Distributed HBV Model

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Table of Contents

Preface

Precipitation-runoff models are used for applications that require simulation of the dynamic water balance of a selected area of the land surface, e.g. a watershed. They provide a capability to predict hydrological state variables and fluxes from atmospheric data, with the purpose of for example hydrological forecasts, hydrological impact simulations or management of water resources. Mathematical models simplify the physical processes and replace them by a set of equations, whose solutions are programmed as a computer code. The results of simulations with the mathematical model are interpreted in terms of the physical system. The structure of models vary in their level of complexity, however, the major mechanisms involved in conversion of precipitation to discharge at the catchment outlet are usually considered in one way or another. In order to be used as a tool for examining spatially distributed hydrological processes and their interactions, both vertical and lateral flow paths should be incorporated in a model. Models to be used for operationally applicable simulation systems often have a simpler structure than required by models used as research tools. In addition to describe the physical processes which govern storage and flow of water as subsurface and overland flow through a catchment, precipitation-runoff models must include the various hydrological and radiative processes at the land surface-atmosphere interface; interception storage, glacier mass balance, snow accumulation and snowmelt, soil evaporation and transpiration from vegetation. The spatially distributed hydrological model described in this document is used for modelling the water balance and lateral transport of water in the land phase of the hydrological cycle. The spatial distribution and shape of discrete landscape elements and the time steps of the model may be selected according to the problem to be solved. The requirements for running the model and the procedures for setting up the model definition files are described.

Oslo, March 2020

Symbols

file.txt data file

file.asc ascii/grid import/export format file

file.var model output time series file

In the examples of information required for running the programs, angle brackets or chevrons indicate that a value is to be inserted, e.g. **`<index>`** is replaced by the value of the index. The file names and extensions are in general optional.

1 Introduction

The spatially distributed HBV hydrological model described in this document is used for modelling the water balance and lateral transport of water in the land phase of the hydrological cycle. The model allows different algorithms to be used for hydrological process descriptions. The spatial distribution and shape of discrete landscape elements and the time steps of the model may be selected according to the problem to be solved. The requirements for running the model and the procedures for setting up the model definition files are described. The model structure is based on Bergström (1995), Lindström et al. (1997) and Beldring et al. (2003). The mathematical and logical expressions used to describe the hydrological system are described, as well as the variables and parameters used for hydrological process simulations. Model parameters remain constant over time or vary in a manner which may be described using physical principles or empirical relationships. Parameters either represent physically measurable properties of a watershed, or are used to describe hydrological processes. A variable may represent: (i) the state of the different storages in the hydrological system as approximated by the forecasting model; (ii) the input signal which drives the model; or (iii) the output from the model. Variables vary with time.

Precipitation-runoff models are used for applications that require simulation of the dynamic water balance of a selected area of the land surface, e.g. a watershed. They provide a capability to predict hydrological state variables and fluxes from atmospheric data, with the purpose of for example hydrological forecasts, hydrological impact simulations or management of water resources (DeVries and Hromadka, 1993). Mathematical models simplify the physical processes and replace them by a set of equations, whose solutions are programmed as a computer code. The results of simulations with the mathematical model are interpreted in terms of the physical system (Freeze, 1978). The structure of the models vary in their level of complexity, however, the major mechanisms involved in conversion of precipitation to discharge at the catchment outlet are usually considered in one way or another. In order to be used as a tool for examining spatially distributed hydrological processes and their interactions, both vertical and lateral flow paths should be incorporated in a model. Models to be used for operationally applicable simulation systems often have a simpler structure than required by models used as research tools (Bronstert, 1999). In addition to describe the physical processes which govern storage and flow of water as subsurface and overland flow through a catchment, precipitation-runoff models must include the various hydrological and radiative processes at the land surface-atmosphere interface; interception storage, glacier mass balance, snow accumulation and snowmelt, soil evaporation and transpiration (DeVries and Hromadka, 1993).

In spite of the variability of catchment properties, storm hydrographs are relatively well-behaved, implying a smoothing effect at the catchment scale which overrides the effect at smaller scales (Grayson et al., 1992b). Similar conclusions can be drawn from the temporal variablity of conservative tracers (Bonell, 1993). In small catchments and on hillslopes the effect of this integration will be less pronounced (Grayson et al., 1995). If the purpose of hydrological modeling is to simulate runoff and evapotranspiration from catchments, it may not be necessary to describe exact patterns of catchment properties and hydrological responses at small scale, however, the distribution of characteristics within the catchments may still be important (Wood et al., 1988, 1990; Seyfried and Wilcox, 1995).

For consideration of runoff generation in small catchments (less than 10 km^2) the channel phase may usually be neglected. Small catchments are dominated by the land phase, and are highly sensitive to intense rainfalls with short duration (Singh, 1995). Kirkby (1988) suggested that satisfactory hydrological models of small catchments could be developed by considering vertical unsaturated flow and downslope saturated subsurface flow and saturation overland flow on two-dimensional hillslope strips which interact negligibly with neighbouring strips. The most general way to develop a model of the land phase of runoff generation is to use the complete equations of saturated and unsaturated subsurface flow and overland flow (Freeze, 1978). However, most models apply an approach based on a simplified representation of the appropriate mechanisms (Dingman, 1994).

If the time of concentration of the catchment is influenced by the transport of the flood wave through the channel system, hydrological models must include procedures for routing of flows down the river channel including lakes and reservoirs. This is the situation for large river systems such as the River Glomma and its major tributaries. River routing models may be classified as either hydraulic (distributed) or hydrological (lumped). In hydraulic routing models the flows and water levels are computed as a function of time simultaneously at several cross sections along the watercourse using the hydrodynamic equations of unsteady flow (the Saint Venant equations) or their dynamic wave or kinematic wave approximations. Hydrological routing is based on continuity considerations for storage of water in reservoirs or river reaches and require less data than hydraulic routing. (Lettenmaier and Wood, 1993).

The majority of hydrological simulation models in use are conceptual models based on a simplified representation of the real system. These models approximate catchment processes by a series of linked storages, which are usually modeled using linear reservoirs (Shaw, 1994). Although conceptual models do not describe in detail the mechanisms by which runoff is generated during rain or snowmelt events, these models are in frequent use due to their low data demand, and the fact that they have proved quite successful when used for operational forecasts of runoff (Bergström, 1991). The HBV model (Bergström, 1995; Lindström et al., 1997) has been used in Scandinavia and other regions of the world for several decades. It is a semi-distributed conceptual precipitation-runoff model which uses sub-catchments as the primary hydrological units, and within these an area-elevation distribution and a crude classification of land use (forest, open, lakes) are applied. The model is run with daily time steps, using rainfall data and air temperature and monthly estimates of potential evaporation as input. It consists of three main components; (i) snow accumulation and snowmelt; (ii) soil moisture and evapotranspiration accounting; and (iii) groundwater reservoir, runoff response and river routing. Groundwater recharge depends on water content in the the soil moisture store. The model has a number of free parameters, whose values are determined by calibration. There are also parameters describing the characteristics of the catchment and its climate. The model exists in several versions.

Building a physