_DEBUG option allows the user to access various pre-defined debugging output files (see Define Debugging Parameters in the global parameter file). Activating the debugging code significantly increases computation time since it adds multiple conditional statements, therefore its use is not recommended unless you are actively working with the code.

SIMULATION TIME

Though the core model for version 4.0.0 is faster than that released with version 3.2.1, the simulation times listed in **Table A.7.I** show that version 3.2.1 is typically the faster model. This is due primarily to the MTCLIM (mountain microclimate simulate model) routine which was added to release 4.0.0 to improve the estimation of incoming radiative fluxes, and atmospheric vapor pressure. Though it does a better job than the previous estimation routines, MTCLIM does require more time to prepare the forcings for each grid cell.

If simulation time is more important than conserving disk space (*e.g.* for calibration which requires many runs over short simulation periods) the sub-daily forcings estimated by MTCLIM can be extracted from the VIC model. By driving VIC directly

with the estimated values, it does not have to run MTCLIM so simulation times should be significantly reduced.

Table A.7.II: Simulation times for various VIC model modes (Note*).

SIMULATION	VERBOSE	OPTIMIZE	LDAS_OUTPUT	QUICK_FS	LOW_RES_MOIST	time 3.2.1 [sec]	time 4.0.0 [sec]
24hr_WB	**TRUE**	**FALSE**	**TRUE**	**FALSE**	**FALSE**	N/A	51.85
24hr_WB_LRM	**TRUE**	**FALSE**	**TRUE**	**FALSE**	**TRUE**	N/A	79.39
24hr_WB_OPTI	**FALSE**	**TRUE**	**TRUE**	**FALSE**	**FALSE**	N/A	52.38
1hr_WB	**TRUE**	**FALSE**	**TRUE**	**FALSE**	**FALSE**	N/A	133.23
1hr_WB_LRM	**TRUE**	**FALSE**	**TRUE**	**FALSE**	**TRUE**	N/A	165.99
1hr_WB_OPTI	**FALSE**	**TRUE**	**TRUE**	**FALSE**	**FALSE**	N/A	119.16
3hr_WB	**TRUE**	**FALSE**	**TRUE**	**FALSE**	**FALSE**	N/A	58.99
1hr_EWB	**TRUE**	**FALSE**	**TRUE**	**FALSE**	**FALSE**	N/A	361.19
1hr_EWB_LRM	**TRUE**	**FALSE**	**TRUE**	**FALSE**	**TRUE**	N/A	411.64
1hr_EWB_OPTI	**FALSE**	**TRUE**	**TRUE**	**FALSE**	**FALSE**	N/A	348.28
1hr_EWBfd	**TRUE**	**FALSE**	**TRUE**	**FALSE**	**FALSE**	N/A	417.02
1hr_EWBfd_NF	**TRUE**	**FALSE**	**TRUE**	**FALSE**	**FALSE**	N/A	438.21
3hr_EWB	**TRUE**	**FALSE**	**TRUE**	**FALSE**	**FALSE**	N/A	142.14
1hr_EWB-FS	**TRUE**	**FALSE**	**TRUE**	**FALSE**	**FALSE**	N/A	937.43
1hr_EWB-FSq	**TRUE**	**FALSE**	**TRUE**	**TRUE**	**FALSE**	N/A	639.74
1hr_EWB-FSq_LRM	**TRUE**	**FALSE**	**TRUE**	**TRUE**	**TRUE**	N/A	705.08
1hr_EWB-FSq_NF	**TRUE**	**FALSE**	**TRUE**	**TRUE**	**FALSE**	N/A	664.82
1hr_EWB-FSq_OPTI	**FALSE**	**TRUE**	**TRUE**	**TRUE**	**FALSE**	N/A	628.14
3hr_EWB-FS	**TRUE**	**FALSE**	**TRUE**	**FALSE**	**FALSE**	N/A	357.20
3hr_EWB-FSq	**TRUE**	**FALSE**	**TRUE**	**TRUE**	**FALSE**	N/A	245.54

Table A.7.II Simulation times for various VIC model modes

Mode Types:

Time Step	Simulation Mode	Special Case
24hr daily time step **3hr** three hourly time step **1hr** hourly time step	**WB** water balance **EWB** energy balance **EWBfd** energy balance w/ finite difference ground heat flux **EWB-FS** frozen soil active **EWB-FSq** quick frozen soil active	**OPTI** optimized code **LRM** low resolution moisture **NF** no flux bottom boundary

*Note: Simulations for Table A.7.Ii were conducted in the Chippewa River basin. The basin consists of five one-degree grid cells in the north central region of the upper Mississippi River basin. Cells have a total of 29 vegetation tiles (5, 4, 7, 6, and 7 tiles, respectively) and the simulation is run from January 1, 1980 to December 31, 1985. Simulations were run on a 450 MHz Pentium II running freeBSD.

ANEXE 8: CALIBRATION OF THE VIC MODEL

INTRODUCTION

While many of the parameters for these models are based on satellite observations or geological surveys, some of them are either heterogeneus in space that in situ measurements cannot capture the large-scale "effective" values, or are more conceptual(such as soil layer boundaries) and do not correspond to actual physically-observable quantities. For these parameters, we either must make assumptions about their values or calibrate them (find optimal values for them) that minimize the differences between model output and observations.

GENERAL NOTES

A parameter estimation scheme for the land surface model VIC-3L is discussed.

VIC-3L parameters are chosen for calibration by a systematic manual calibration approach in the period of record of 1/08/2002 - 31/12/2008 for the catchment SKJERKA to predict the streamflow.

Comparisons of the simulated results using the a priori (what I call given parameters) show that the calibrated parameters are able to reduce bias and increase the Nash-Shutcliffe efficiency coefficient of the streamflow simulation.

A sensitivity analysis on calibrated parameters will show which parameters are more sensitive. Therefore, suitable calibration for the parameters of the land surface model VIC-3L (specially for the variable infiltration curve parameter and the depth of the second soil layer Z2) is very important for simulating land surface behaviour in a specific region.

The usual implementation approach involves calibration of six parameters:

d) **The infiltration parameter (b_i),** which controls the partitioning of rainfall (or snowmelt) into infiltration and direct runoff (a higher value of b_i gives lower infiltration and yields higher surface runoff);
e) ***D_2* and *D_3*,** (named Z2 and Z3 as well) which are the second and third soil layer thicknesses (D_1, the top soil layer depth, is usually specified *a priori*) and affect the water available for transpiration and baseflow respectively (thicker soil depths have slower runoff response — baseflow dominated —with higher evapotranspiration, but result in longer retention of soil moisture and higher baseflow in wet seasons);
f) ***Ds_{max}*, *Ds*, and *Ws*,** which are baseflow parameters and also are estimated via calibration. Ds_{max} is the maximum baseflow velocity, *Ds* is the fraction of maximum baseflow velocity, and *Ws* is the fraction of maximum soil moisture content of the third soil layer at which non-linear baseflow occurs. These three baseflow parameters determine how quickly the water stored in the third soil layer is evacuated as baseflow. The three baseflow parameters and the third soil layer depth (d_3) are used with only minor adjustment during the calibration,

while the infiltration parameter (b_i) and the second soil depth (d_2) are targeted for intensive calibration. Parameters b_i and d_2 are calibrated independently.

The calibration of these parameters is conducted via a trial and error procedure that leads to an acceptable match of model-predicted discharge with observations. Besides visual comparison of monthly simulated and observed hydrographs, two objective functions are often used:

- **Nash-Sutcliffe efficiency (E_f)** which describes the prediction skill of the modeled streamflow as compared to the observed value.
- **The relative error (*Er*)** between simulated and observed mean annual runoff. E_f and *Er* are calculated as:

$$E_f = 1 - \frac{\sum_{i=1}^{N}(Q_{\mathrm{mod},i} - Q_{obs,i})^2}{\sum_{i=1}^{N}(Q_{obs,i} - \overline{Q_{obs}})^2}$$

$$E_r = (\overline{Q_{\mathrm{mod}}} - \overline{Q_{obs}}) / \overline{Q_{obs}}$$

$Q_{mod,i}$ =monthly modeled streamflow for month *i*,
Q_{obs} = monthly observed streamflow for month *i*,
N =the number of months, and
$\overline{Q_{\mathrm{mod}}}$ and $\overline{Q_{obs}}$ = mean of the monthly modeled and observed streamflows, respectively.

When E_f equals 1.0 it means that the model perfectly predicts the observations.

PARAMETER ESTIMATION

Although the VIC model contains many parameters it is more appropiate to adjust some of these parameters during calibration than others. Often the distinction is based on the degree to which the parameter values can actually be measured or observed.

In this study simulations are carried out under water balance mode. The parameters that are implicated on the model calibration are summarized in the table A.8.1 though only soil parameters are going to be calibrated.

Soil parameter	Snow parameters	Global parameter file	Gauge correction
Depth 1 (z1) **Depth 2 (z2)** **Depth 3 (z3)** **B_inf** **Ws** **Ds** **Rc** **Ds max**	Max snow temp Min rain temp Snow rough Snow albedo	**Water Balance mode:** Quick_flux=true Implicit=false Quick_solve=false No_flux=false Exp_trans=false Grnd_flux_type=GF_410	**Rain correction** **Snow correction**

Table A.8.1: Parameters that are typically involved in the calibration of the VIC model.

Therefore, the model calibration in this study means to determine the set of free parameters in the model that gives the best possible correspondence between observed and simulated runoff for the catchment Sjkerka

During the model calibration it is always necessary to have a clear understanding of the model structure, and to remember how the different parameters affect the model response. Further information can be found in "Annexe5: Input files"

SOIL PARAMETERS

Soil moisture determines whether the soil column can meet the atmospheric demand for moisture; either at the surface (bare soil evaporation) or in the root zone (transpiration). There are five soil parameters that comprise the set of variables to rely on for model calibration. These parameters, their typical ranges, and a short description are given in the table A.8.2:

	Range	Description
Ds	**[>0 to 1]**	This is the fraction of Ds_{max} where non-linear (rapidly increasing) baseflow begins. With a higher value of Ds, the baseflow will be higher at lower water content in lowest soil layer.
Ds_{max}	**[>0 to ~30]**	This is the maximum baseflow that can occur from the lowest soil layer (in mm/day). That occurs when the third soil layer moisture is saturated.
Ws	**[>0 to 1]**	This is the fraction of the maximum soil moisture (of the lowest soil layer) where non-linear baseflow occurs. This is analogous to Ds. A higher value of Ws will raise the water content required for rapidly increasing, non-linear baseflow, which will

		tend to delay runoff peaks.
b_{inf}	**[>0 to ~0.4]**	This parameter defines the shape of the Variable Infiltration Capacity curve. It describes the amount of available infiltration capacity as a function of relative saturated gridcell area. A higher value of b_{inf} gives lower infiltration and yields higher surface runoff
Soil Depth **(of each layer)**	**[Typically 0.1 to 1.5 m]**	Soil depth effects many model variables. In general, for runoff considerations, thicker soil depths slow down (baseflow dominated) seasonal peak flows and increase the loss due to evapotranspiration.

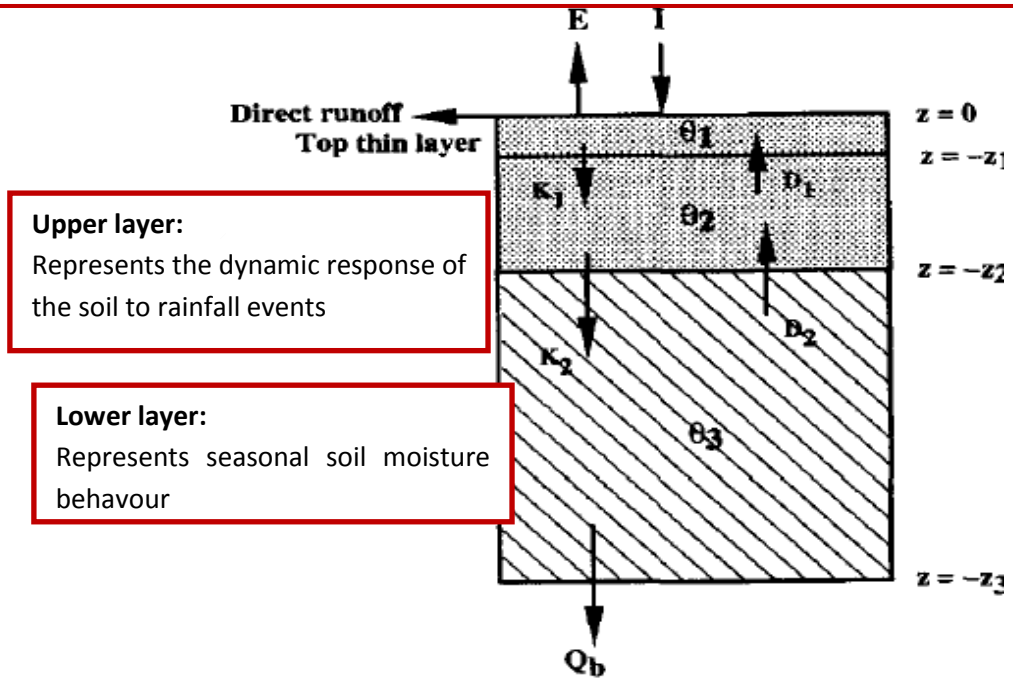
Table A.8.2: Soil parameters that under adjustment. In the first column are the names of the parameters. Second column contains the range of the value of the parmeters. Third column gives a brief description of the parameter.

For understanding the dynamics of baseflow and runoff, and how baseflow is calculated:

- The variable infiltration capacity model (VIC), called VIC-2L includes **two different time scales**, the fast and slow, for runoff to capture the dynamics of runoff generation. The upper soil layer of the model is designed to represent the dynamic response of the soil to rainfall events, and the lower layer is used to characterize the seasonal soil moisture behaviour.
- The VIC model uses **physically-based formulations** for the calculation of the sensible and latent heat fluxes, but uses the conceptual ARNO baseflow model to simulate runoff generation from the deepest soil layer. To better represent quick bare soil evaporation following small summer rainfall events, a thin soil layer is included in VIC-2L and it becomes VIC 3L. Soil moisture diffusion processes between the three soil layers are considered in VIC 3L

Figure A.8.1 is an illustration of the process. Main events are described in the figure: Thicknesses of soil layers are Z=Z1 for the topthin soil layer, Z= Z2 for the second soil layer and Z=Z3 for the third soil layer. Direct runoff flows from the upper layer and basflow flows from the bottom layer. This stream flow is described by the curve “baseflow curve”:

Top thin layer: To better represent quick bare soil evaporation following small summer rainfall events



$$Qbaseflow = \frac{D_s \cdot D_{smax}}{W_s W_2^c} \cdot W_2$$

Figure A.8.1: Representation of land-surface behave. Soil is divided into three soil layers: the top thin soil layer, upper layer and lower layer. Different stream flows are the direct runoff from the top thin soil layer, and the baseflow that flows from the lower layer. Thicknesses of the soil layers: Z1 (thop thin layer), Z2(upper layer) and z3 (bottom layer).

Table A.8.3 lists the main events of the soil layers:

UPPER LAYER (Surface)	**BOTTOM LAYER (Subsurface)**
PARAMETERS **B_infilt** **Z1, m** **Z2, m**	**PARAMETERS** **Z3,** **Ws** **Ds** **Ds max**
EVENTS	**EVENTS**

• **Bare soil evaporation:** When surface soil is saturate, it evaporates at the potential evaporation rate. When the top soil layer is not saturated, its evaporation rate E is calculated using the Arno formulation, where the parameter <u>B= infiltration shape</u>	• **Bare soil evaporation:** Needs to be taken into account if vegetation: if roots go through into the lower soil layer, evapotranspiration term needs to be considered
• **Surface runoff (direct runoff):** Since the top thin soil layer has a very small water holding capacity, the direct runoff within each time step is calculated for the entire upper layer, **Qd**	• **Subsurface runoff, baseflow** For the lower soil layer, an empirical formulation derived from a large scale catchment hydrology is used in which the drainage and subsurface drainage are lumped together as a baseflow, **Qb** Parameters for calculations: <u>Depth 3, Ws, Ds</u>

Table A.8.3: List of events and parameters that characterize soil layers.

PROCEDURE:

The procedure is the following: there is a initial phase where simulations are run simultaneously. In this phase I got an idea of how different parameters affect land-surface behavior. Also the year of the calibration was chosen (year 2006). That means that the program was running for the whole entire data-period. Different parts of the water balance were plotted to make sure that it was running properly. Graphs and plots govern as analysis method in this phase, when I didn't know how to schedule the parameter estimation step. In this phase, was intended to adjust as well the gauge correction parameters though It was realized that they don't affect the model when the option "snow elevation band".

The second phase was the parameter estimation step. In this phase an order was followed to calibrate the parameters. The given range of the parameters was taken into account, and objective method was used to measure the fitness of good. Parameters were divided in two blocks: first parameters involved in the upper layer were calibrated, and then the parameters that affect the bottom layer behave. Therefore, in steps:

1. INITIAL SIMULATIONS. Detailed information located in the Annexe 9: Initial simulations

2. PARAMETER ESTIMATION SCHEME. Detailed information is located in the Annexe 10: Upper layer adjustment, Annexe 11: Baseflow adjustment and Annexe 12: Final adjustment.

Soil parameter	Snow parameters	Global parameter file	Gauge correction
1 **RUNOFF** **Depth 2, Z2** **B_infiltration** **Depth 3, Z3**	Max snow temp Min rain temp Snow rough Snow albedo	**Water Balance mode:** Quick_flux=true Implicit=false Quick_solve=false No_flux=false Exp_trans=false Grnd_flux_type=GF_410	**Rain correction** **Snow correction** ↓ Those parameters don't need to be calibrated because we are using 5 snow/elevation bands. CORREPREC option in global parameter file is not supported when using snow/elevation bands.
2 **BASEFLOW** **Ws** **Ds** **Ds max**			
Depth 1, Z1: keep it constant (follows small summer rainfall events)			

STEPS:

UPPER LAYER PARAMETERS ADJUSTMENT: Adjust the first block, that corresponds to parameters that describes upper layer behave to fit the runoff (z2 and b_infiltr) and the relation with third layer depth, Z3

- Sensitivity of Z2, Z3, interactions
- Set the estimated value for *Z*2 and Z3 (commonly with a deeper depth for arid regions and a lower depth for humid regions). Select best combinations.
- Determine b
- Analysis of baseflow and runoff

BASEFLOW PARAMETERS ADJUSTMENT: Calibrate the ARNO model parameters (*D*m, Ws, *D*s) to fit the low flow.

- Select cases from the first block adjustment. Runoff and baseflow analysis: I am interested on the cases where more amount of baseflow is obtained.
- Adjust Ws and Ds. Study Ds/Ws as one single parameter
- Adjust Ds max
- Repeat the process for the different combinations from the first block adjustment

FINAL ADJUSTMENT: Make a fine adjustment to these parameters to get the best simulation results.

ANEXE 9: INITIAL SIMULATIONS

This is an initial phase of model calibration, where several parameters need to be changed simultaneusly.

In this step of calibration procedure simulations are based on intuition before starting an organized schedule of simulations.

The subjective method is most efficient in this part, when objective methods are more appropiate during the final 'fine tuning' of the model where parameters are close to their optimal values.

At this step, the idea is the calibration of two blocks: Soil parameters and Gauge correction parameters separately. A relation between rain correction factor and the second soil depth layer is going to be under analysis as well:

Soil parameter	Snow parameters	Global parameter file	Gauge correction
Depth 1 **Depth 2** **Depth 3** **B_inf** **Ws** **Ds** **Ds max**	Max snow temp Min rain temp Snow rough Snow albedo	**Water Balance mode:** Quick_flux=true Implicit=false Quick_solve=false No_flux=false Exp_trans=false Grnd_flux_type=GF_410	**Rain correction** **Snow correction**

Table A.9.1: Parameters that affects the model calibration. Two blocks were under study in this phase: soil parameters and gauge correction parameters.

It is important to mention that data for the whole time period were used, therefore it is not possible appreciate signifficant trend or evaluate correctly any parameter.

In this section, we study the calibration period for six years in four different situations.

A comparison of different simulations changing soil depths and rain correction parameter is carried out for period 1.08.2002 – 31.12.2008. Table A.9.2 shows different combination of parameters in this step: different values were given to the rain correction factor for different combinations of soil depths. Soil parameters were varying by multiplying the initial depth of soil parameters by a factor (the factor that multiplies "initial soil depths")

1	2	3	4
Rain correction=1.05 (1.15, 1.25) **Soil Depths:** **1)** 0.7* Initial depth **2)** 1.5* Initial depth **3)** 10*Initial depth	**Rain correction= 1.55 (1.25, 1.05)** **Soil Depths**: 1) 0.7*Initial depth 2) 0.7*Initial depth 3) 0.7*Initial depth	**Rain correction= 1.35** **Soil Depths**: 1) 0.7*Initial depth 2) 0.7***I**nitial depth 3) 0.7*Initial depth	**Rain correction= 1.15** **Soil Depths**: 1) 0.7*Initial depth 2) 0.7*Initial depth 3) 0.7*Initial depth

Table A.9.2 Initial combinations of parameters. Gauge correction and soil parameters involved on this step.

	1		2		3		4	
	R2	**RMSE**	**R2**	**RMSE**	**R2**	**RMSE**	**R2**	**RMSE**
2002	0.3162	0.9104	0.3806	0.8743	-0.0302	1.1431	0.1413	1.1239
2003	0.4860	1.0948	0.4844	1.0945	0.2380	1.3280	0.1821	1.6592
2004	0.4764	1.1068	0.5710	1.0010	0.1374	1.4202	0.2373	1.6096
2005	0.3297	1.2195	0.3854	1.1676	0.1932	1.3381	0.1788	1.6061
2006	0.7050	0.1476	0.7294	0.1414	0.5592	0.1803	0.2172	0.2759
2007	0.1241	1.2536	0.1960	1.2032	-0.081	1.3963	0.0949	1.6285
2008	0.2865	1.7668	0.3622	1.6698	0.2795	1.7749	0.1456	2.2629

Table A.9.3: results from the selection of the year that was under studying for the calibration. R2 and RMSE measure the good of fitness. Year 2006 got the better adjustment

VALIDATION PERIOD: ANNUAL VALUES

Long data series were given for this project. For the calibration it is not representative since there is a large hydrology variability, and parameters that measure the error wouldn't be representative neither. In this phase of the project, a year was choosen. Table A.9.3 shows the results of a yearly analysis of the data base. The year that best represents the reality is the year 2006, measured by R2 and RMSE. More information of thESE parameters is described in the Annexe 9: Calibration of the VIC model. Objective methods were applied in this step. Figure A.9.1 is an example of how objectives methods were applied:

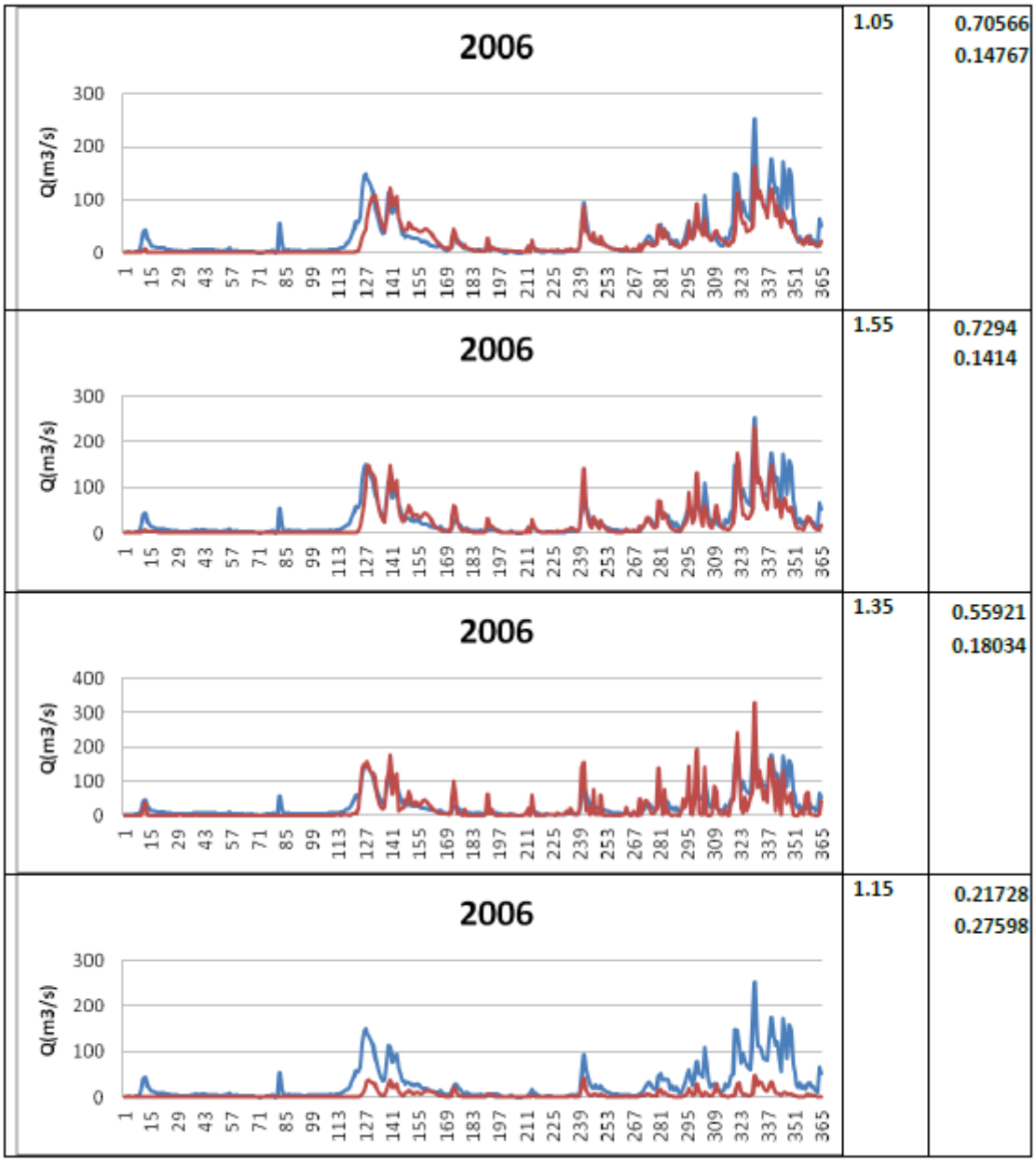


Figure A.9.1 represent different results for 2006 year. For four simulations Observed runoff (blue) and Qsimulated runoff(red) in m3/s were plotted or each day of the year (X axis). Rain correction factor value is located in the second column. Third column shows the values of R2 and RMSE

BASEFLOW PARAMETERS: Parameteres corresponding to baseflow are changed follwing different combinations. In order to predict a possible relation between Ws and Ds the some combinations were carried out. An example s represented on the table A.9.4:

Ws=0.93	**Ds=1**	**b**		**R2**	**RMSE**
		0.001		0.173913	28.65261
		0.4		0.265586	27.01219
	Ds=0.5	**b**		**R2**	**RMSE**
	outvic_0.4.A	0.001		0.14474	29.15479
	outvic_1.4.A	0.01		0.149094	29.08034
	outvic_4.4.A	0.3		0.225197	27.74615
	Ds=0.1	**b**		**R2**	**RMSE**
	outvic_0.1	0.001		0.194867	28.29007
	outvic_5.1	0.4		0.251372	27.29206
	Ds=0.01	**b**		**R2**	**RMSE**
	outvic_0.2	0.001		0.26332	27.0668
	outvic_1.2	0.01		0.265552	27.0257
	outvic_2.2	0.1		0.282071	26.71949
	outvic_5.2	0.4		0.236226	27.54717
	Ds=0.001	**b**		**R2**	**RMSE**
	outvic_0.3.A	0.001		0.27068	26.93223
	outvic_1.3.A	0.01		0.272847	26.89214
	outvic_2.3.A	0.1			
	outvic_4.3.A	0.3		0.302926	26.32859
	outvic_5.3.A	0.4		0.32875	26.11324

Table A.9.4: Different combinations of parameters at the initial phase of the calibration: Ws= 0.93, Ds=1, 0.5, 0.1, 0.01, 0.001. b values are located in the third column. Results of the adjustment, R2 and RMSE and located in columns 4 and 5 .

WATER BALANCE:

Table A.9.5 lists the variables that we find in water balance **output files:**

Column number	Parameter	Meaning
3	Out_prec	Precipitation , mm
4	Out_evap	Total net evaporation, mm
5	Out_runoff	Direct runoff (surface), mm
6	Out_baseflow	Subsurfacerunoff. Baseflow out from the bottom layer, mm
7	Out_delintercept	Change in canopy interception storage, mm
8	Out_delswe	Change in snow water equivalent, mm
9	Out_delsurfstor	Change in surface liquid storage, mm
10	Out_delsoilmoisture	Change in soil water content, mm
11	Out_Wdew	Total moisture interception storage in canopy, mm
12	Out_swe	Snow water equivalent in the snowpack, mm
13	Surfstor	
14	Soil moisture	
15	Soil moisture	
16	Soil moisture	

Table A.9.5: List of variables of the output files. The number of the column is located on the first column of the table, output variables are located in the second column, and the significance is in the third column. Marked variables are used for the water balance calculations.

And this is **the water balance**: (more information located in Annexe 3: VIC model overview)

P=Q + ET +Δsoil + Δswe ➔ Q= P - ET + Δsoil + Δswe

Where:
P = precipitation = out_prec
ET= evapotranspiration = out_evap
Q= total runoff = out_runoff + out_baseflow
Δsoil = out_delsoilmoisture
Δswe= out_delswe

Therefore, in **columns**: **[5] + [6] = [3] - [4] + [8] - [10]**

SOIL DEPTHS AND RAIN CORRECTION FACTOR: soil depths of the different soil moisture layer were modified and the rain correction factor simultaneously.

STUDY SENSITIVITY OF PARAMETERS: Procedure followed these steps:

- I set **case base**: this is the soil file without any change, when the soil layers have the same depth (Z1=Z2=Z3)
- I set **new case base**: after reading articles and seeking information on internet, I set the values to: Z1=0.1m ; Z2= 0.5m; and Z3=1.6 m
- Then I modified each parameter: +25% +10% -10% -25%

GAUGE CORRECTION FACTORS: this was an analysis based on correcting some mistakes from the first simulations. The effect of rain correction and snow correction factor was under study. It is in this analysis when I realized that rain correction factor does not have any influence on the results (it happens when option "5 snow/elevation bands" is activated). Table A.9.6 shows an example of the cases when rain correction factor didn't alter the results:

SOIL DEPTHS	RAIN CORRECTION	
Z1= 0.1 Z2=0.5 Z3=1.6	1.25 1.35 1.45 1.55 1.8 2	Same outputs
Z1=0.125 Z2=0.625 Z3=1.6	1.55 1.8	Same outputs
Z1=0.08 Z2=0.2 Z3=1.6	1.35 3.06	Same outputs

Table A.9.6: Different combinations when the outputs weren't altered by changing rain correction factor. For Three different combinations of soil parameters (first column), different values of rain correction factor were given (second column)

MONTHLY VALUES AND WATER BALANCE: monthly values and water balance were calculated for one simulation in order to make sure that different parts of the water balance(evaporation, runoff, precipitation, and the three soil moisture storage layers) were right and have values that are close to what it is expected is convenient to calculate it.

SOIL DEPTHS WITH OTHER PARTS OF WATER BALANCE:

These parameters were changed simultaneously. No conclusions were obtained since non organized schedule was followed.

- Z1 - Evapotranspiration
- Z2 - Runoff
- Z3 – Baseflow

The goal is appreciate possible trends for future simulations. Another point to mention is that monthly average values are not used in this study, what could be another reason why is not possible to appreciate any relevant information.

The most difficult part of the procedure is the evaluation of the difference between observed and simulated runoff, and decide which parameter(s) should be changed and how much

ANEXO 10: UPPER PARAMETERS ADJUSTMENT

This is the document that contents the upper layer parameters adjustment procedure and results. Though Z3 is the depth of the third soil layer, is also going to be adjusted in this block since Z2-Z3 interactions are going to be studied and best combinations are chosen. The procedure is focus on the following tasks:

Z2-Z3: INTERACTION AND SENSITIVITY

In order to study their sensitivity and interactions, various values are given while the rest of parameters have constant values as it is shown in Figure A.10.1:

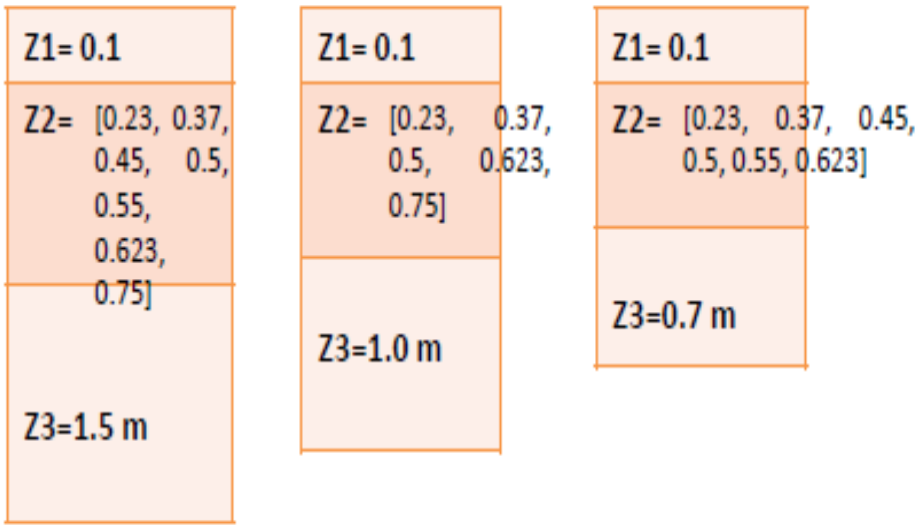


Figure A.10.1: Different combinations of Z2-Z3soil depths. Different values were given to Z2 when Z3 was set to 1.5, 1 and 0.7 meters. All the values are given in meters

After running simulations for these different combinations, we compare simulated results with observed values using the Nash Sutcliffe model efficiency. Figure A.10.2 shows some of the results:

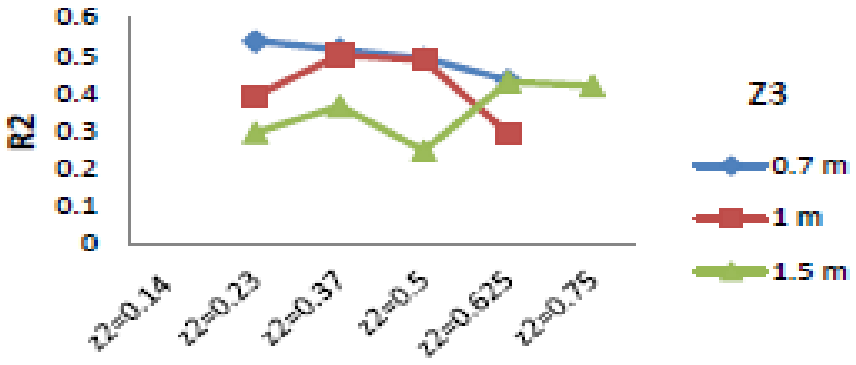
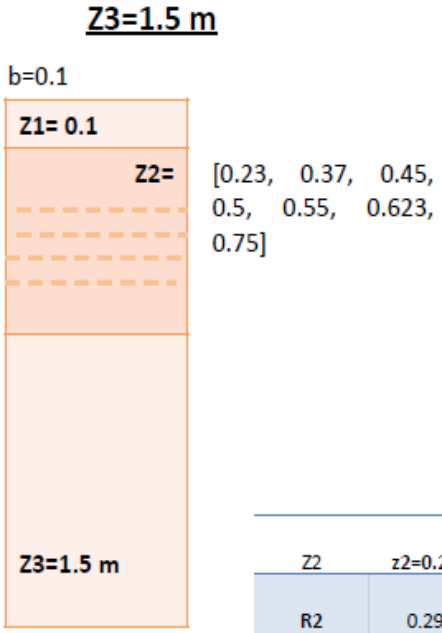
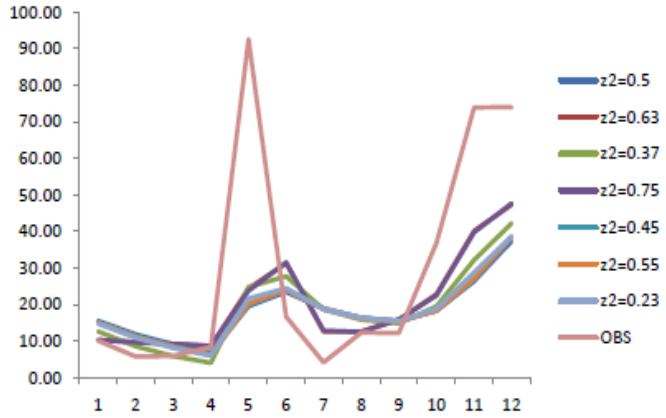


Figure A.10.2: R2 for different Z2-Z3 combinations. Y axis represents R2 and X axis the depth of the second layer in meters. R2 is calculated for different combinations when Z3=0.7, 1 and 1.5 meters. The general trend, is that thinner soil layers yields to better adjustment.

Figure A.10.2 Illustrate results for Z3= 1.5 m. The same analysis was made for Z3=1.0 and z3= 0.7. For all the cases b is set to 0.1 (given value, it is not adjusted yet). The figure has:

- A picture: represents the three soil layers.
- A graph: represents the total runoff, Q (m3/s) for the year (2006) for different values of Z2. Observed is plotted as well. It allows to a visual appreciation of the error.
- A table: give the results of the error calculations: R2 and RMSE.





Z2	z2=0.23	z2=0.37	z2=0.45	z2=0.5	z2=0.55	**z2=0.63**	0.75
R2	0.29	0.36	0.26	0.25	0.27	0.43	0.42
RMSE	27.37	25.86	28.08	28.35	27.93	24.17	24.40

Figure A.10.2: Analysis of Z2-Z3 interactions when Z3 is set to a constant value: 1.5 m. Z2 is set to 0.23, 0.37, 0.45, 0.5, 0.55, 0.63 and 0.75 meters. The marked case on the table is the best case.

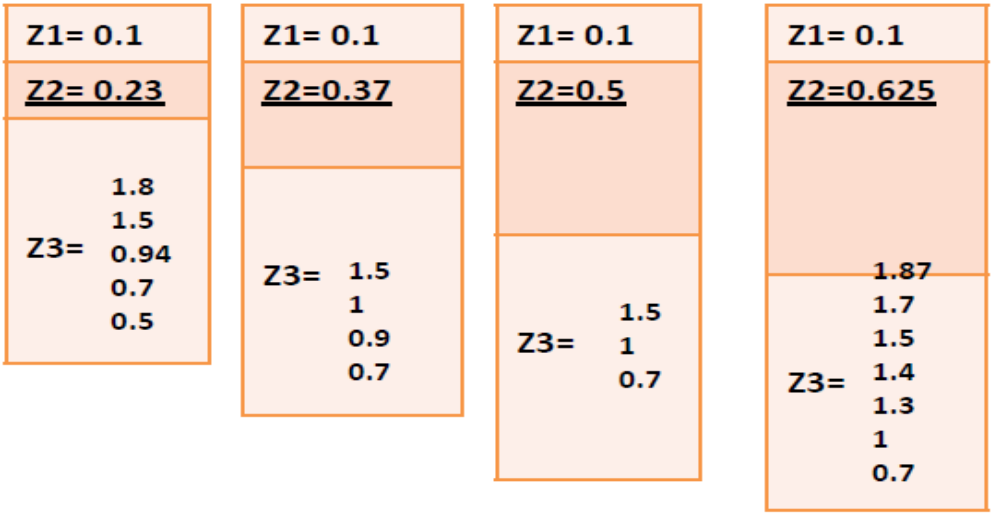
Best cases are selected as following and we can observe that in general, best results are obtained when layers are thinner, what has sense since it indicates that there is less transpiration from roots.

Cases are selected under R2 and RMSE criteria and thin layer yield better adjustment, though it is necessary to take into account that the thickness of each layer has to be

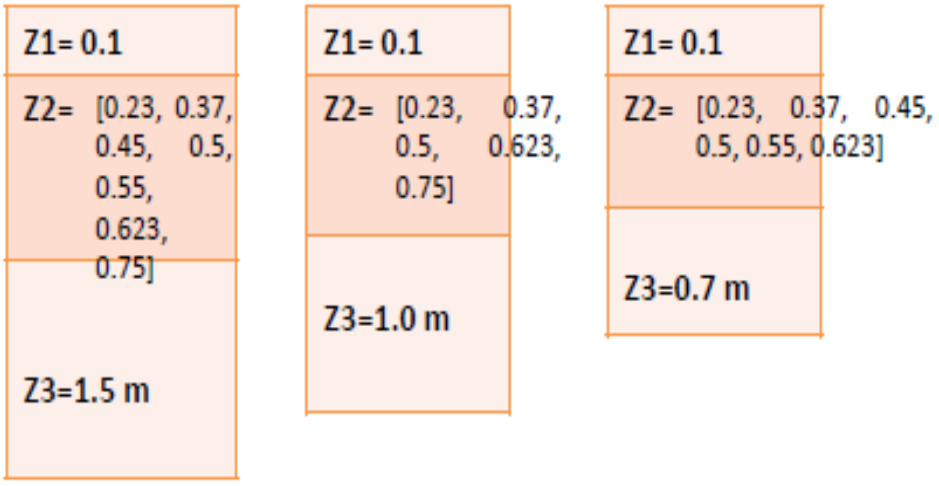
representative, what means that it has no sense to have, for example a layer with 0.14 m thickness.

SUMMARIZING RESULTS:

Results can have different interpretations. For analyze only the effect of Z2, you can take the view point from figure A.10.3.b (when only varies Z2 while keeping constant the rest of parameters). If you want to see the effect of Z3, you can take the view point from figure A.10.3 (a), when you can analyze the sensitivity of Z3. You can see how it varies when keeping constant the rest of parameters, for different cases.



(a)



(b)

Figure A.10.3: Representation of different soil layer depth combinations. (a) Represents the variation of z3 when keeping constant the rest of parameters. (b) represents the variation of Z2 while keeping constant the rest of parameters.

All the results are analyzed mainly by measuring the error with R2 parameters. Results for all combinations are summarized on the table A.10.1 and graph A.10.1

		Z3									
		1.8 m	1.6 m	1.5 m	1.4 m	1.3 m	1 m	0.94	0.9 m	0.7 m	0.5 m	0.18 m
Z2=	0.14 m											0.77
	0.23 m	0.46		0.29			0.39	0.39		0.54	0.58	
	0.37 m			0.36			0.48		0.49	0.52	0.55	
	0.5 m			0.25			0.47			0.49		
	0.625 m	0.22	0.43	0.43	0.43	0.44	0.29					
	0.75 m			0.42								

Table A.10.1: Table with the values of R2 for all the z2-z3 combinations. Z2 values are located on the first column. Z3 values are given on the first row.

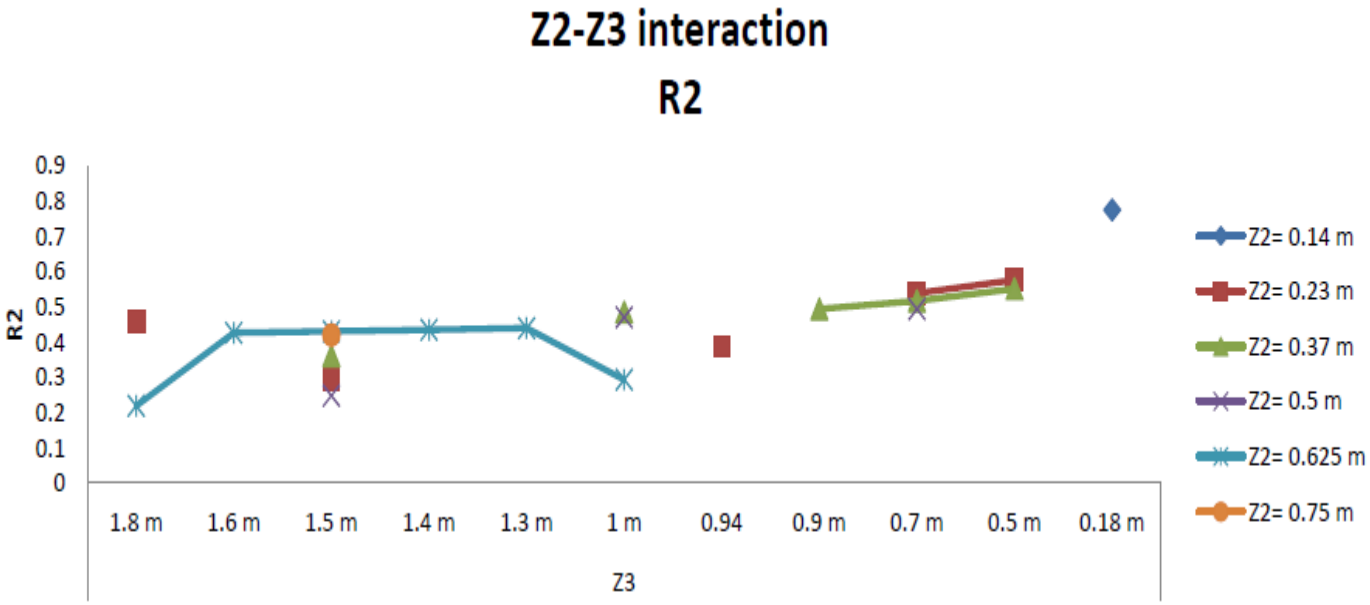


Figure A.10.4: Graph with R2 for different Z2-Z3 combinations

B_INFILTRATION ADJUSTMENT

B infiltration is the parameter that defines the shape of variable infiltration capacity curve. It describes the amount of available infiltration capacity as a function of relative saturated gridcell area. Higher values give lower infiltration and yields higher surface runoff.First a general overview is given to show how sensitive is this parameter, and b is set to 0.4 and 0.1 (taking into account the range of b [0-0.4] while keeping constant Z1= 0.1m and Z2=1.5 m). Graphic results are plotted on figure A.10.5: shows the effect of varying b for the same combinations of Z2-Z3. Simulated total runoff, Qsim and

Observed Q in m3/s are represented in both graphs. Y axis represents Q in m3/s and X axis the time period (year 2006).

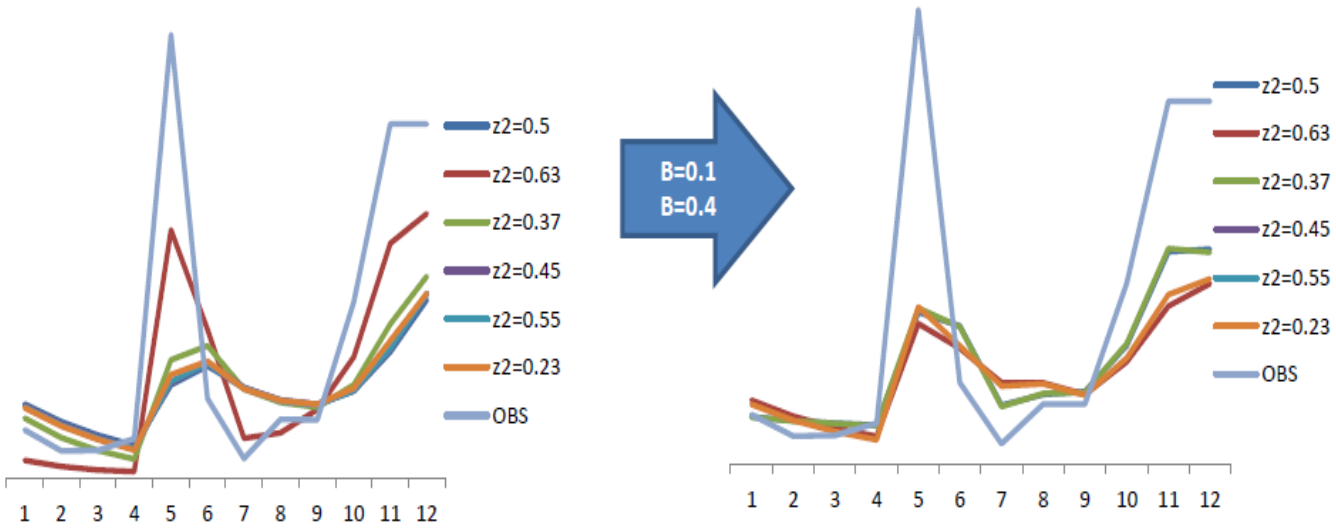


Figure A.10.5.Simulation results for b_infiltration parameter. B_intilt is set to 0.4 and 0.1

The next step is give different values to b, for different values of Z2 while keeping constant the rest of parameters. This is mainly because b_infiltration is a parameter that describes the behave of the upper layer, b_infil is studied for two different cases:
Z1=0.1, Z3=1.5, Z2= 0.23, 0.625
Graphic results of the error are on the table A.10.6:

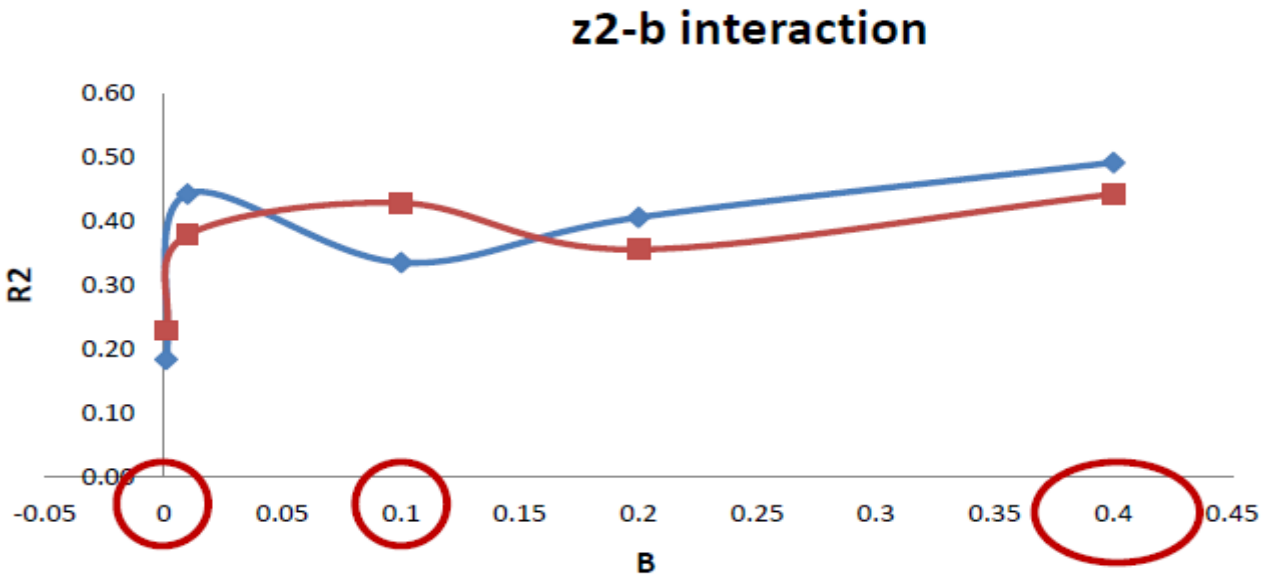
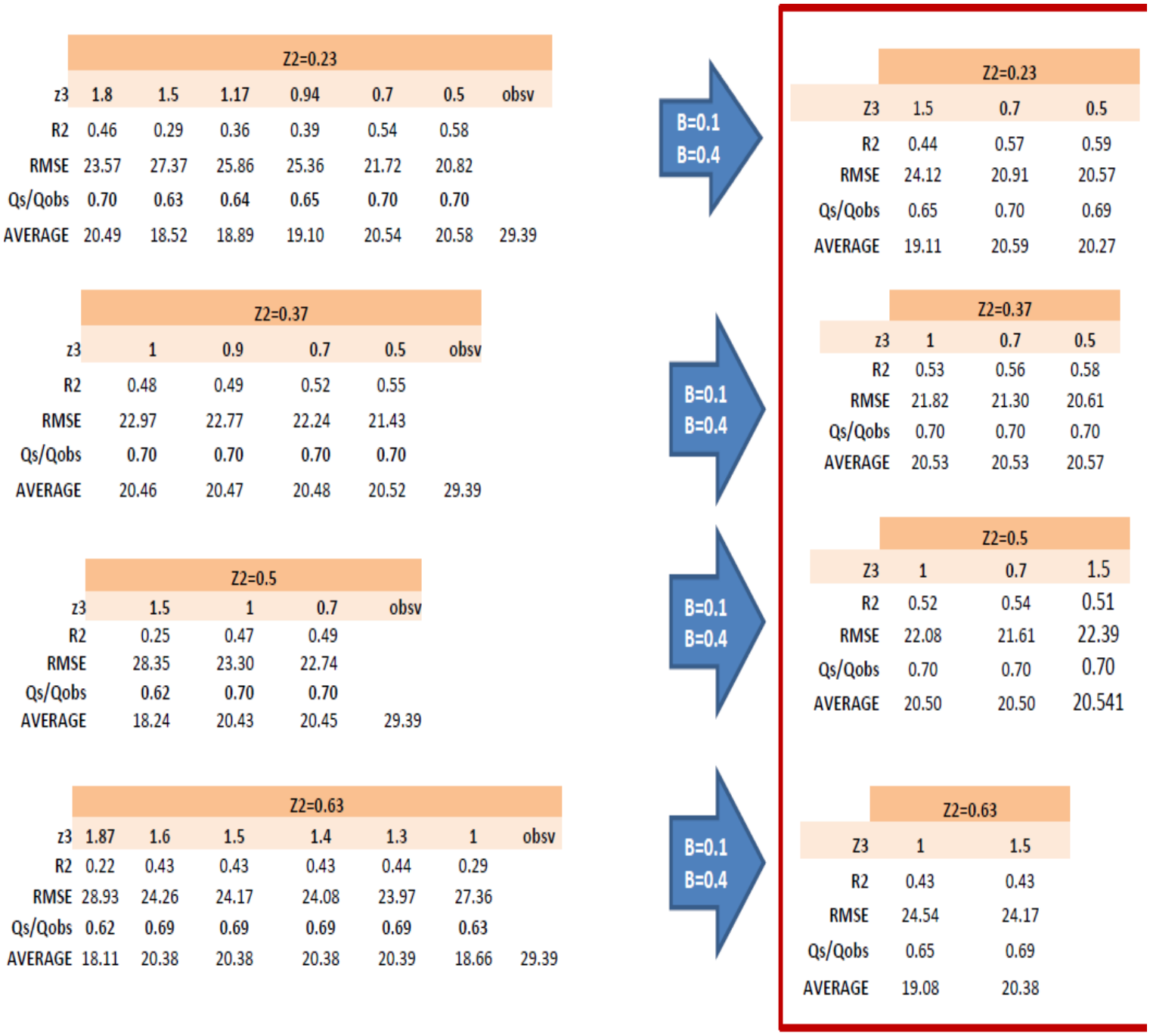


Figure A.10.6: Plot of the obtained error when varying the value of b_infiltration. Y axis

represents R and X axis B_intiltration. Two cases are represented: when z2=0.23 (blue line), when z2=0.625 (red line)

Until know, there has been proved that simulation results improve when b_infiltration is set to 0.4.

The next step is to run the simulations for all the cases (z2-z3 combinations) and analyze the results in order to make sure that b_infiltration must be set to 0.4. Comparisons of Qsimulated and Qobserved using R2 calibration is carried out. The results are shown on the figure A.10.7:



(b)

Figure A.10.7: Measurement and comparison of the different values of b_infiltration. Figure A.10.6 shows the value of R2 for all Z2-Z3 combinations when b=0.4. Figure (b) compares the results of the error when b is set to 0.1 and 0.4 for all the Z2-Z3 combinations. Figure b shows the results of other error parameters, such as RMSE and Qsimulated/ Qobserved, though the most representative is R2. R2 gets closer to 1 after setting b=0.4 for all the cases.

Figure A.10.7 shows the results of interest from the upper layer adjustment**.** Runoff and baseflow are also calculated. We are interested in the cases where maximun baseflow is obtained in order to get results as close as possible to observed values.
A coulple of cases are chosen for the best cases. Though these cases don't have the best adjustment results, they are more suitable: this combinations represents better the reality (it has no sense to set Z2= 0.23, it would be to thing as to represent a soil layer).There has to be a compromise between R2 and logical values of parameters. Selected best cases are:

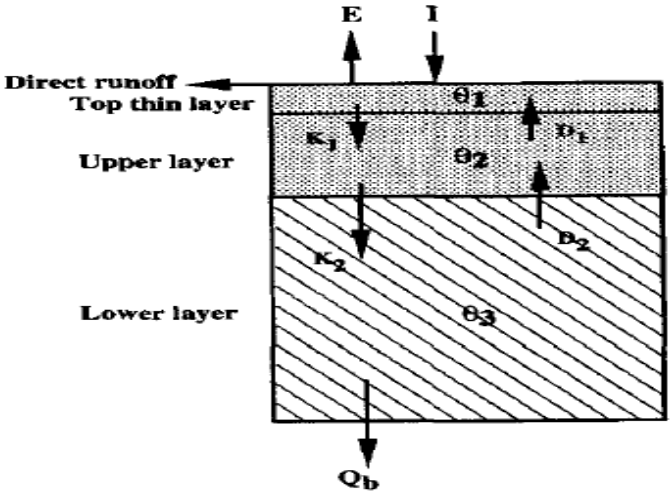
CASE 1	CASE 2
b_infil=0.4	B_infil=0.4
Z1=0.1 m	Z1=0.1 m
Z2=0.37 m	Z2=0.5 m
Z3=0.7 m	Z3=0.1 m

		Z3	**Q**		**runoff**	**baseflow**	**R2**	**RMSE**	**Qs/Qobs**	**Q,AVERAGE**
b=0.4	**Z2=0.23**	**1.5**	19.11		6.52	12.59	0.44	24.12	0.65	19.11
		0.7	20.59		6.58	14.01	0.57	20.91	0.70	20.59
		0.5	20.27		6.54	14.01	0.59	20.57	0.69	20.27
	Z2=0.37	**1.5**	20.57		6.30	14.27	0.52	22.16	0.70	20.53
		1	20.53		6.31	14.22	0.53	21.82	0.70	20.53
		0.7	20.53		6.32	14.21	0.56	21.30	0.70	20.53
		0.5	20.57		6.33	14.24	0.58	20.61	0.70	20.57
	Z2=0.5	**1.5**	20.54		6.17	14.38	0.51	22.39	0.70	20.54
		1	22.08		6.17	14.32	0.52	22.08	0.70	20.50
		0.7	20.50		6.18	14.32	0.54	21.61	0.70	20.50
	Z2=0.63	**1.5**	18.80		6.06	12.74	0.39	25.36	0.64	18.80
		1	19.08		6.06	13.02	0.43	24.54	0.65	19.08

Figure A.10.8: Results from upper layer parameters adjustment. Different combinations of Z2-Z3 when b_infilt=0.4. Error measurement results for R2, RMSE, Qobs/Qsimulated are located in the table

ANEXE 11: BASEFLOW PARAMETERS ADJUSTMENT

This annexe contains the process description and the results of the calibration of the baseflow parameters. The baseflow parameters are the parameters that describe the baseflow curve, which equation is shown on Figure A.11. The parameters that are calibrated in this section are: Ds, Ws, Dsmax. Figure A.11 illustrates the structure of the soil and baseflow equation. For more information go to the **Annexe 5: Input files**.



$$Qbaseflow = \frac{D_s \cdot D_{smax}}{W_s W_2^c} \cdot W_2$$

Figure A.11.Illutration of Soil structure. Soil is divided into three layer: top thin layer, upper layer and lower layer. There are two stream flows from the soil: direct runoff from the upper layer and baseflow, Qb from the bottom layer. Qb describes the response of the soil to hydrological processes and it is described by the baseflow curve.

The procedure is the following:

1. **Select cases from the first block adjustment.**
2. **Adjust Ws and Ds. Study Ds/Ws as one single parameter**
3. **Adjust Ds max**
4. **Repeat the process for the different combinations from the first block adjustment.**

STEP 1: Select cases from the first block adjustment.

From the adjustment of the upper layer parameters a couple of cases are selected in order adjust baseflow parameters for those combinations. First, the case when b=0.4, Z2=0.37 and Z3=0.7 is selected and we keep constant this values. This case is selected from the table A.11.1

The main purpose at this point, is to see how is possible to increase the baseflow stream flow.

FIRST BLOCK ADJUSTMENT

		Z3	Q	runoff	baseflow		R2	RMSE	Qs/Qobs	Q,AVERAGE
b=0.4	Z2=0.23	1.5	19.11	6.52	12.59		0.44	24.12	0.65	19.11
		0.7	20.59	6.58	14.01		0.57	20.91	0.70	20.59
		0.5	20.27	6.54	14.01		0.59	20.57	0.69	20.27
	Z2=0.37	1.5	20.57	6.30	14.27		0.52	22.16	0.70	20.53
		1	20.53	6.31	14.22		0.53	21.82	0.70	20.53
		0.7	**20.53**	**6.32**	**14.21**		**0.56**	**21.30**	**0.70**	**20.53**
		0.5	20.57	6.33	14.24		0.58	20.61	0.70	20.57
	Z2=0.5	1.5	20.54	6.17	14.38		0.51	22.39	0.70	20.54
		1	**22.08**	**6.17**	**14.32**		**0.52**	**22.08**	**0.70**	**20.50**
		0.7	20.50	6.18	14.32		0.54	21.61	0.70	20.50
	Z2=0.63	1.5	18.80	6.06	12.74		0.39	25.36	0.64	18.80
		1	19.08	6.06	13.02		0.43	24.54	0.65	19.08

Table A.11.1: Results from the first block adjustment. The selected case to proceed to the baseflow adjustment is marked. Selected cases: 1) b=0.4, Z2=0.37 and Z3=0.7 and 2) b=0.4, Z2=0.5 and Z3= 1 m.

First combination for baseflow adjustment:

Upper layer	**Baseflow parameters**
B=0.4	**Ws=0.93**
Z1=0.1 m	**Ds=0.1**
Z2=0.37 m	**Dsmax=30**
Z3= 0.7 m	

STEP 2: Adjust Ws and Ds. Study Ds/Ws as one single parameter

This step consists on running simulations with different combinations of Ws and Ds while keeping constant the rest of parameters (Dsmax =30). Ds and Ws are treated as one single parameter, Ds/Ws though It doesn't give any relevant information.

WS-DS COMBINATIONS:

Ws	Ds	Ds/Ws	R2	RMSE	Qs/Qo	Q	baseflow	Runoff	layer2
0.99	**0.9**	0.91	0.58	20.77	0.69	20.17	13.90	6.27	405.83
0.99	**0.01**	0.01	0.81	13.69	0.73	21.58	15.22	6.36	3232.12
0.99	**0.001**	0.00	0.83	13.20	0.74	21.63	15.28	6.36	3,266.63
0.93	**0.93**	1.00	0.60	20.37	0.69	20.29	14.02	6.27	377.82
0.93	**0.7**	0.75	0.55	21.53	0.68	19.95	13.68	6.27	468.69
0.93	**0.05**	0.05	0.67	18.16	0.72	21.12	14.79	6.33	2387.45
0.93	**0.01**	0.01	0.80	14.19	0.73	21.48	15.15	6.34	3078.34
0.93	**0.001**	0.00	0.81	13.70	0.73	21.55	15.21	6.34	3117.85
0.8	1	1.25	0.61	19.86	0.70	20.44	14.17	6.27	346.34
0.8	**0.6**	0.75	0.55	21.53	0.68	19.95	13.68	6.27	469.65
0.8	**0.05**	0.06	0.64	19.07	0.71	20.99	14.69	6.30	2117.27
0.8	**0.001**	0.00	0.77	15.11	0.73	21.35	15.04	6.30	2799.92
0.6	**0.6**	1.00	0.60	20.37	0.69	20.29	14.02	6.27	377.82
0.6	**0.001**	0.00	0.70	17.53	0.715	21.01	14.72	6.28	2317.69
0.4	**0.4**	1.00	0.60	20.37	0.69	20.37	14.46	5.90	386.95
0.4	**0.001**	0.00	0.63	19.46	0.70	20.68	14.41	6.28	1839.81
0.2	**0.15**	0.75	0.64	19.07	0.71	20.99	14.69	6.30	2117.27
0.2	**0.001**	0.01	0.58	20.77	0.69	20.40	14.13	6.27	1362.75
0.01	**0.9**	90.00	0.83	13.19	0.74	21.66	15.39	6.27	72.63
0.01	**0.001**	0.10	0.54	21.77	0.68	20.12	13.85	6.27	810.90

Table A.11.2: simulations for different combinations of Ds-Ws. To measure the adjustment, parameters R2, RMSE and Qs/Qo are calculated. The stream flows: Q, baseflow and runoff values are in m3/s units. Last column is the soil moisture storage in the second soil layer, in m3.

The most interesting combinations are the ones that yield best R2 adjustment. R2= 0.83 for both combinations, what it is a good adjustment.
Ws= 0.99, Ds= 0.001
Ws=0.01, Ds= 0.9

STEP 3: Adjust Ds max:

Though a good adjustment is obtained in the step 2 for a couple of combinations, other combinations are going to be under study in order to see the effect of Dsmax. Results are in the table A.11.3:

SELECTED CASES FOR Ds max adjustment										
Ws	**Ds**	**Ds/Ws**	**Dsmax**	**R2**	**RMSE**	**bias**	**Q**	**baseflow**	**Runoff**	**layer2**
0.99	**0.9**	0.91	**30**	0.58	20.77	0.69	20.17	13.90	6.27	405.83
			15	0.48	23.18	0.66	19.45	13.04	6.42	697.91
			5	0.63	19.44	0.70	20.37	11.46	5.88	1685.23
			0.10	0.83	12.92	0.75	21.97	0.49	21.49	3293.07
			0.001	0.84	12.63	0.75	22.04	0.00	22.03	3293.07

Ws	**Ds**	**Ds/Ws**	**Dsmax**	**R2**	**RMSE**	**bias**	**Q**	**baseflow**	**Runoff**	**layer2**
0.99	**0.001**	0.00	**30**	0.83	13.20	0.74	21.63	15.28	6.36	3,266.63
			15	0.80	14.05	0.74	21.62	14.17	7.45	3270.08
			10	0.77	15.15	0.73	21.48	12.84	8.64	3272.39
			5	0.71	17.06	0.71	20.80	9.73	6.27	3276.70
			0.10	0.64	19.07	0.71	20.99	0.49	21.49	3293.07
			0.001	0.84	12.63	0.75	22.04	0.00	22.03	3293.07

Ws	**Ds**	**Ds/Ws**	**Dsmax**	**R2**	**RMSE**	**bias**	**Q**	**baseflow**	**Runoff**	**layer2**
0.01	**0.9**	90.00	**30.00**	0.83	13.19	0.74	21.66	15.39	6.27	72.63
			25	0.83	13.22	0.74	21.65	15.38	6.27	75.71
			15	0.83	13.23	0.74	21.65	15.38	6.27	76.40
			5	0.82	13.39	0.74	21.63	15.36	6.27	89.69
			0.1	0.80	14.31	0.73	21.48	1.52	6.27	2166.14
			0.001	0.84	12.65	0.75	22.03	0.05	21.98	3293.07

Ws	Ds	Ds/Ws	Dsmax	R2	RMSE	bias	Q	Baseflow	Runoff	layer2
0.6	**0.6**	1.00	**30.00**	0.60	20.37	0.69	20.29	14.02	6.27	377.82
			15	0.49	22.96	0.66	19.49	13.12	6.38	646.80
			10	0.46	23.77	0.66	19.32	12.56	6.76	898.54
			0.1	0.83	12.92	0.75	21.97	0.49	21.49	3293.07
			0.001	0.84	12.65	0.75	22.03	0.05	21.98	3293.07

Ws	Ds	Ds/Ws	Dsmax	R2	RMSE	bias	Q	Baseflow	Runoff	layer2
0.4	**0.4**	1.00	**30.00**	0.60	20.37	0.69	20.29	14.02	6.27	377.82
			15	0.49	23.03	0.66	19.39	10.96	6.50	1367.32
			0.001	0.84	12.65	0.75	22.03	0.05	21.98	3293.07

Table A.11.3: Dsmax adjustment results. To measure the adjustment, parameters R2, RMSE and Qs/Qo are calculated. The stream flows: Q, baseflow and runoff values are in m3/s units. Last column is the soil moisture storage in the second soil layer, in m3.

It is observable that Dsmax=0.001 gives always the best results, and gives always the same results (no matter which Ds-Ws combinations are chosen) which is R2= 0.84. When Dsmax= 0.001 there is no baseflow (the maximum value of runoff is 0.001) and all the streamflow comes from the upper layer runoff (you can see it on the table). For these cases, Ws and Ds loose effect.

STEP 4: Repeat the process for the different combinations from the first block adjustment:

STEP 1: Select cases from the first block-→ second case

From the adjustment of the upper layer parameters a couple of cases are selected in order adjust baseflow parameters for those combinations. Now the case b=0.4, Z2=0.5 and Z3=1 meter is selected and we keep constant this values. Both selected cases are shown in the table A.11.4

FIRST BLOCK ADJUSTMENT:

		Z3	Q	runoff	Baseflow	R2	RMSE	Qs/Qobs	Q,AVERAGE
b=0.4	**Z2=0.23**	**1.5**	19.11	6.52	12.59	0.44	24.12	0.65	19.11
		0.7	20.59	6.58	14.01	0.57	20.91	0.70	20.59
		0.5	20.27	6.54	14.01	0.59	20.57	0.69	20.27
	Z2=0.37	**1.5**	20.57	6.30	14.27	0.52	22.16	0.70	20.53
		1	20.53	6.31	14.22	0.53	21.82	0.70	20.53
		0.7	20.53	6.32	14.21	0.56	21.30	0.70	20.53
		0.5	20.57	6.33	14.24	0.58	20.61	0.70	20.57
	Z2=0.5	**1.5**	20.54	6.17	14.38	0.51	22.39	0.70	20.54
		1	22.08	6.17	14.32	0.52	22.08	0.70	20.50
		0.7	20.50	6.18	14.32	0.54	21.61	0.70	20.50
	Z2=0.63	**1.5**	18.80	6.06	12.74	0.39	25.36	0.64	18.80
		1	19.08	6.06	13.02	0.43	24.54	0.65	19.08

Table A.11.4: Results from the first block adjustment. The selected case to proceed to the baseflow adjustment is marked. Second selected case: b=0.4, Z2=0.5 and Z3=1 meter.

Second combination for the adjustment of baseflow parameters:

Upper layer	Baseflow parameters
B=0.4	**Ws=0.93**
Z1=0.1 m	**Ds=0.1**
Z2=0.5 m	**Dsmax=30**
Z3= 1 m	

STEP 2: Adjust Ws and Ds.

This step consists in running simulations with different combinations of Ws and Ds while keeping constant Dsmax (Dsmax =30). The combinations that best fit the model are selected in order to adjust Dsmax. Ds/Ws is also calculated, though this "parameter" is not relevant

WS-DS COMBINATIONS:

Ws	Ds	Ds/Ws	R2	RMSE	Qs/Qo	Q	baseflow	Runoff	layer2
0.99	**0.99**	1.00	0.52	22.41	0.67	19.72	13.58	6.14	525.88
0.99	**0.40**	0.40	0.42	24.57	0.65	19.09	12.94	6.15	1084.87
0.99	**0.1**	0.10	0.52	22.18	0.67	19.80	13.66	6.14	502.19
0.99	**0.001**	0.00	0.80	14.24	0.73	21.46	15.25	6.21	4633.38
Ws	**Ds**	**Ds/Ws**	**R2**	**RMSE**	**Qs/Qo**	**Q**	**baseflow**	**Runoff**	**layer2**
0.93	**0.99**	1.06	0.52	22.18	0.67	20.32	14.54	5.75	528.25
0.93	**0.93**	1.00	0.52	22.41	0.67	19.72	13.58	6.14	525.88
0.93	**0.001**	0.00	0.78	14.72	0.73	21.38	15.19	6.19	4457.67
Ws	**Ds**	**Ds/Ws**	**R2**	**RMSE**	**Qs/Qo**	**Q**	**baseflow**	**Runoff**	**layer2**
0.6	**0.99**	1.65	0.59	20.46	0.69	20.33	14.19	6.14	369.07
0.6	**0.8**	1.33	0.56	21.32	0.68	20.07	13.93	6.14	427.26
0.6	**0.6**	1.00	0.52	22.41	0.67	19.72	13.58	6.14	525.88
0.6	**0.1**	0.17	0.48	23.15	0.68	20.15	14.32	5.83	1946.84
0.6	**0.001**	0.00	0.61	19.92	0.701	20.61	14.46	6.15	3322.24
Ws	**Ds**	**Ds/Ws**	**R2**	**RMSE**	**Qs/Qo**	**Q**	**baseflow**	**Runoff**	**layer2**
0.4	**0.99**	2.48	0.65	18.75	0.71	20.78	14.64	6.14	284.52
0.4	**0.6**	1.50	0.58	20.85	0.69	20.21	14.07	6.14	525.88
0.4	**0.4**	1.00	0.52	22.41	0.67	19.72	13.58	6.14	525.88
0.4	**0.001**	0.00	0.54	21.64	0.69	20.21	14.07	6.14	2642.77
Ws	**Ds**	**Ds/Ws**	**R2**	**RMSE**	**Qs/Qo**	**Q**	**baseflow**	**Runoff**	**layer2**
0.2	**0.99**	4.95	0.50	22.65	0.68	20.17	14.36	5.80	1952.76
0.2	**0.6**	3.00	0.68	17.97	0.71	20.35	14.60	5.75	253.28
0.2	0.2	1.00	0.52	22.41	0.67	19.72	13.58	6.14	525.88

0.2	**0.001**	0.00	0.50	22.65	0.68	19.90	13.76	6.14	1963.18
Ws	**Ds**	**Ds/Ws**	**R2**	**RMSE**	**Qs/Qo**	**Q**	**baseflow**	**Runoff**	**layer2**
0.001	**0.99**	990.00	0.81	13.75	0.73	21.54	15.39	6.14	98.87
0.001	**0.4**	400.00	0.81	13.76	0.73	21.54	15.26	6.11	133.36
0.001	**0.1**	100.00	0.81	13.81	0.73	21.53	15.39	6.14	103.23
0.001	**0.001**	1.00	0.52	22.41	0.67	19.72	13.58	6.14	525.88

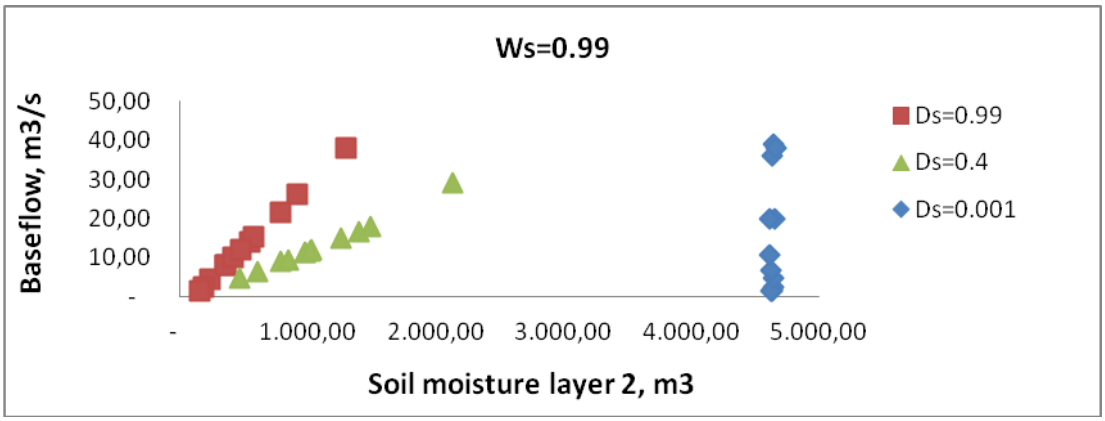
Table A.11.5: Simulations for different combinations of Ds-Ws. To measure the adjustment, parameters R2, RMSE and Qs/Qo are calculated. The stream flows: Q, baseflow and runoff values are in m3/s units. Last column is the soil moisture storage in the second soil layer, in m3.

Best combinations are:

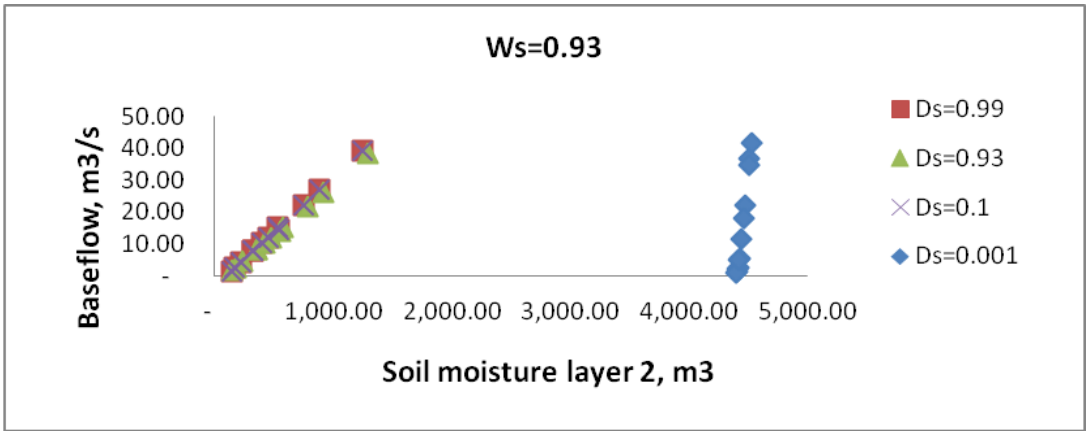
Ws= 0.99 Ds=0.001

Ws= 0.001 and Ds= 0.99

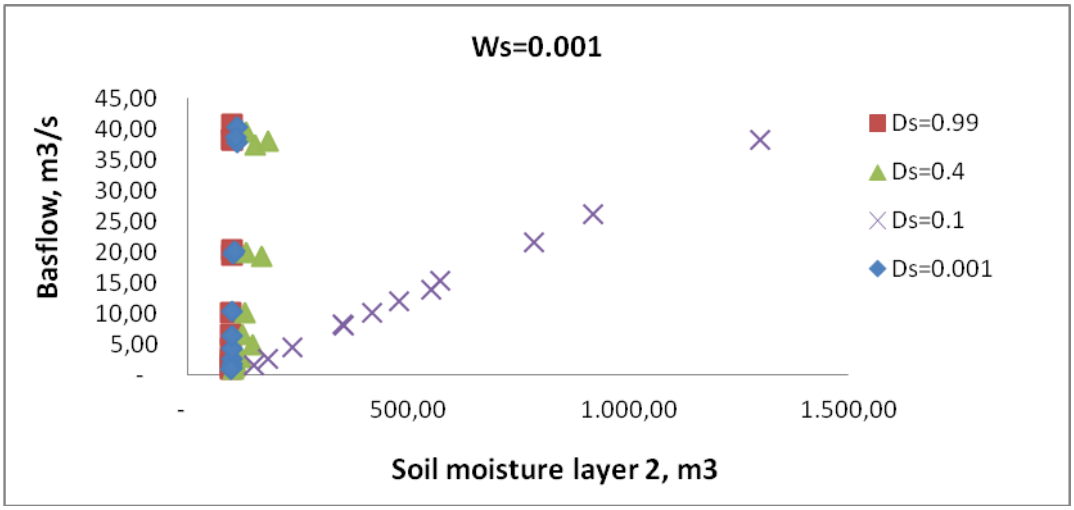
For these combinations: R2= 0.8 and R2= 0.81 respectively. This is a good adjustment. (larger than 0.8). Though this is a good adjustment, we can see that best results were obtained on the first case, when R= 0.83. Thicker soil layers give worse adjustment. (for a better understanding of this conclusion go to “Annexe 10: Upper layer adjustment”). The baseflow curve is represented. Best casses are shown in figure A.11.15.



(a)



(b)



(c)

Figure A.11.5 from (a) to (b) is the baseflow curve for different combinations from the table A.11.5.

STEP 4: Adjust Ds max

Though a good adjustment is obtained in the step two for a couple of combinations, other combinations are going to be under study in order to see the effect of Dsmax. Results are in the table A.11.6:

SELECTED CASES for Ds max adjustment										
Ws	**Ds**	**Dsmax**	**R2**	**RMSE**	**Qs/Qo**	**Q**	**baseflow**	**Runoff**	**layer2**	**EVAP**
0.99	**0.001**	**30**	0.80	14.24	0.73	21.46	15.25	6.21	4633.38	4.14
		20	0.80	14.25	0.73	21.49	14.92	6.57	4671.27	4.14
		10	0.73	16.52	0.72	21.18	13.04	8.14	4676.66	4.14
		0.001	0.84	12.69	0.75	22.03	0.00	22.02	4704.39	4.15

Ws	**Ds**	**Dsmax**	**R2**	**RMSE**	**Qs/Qo**	**Q**	**baseflow**	**Runoff**	**layer2**	**EVAP**
0.001	**0.00**	**30**	0.81	13.75	0.73	21.54	15.39	6.14	98.87	4.13
		20	0.81	13.75	0.73	21.54	15.39	6.14	99.12	4.13
		10	0.81	13.76	0.73	21.53	15.39	6.14	99.85	4.13
		0.001	0.84	12.69	0.75	22.03	0.00	22.02	4704.39	4.15

Table A.11.6: Dsmax adjustment results. To measure the adjustment, parameters R2, RMSE and Qs/Qo are calculated. The stream flows: Q, baseflow and runoff values are in m3/.Last column is the soil moisture storage in the second soil layer, in m3.

It is observable that Dsmax=0.001 gives always the best results, as in the first case. It gives always the same results (no matter which Ds-Ws combinations are chosen) which is R2= 0.84, the same that in the first case. This is because when Dsmax= 0.001 there is no baseflow (the maximum value of runoff is 0.001) and all the streamflow comes from the upper layer runoff (you can see it on the table). For these cases, Ws and Ds loose effect.

ANEXE 12: FINAL ADJUSTMENT

In this step, a fine adjustment is done. Small variations are made to the best combinations of parameters with the purpose of making sure that there are no better options.

For the case:

Ds max was changed in small amounts. Results are on the table A.12.1**:**

Upper layer	Baseflow parameters
B=0.4	**Ws=0.99**
Z1=0.1 m	**Ds=0.1**
Z2=0.5 m	**Dsmax=0.001**
Z3= 1 m	

Ds max was changed in small amounts. Results are on the table A.12.1**:**

Ws	Ds	Dsmax	R2	RMSE	Qs/Qo	Q	Baseflow	Runoff	layer2
		0.05	0.84	12.83	0.75	22.00	0.24	21.75	4704.39
0.99	**0.001**	**0.001**	0.84	12.69	0.75	22.03	0.00	22.02	4704.39
		0.005	0.84	12.70	0.75	22.03	0.02	22.00	4704.39

Ws	Ds	Dsmax	R2	RMSE	Qs/Qo	Q	baseflow	Runoff	layer2
		0.05	0.73	16.44	0.71	20.94	14.84	6.10	1475.70
0.001	**0.99**	**0.001**	0.84	12.69	0.75	22.03	0.00	22.02	4704.39
		0.005	0.82	13.40	0.74	21.86	0.64	21.21	3747.76

Table A.12.1: Results of the final adjustment. Variations of Ds max don't improve the results (R2 does not increase)

Z3 parameter was also changed, while baseflow parameters were kept constant with the following values:

Lower layer:

Ws= 0.99, Ds= 0.001, Dsmax= 0.001

Ws= 0.001, Ds= 0.99, Dsmax= 0.001

For some of the combinations from the upper layer, Z3 was changed. Different combinations with the results are located on the table A.12.2:

				Ws	Ds	Dsmax	Ws	Ds	Dsmax
				0.99	0.001	0.00	0.001	0.99	0.00
Z1	Z2	Z3	B	R2	RMSE	bias	R2	RMSE	bias
0.1	0.37	0.7	0.4	0.83	12.72	0.74	0.84	12.63	0.75
		1		0.84	12.63	0.75	0.84	12.63	0.75
		1.5		0.84	12.63	0.75	0.84	12.64	0.75
Z1	Z2	Z3	B	R2	RMSE	bias	R2	RMSE	bias
0.1	0.5	1	0.4	0.84	12.69	0.75	0.84	12.69	0.75
		0.7		0.81	13.82	0.73	0.84	12.69	0.75
		1.5		0.84	12.69	0.75	0.84	12.69	0.75
Z1	Z2	Z3	B	R2	RMSE	bias	R2	RMSE	bias
0.1	0.23	0.5	0.4	0.84	12.54	0.75	0.84	12.54	0.75
		0.7		0.84	12.54	0.75	0.84	12.54	0.75
		1.5		0.84	12.54	0.75	0.84	12.54	0.75
Z1	Z2	Z3	B	R2	RMSE	bias	R2	RMSE	bias
0.1	0.63	1	0.4	0.84	12.73	0.75	0.84	12.73	0.75
		1.5		0.84	12.73	0.75	0.84	12.73	0.75

Table A.12.2: Different combinations for the final adjustment and results. Four different combinations of upper layer parameters (yellow) with two different combinations of the baseflow: pink color (Ws=0.99, Ds= 0.001, Ds max= 0.001 and Ws=0.001, Ds=0.99, Ds max=0.001). In all the cases, variations of Z3 don't yield to better results.

ANEXE 13. GEOGRAPHYC STUDY AREA: SKJERKA

In this project, VIC model is applied to a watershed called “Skjerka”, a region located in the south of Norway. Some of the characteristics of Skjerka are the following:

- AREA= 425 Km2
- Lake fraction= 0.15
- Average Elevation: 460 meters
- Time Zone: Europe/Oslo

A river in this area is named Skjerka as well: it is a stream located in the southern part called Vest-Agder of Norway (Europe).It is located at an elevation of 460 meters above sea level. The area center is represented like a point, the “center point” which coordinates are 58°34'60" N and 7°24'0" E in DMS (Degrees Minutes Seconds) or 58.5833 and 7.4 (in decimal degrees).
Some of the components of this area are in the table below:

	Name	country	feature	km to center
1	Skjerka	Norway	stream	0.04 km
2	Ørevatnet	Norway	lake	0.04 km
3	Fiskland	Norway	farms	1.82 km
4	Åsland	Norway	populated place	1.89 km
5	Kyrkjebygda	Norway	seat of a second-order administrative division	3.67 km
6	Madland	Norway	populated place	3.79 km
7	Kylland	Norway	populated place	3.79 km
8	Logna	Norway	stream	3.87 km
9	Åseral	Norway	populated place	3.87 km
10	Kyrkjebygdi	Norway	populated place	3.87 km
11	Åseral	Norway	second-order administrative division	3.87 km
12	Handeland	Norway	farms	4.27 km

13	Tveit	Norway	populated place	4.27 km
14	Nåvatnet	Norway	Lake	4.3 km
15	Hagedalsvatnet	Norway	Lake	5.16 km
16	Storavatnet	Norway	Lake	5.33 km
17	Sågja	Norway	Farm	5.38 km
18	Ekså	Norway	Farms	6.76 km
19	Dyrvatnet	Norway	Lake	6.76 km
20	Snøfjell	Norway	Mountain	7.7 km

The study area in this project is described as a Catchment where the VIC model is applied.

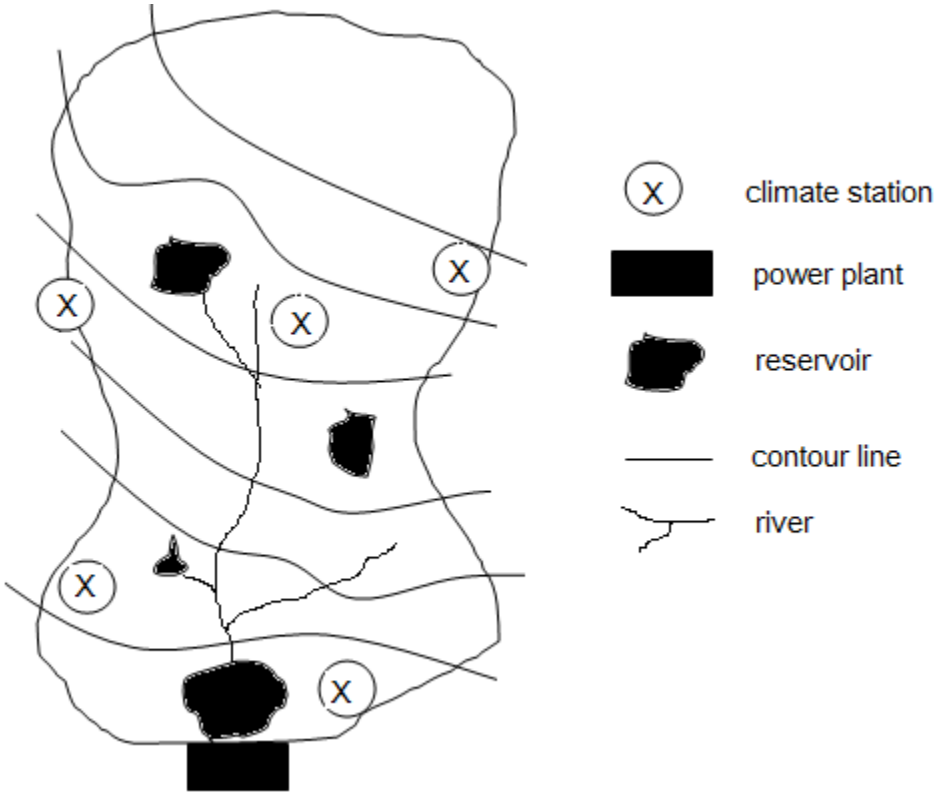


Figure A.13.1. Catchment illustration

Figure A.13.1 Illustrates a catchment (in our case Skjerka). A catchment is a closed area,(the area is then divided into 160 cells). The climate stations are in and around the catchment at different height in terrain, and provide the observation data to compare with the weather forecasts. The stream flow (water runoff) may take different paths (and depths in the ground), before it generally pour into the rivers and end up in the reservoir. Then the power plant uses the runoff to produce electricity.

THE WEATHER STATIONS NEAR AND INSIDE THE CATCHMENT

In the Skjerka catchment the weather forecast is compared with the 6 meteorological measuring stations. They are named after the closest place or lake. There is Juvann, Langevann, Navann, Orevann, Sjavasskn and Storevatn.One important thing to remember, is that the weather forecasting positions in Skjerka is not necessarily identical with the weather measuring positions or representative as an average for the area. We have chosen to compare with the weather forecast for each station based on geographic coordinates, but there could be local variations in height above sea level etc.
Therefore some calibration is needed, and the meteorological data which is used as input into VIC model is not exactly as the local conditions even with a good forecast for that position. Due to this situation, some extra uncertainty is added to the meteorological forecasting data.

SKJERKA LOOKED UPON AS A GRID CELL

The land surface of Skjerka is modelled as a grid of large (>1km), flat, uniform cells. A list of the main features of the grid cell is the following:

- Sub-grid heterogeneity (e.g. elevation, land cover) is handled via statistical distributions.
- Inputs are time series of daily or sub-daily meteorological drivers (e.g. precipitation, air temperature, wind speed).
- Land-atmosphere fluxes, and the water and energy balances at the land surface, are simulated at a daily or sub-daily time step.
- Through the grid cell, water can only enter a grid cell via the atmosphere.
- Another characteristic is that non-channel flow between grid cells is ignored.
- Once water reaches the channel network, it is assumed to stay in the channel (it cannot flow back into the soil)

This last point has several consequences for VIC model implementation: **Grid cells are simulated independently of each other**. **Entire simulation is run for each grid cell separately, 1 grid cell at a time**, rather than, for each time step, looping over all grid cells. Meteorological input data for each grid cell (for the entire simulation period) are read from a file specific to that grid cell. Time series of output variables for each grid cell (for the entire simulation period) are stored in files specific to that grid cell. In Skjerka, grid system is formed by 160 uniform and flat cells. Each cell is represented by

it coordinates as it is shown in the table below. Coordinates are the center of the cell. The table below shows the 160 cells of Skjerka: each cell has a number, and latitude and longitude coordinates as following:

LOCALIZATION OF THE CELLS IN SKJERKA:

cell	lat	long	cell	lat	long
39136	58.99	7.27	80785	58.87	7.33
28721	58.99	7.29	94282	58.87	7.35
16138	58.97	7.21	54162	58.87	7.37
74245	58.97	7.23	67951	58.87	7.39
84451	58.97	7.25	42915	58.85	7.25
58759	58.97	7.27	58802	58.85	7.27
69288	58.97	7.29	64135	58.85	7.29
27916	58.97	7.31	71441	58.85	7.31
63764	58.95	7.21	58384	58.85	7.33
26655	58.95	7.23	2861	58.85	7.35
55144	58.95	7.25	10427	58.85	7.37
52254	58.95	7.27	40996	58.85	7.39
7686	58.95	7.29	8734	58.85	7.41
44080	58.95	7.31	44952	58.85	7.43
94753	58.93	7.23	58010	58.83	7.25
9901	58.93	7.25	28640	58.83	7.27
71260	58.93	7.27	78206	58.83	7.29
64948	58.93	7.29	16394	58.83	7.31
64813	58.93	7.31	90768	58.83	7.33
35890	58.93	7.33	55641	58.83	7.35
19631	58.93	7.35	21159	58.83	7.37
4918	58.93	7.37	82487	58.83	7.39
9694	58.91	7.27	20138	58.81	7.23
14305	58.91	7.29	89628	58.81	7.25
82847	58.91	7.31	4379	58.81	7.27
21563	58.91	7.33	78108	58.81	7.29
62342	58.91	7.35	68708	58.81	7.31
918	58.91	7.37	37572	58.79	7.21
16316	58.91	7.39	45037	58.79	7.23
65529	58.91	7.41	53817	58.79	7.25
65717	58.91	7.43	67932	58.79	7.27
42687	58.89	7.25	76076	58.79	7.29
20407	58.89	7.27	791	58.79	7.31
63873	58.89	7.29	27403	58.77	7.21
89380	58.89	7.31	62029	58.77	7.23
33977	58.89	7.33	999	58.77	7.25
68019	58.89	7.35	59342	58.77	7.27
26160	58.89	7.37	36246	58.77	7.29
60223	58.89	7.39	10239	58.77	7.31

85590	58.87	7.25	44842	58.77	7.33
245	58.87	7.27	64611	58.75	7.15
71301	58.87	7.29	75509	58.75	7.17
64366	58.87	7.31	72173	58.75	7.19

cell	lat	long	cell	lat	long
53369	58.75	7.21	66339	58.67	7.25
32498	58.75	7.23	77535	58.67	7.27
18830	58.75	7.25	39756	58.67	7.29
59561	58.75	7.27	33741	58.67	7.31
45974	58.75	7.29	44672	58.67	7.33
47316	58.75	7.31	38144	58.67	7.35
25267	58.75	7.33	28010	58.65	7.25
36627	58.73	7.17	14859	58.65	7.27
10813	58.73	7.19	47703	58.65	7.29
53368	58.73	7.21	42185	58.65	7.31
40815	58.73	7.23	55303	58.65	7.33
51294	58.73	7.25	29322	58.65	7.35
20309	58.73	7.27	87328	58.65	7.37
30931	58.73	7.29	20642	58.63	7.27
3993	58.73	7.31	81662	58.63	7.29
76078	58.73	7.33	8112	58.63	7.31
14275	58.73	7.35	42330	58.63	7.33
48759	58.73	7.37	64221	58.61	7.27
69644	58.71	7.17	20496	58.61	7.29
11434	58.71	7.19	18401	58.61	7.31
72971	58.71	7.21	78703	58.61	7.33
62645	58.71	7.23	21458	58.59	7.25
68614	58.71	7.25	2695	58.59	7.27
63441	58.71	7.27	85028	58.59	7.29
18493	58.71	7.29	30290	58.59	7.31
88512	58.71	7.31	43544	58.59	7.33
44275	58.71	7.33	33932	58.57	7.29
54668	58.71	7.35	14604	58.57	7.31
93937	58.71	7.37	87455	58.67	7.23
83733	58.69	7.15	92890	58.67	7.21
90724	58.69	7.17			
15393	58.69	7.19			
49598	58.69	7.21			
35956	58.69	7.23			
42783	58.69	7.25			
79348	58.69	7.27			
39662	58.69	7.29			
30263	58.69	7.31			
90577	58.69	7.33			
9594	58.69	7.35			

67293	58.69	7.37
17676	58.67	7.15
53964	58.67	7.17
37515	58.67	7.19

C. MAPS AND ROUTES

In this project, VIC model is applied to a watershed called “Skjerka”, a region located in the south of Norway. Figure C.1 Illustrates the location of Skjerka in Norway :



Figure C.1 Illustration of Skjerka location in Norway.



Figure C.2: Illustration of Skjerka

In figure C.3 some meteorological stations (where the meteorological measurements are taken). They are located in lakes and the names of the lakes are given to them. They are called Juvant, Orevan and Langevan. Red point is where the power station name Skjerka, and the river are located.

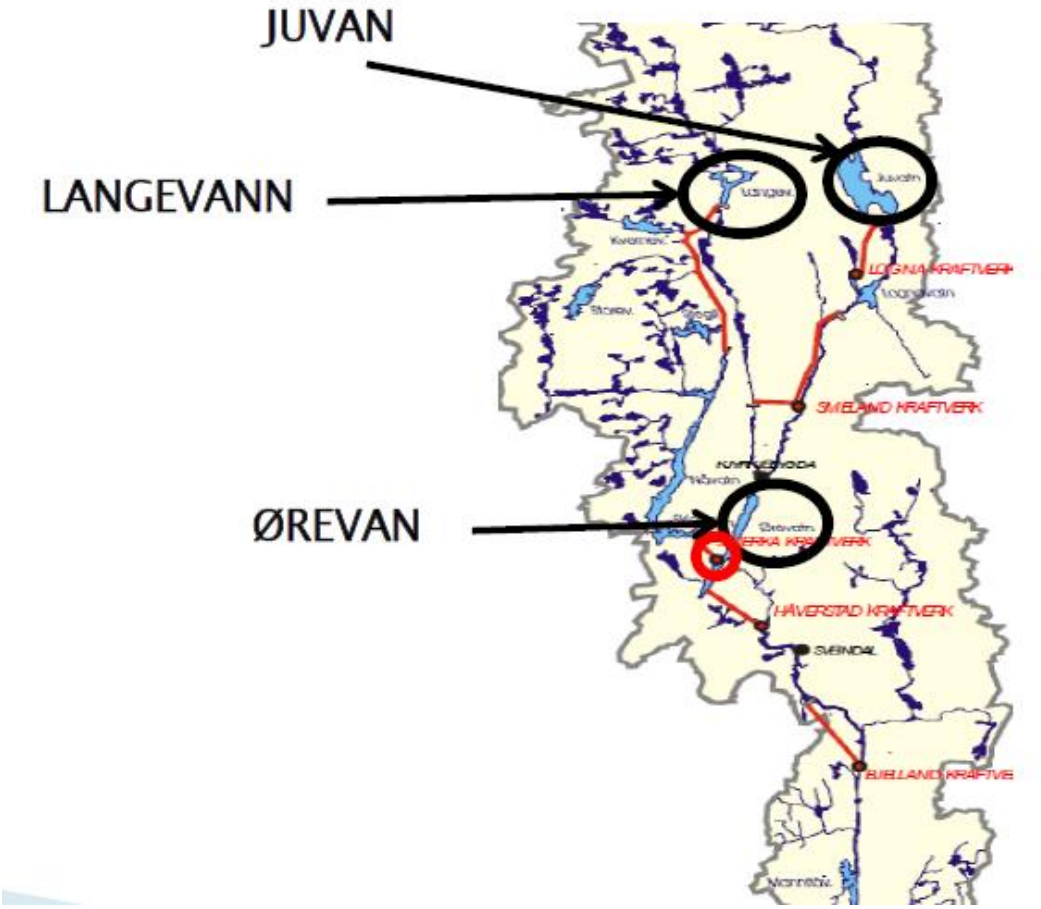


Figure C.3: Map of Skjerka. Meteorological stations are located in the map: Juvan, Langevann, and Orevan. The hydropower and river named Skjerka are located in the red point. It represents the “center point” of the region.

D. TECHNICAL SPECIFICATIONS

ASSUMPTIONS AND LIMITATIONS

The forecast and observation data are provided by Agder Energy A/S and the results apply to a possible practical implementation.
There was some limitation in data sets: Originally I had data from 01/08/2002 until 16/02/2010. Unfortunately, there were periods of data missing, so the VIC forecast is can run on data period of 1/08/2002 to 31/12/2008.
For the calibration only one year of information is taken. If longer data series for the calibration are taken, data become no representative.
Another limitation is that VIC is time consumer: running long data series takes longer. This is another reason why the whole data period it is not used for the simulation. Many simulations must be run until VIC is calibrated. Using the whole data-period would take too much time.
In our study simulations run for one year data-serie and VIC takes around two hours for each simulation.

TECHNICAL REQUIREMENTS

-Automatic data acquisition systems: for hydropower operation, more input data and frequent model updating is required. These, has created a demand for completely automatic data acquisition systems, when the flow of data from sensors into the forecasting models can be made automatically and without human interruption or delays. Sources of error and methods used to reduce or eliminate such errors are needed due to the different measuring methods.

-Unix/linux plattforms: It is necessary for running VIC. All the workers at the department of Research of Development at Agder Energi own excellents skills of C/C++ programming. Also, was required that I acquired knowledge of programming during my stay at the company

-***The program:*** the source code and all the necessary tools for running the VIC model are available on the website. Some of the tools are input files(unfilled), instructions, how to apply VIC, how to install meteorological programs and geological programs to get information of the region (it wasn't my case)….

LEGALITIES AND OBLLIGATIONS

The project was made at the company Agder Energi as part of a training program. There was an agreement regarding this industrial training program (temporary internship). Some of the points of the agreement are the following:

The start date has been set to: 1. February, 2012 .

Conditions for / time-limited work that shall be performed – the reason for the temporary nature of the employment shall appear:
The position is an internship and part of an industrial training program through ERASMUS. The student will be involved in Research and development projects at Agder Energi as part of the training.
Estimated duration of the agreement and estimated ending date: 31 September, 2012
The position is conditioned on the student receiving ERASMUS scholarship as part of living costs. The position is conditioned on the student having a legal working visa for Norway.
Agder Energi will contribute with a scholarship amounted to 8000 NOK/month during Susana Maria Moreno Colomer's stay at Agder Energi.
Trial period:
The employment will occur with a 3-month trial period. The mutual notice period during the trial period is 14 days. In the event of absences from work during the trial period that are not caused by the employer, the employer may demand that the trial period be extended by a period corresponding to the absences.
Working hours/breaks:
Working hours and breaks are with respect to the Working Environment Act, collective bargaining agreement, company rules and flextime rules in force at any point in time.
Holiday:
Right to holidays/holiday allowance/holiday scheduling is with respect to the Norwegian Holidays Act and collective bargaining agreements.
Travel and subsistence compensation:
In accordance with the travel rules of the company applicable at any point in time.
Pensions and personnel insurance:
In accordance with the applicable rules at any point in time for pensions and personnel insurance.
Termination of the working relationship:
The mutual notice period after expiry of the trial period is 1 month (date/date), otherwise with respect to the provisions of the Personnel Handbook and the Working Environment Act.
Non-disclosure agreement:
The employee is obligated during both the training period as well as after the termination of the employment relationship to maintain complete confidentiality towards third parties concerning business and trade secrets and information concerning a person's personal circumstances as well as corresponding information involving the Company's customers and working partners that the individual concerned may become aware of during their work.
A breach of the non-disclosure obligation may lead to a liability to pay compensation to the Company.
Upon cessation of the employment relationship, regardless of the specific basis for such, the Employee is obligated to surrender to the Company all documents, electronically stored information, etc. that belong to the Company, regardless of where such may be located and how it is stored
Consent to handling of personal information:

The Employee consents to the Company being able to handle sensitive and non-sensitive personal information about myself associated with my employment relationship and as an element of its personnel administration, including:
Information concerning possible membership in trade unions.
Requisite information concerning absences from work and information that it is obligatory to record pursuant to the Working Environment Act.
Any possible information that is necessary in order to arrange the work situation with respect to health conditions.

Rights to inventions:
Concerning inventions, the Norwegian Act of 17 April 1970 relating to the rights to inventions made by an employee shall apply.
Other information:
The employment agreement shall apply with respect to the conditions that are established in the applicable company rules. The Employee understands and accepts that the content of the Personnel Handbook and the ethical guidelines applicable at any point in time shall be incorporated as a part of the written employment agreement. The Personnel Handbook may be altered unilaterally by the Company unless such is regulated in further detail by statutes, collective bargaining agreements or local special agreements.
The employment agreement has been reviewed by the parties together.
The Company's company rules have been furnished to the employee.
This employment agreement is being executed in 2 copies – one for each of the parties.

The proposed training programme was completed following the tasks:

Knowledge, skills and competences acquired:

The student acquired knowledge within the field of geophysics, hydrology, computer programming and mathematical modelling. All the work was in connection with research and development projects at Agder Energi. In addition the student learned about project management, presentation techniques and communication. The working language was English.

Detailed programme of the training period:

Q1: Hydrology textbooks, C/C++ and python programming
Q2: Mathematical modelling of hydrological processes, presentations, reports
Q3: Calibration of hydrological models, presentation and reports

Task of the trainee:
Apply numerical models to various project assignments, calibration of hydrological models. Data formatting Cooperation with other co-workers

Monitoring and evaluation plan:

The student was reporting weekly to head of R&D Bernt Viggo Matheussen (Ph.D.). The student gave talks and presentation on the results from the projects. Written reports that document the project were given. Qualitative evaluations and feed back were given to the student on a regular basis.

E. BUDGETS

The cost of this Project it is not possible to measure with exactitude due to the following reasons:

-The tools for installing the model are available on the website, and you can get them for free.

-Cooperation from others coworkers was made when providing data formatting. The main task of their jobs wasn't related with this project, and the provided information had many other applications. Therefore cooperation from other workers cannot be masured in terms of money, though there is a cost since they have spent some time on it. Also they have spent time on meetings, assistance, arguments, direction, and other times when I had problems or questions.

An approximation of the cost of this project is the salary of the person that had done it: an average of 8000 NOK per month. These Norwegian coronus are conversed to 1000 euros per month. That sums a total of 8000 euros. This amount was paid for an average of 800 worked hours (though an extra time was spent for reading text books). Other costs that could be included are the costs of the trips and a programming course provided by the company. They are not measurable since it involved a group of people.

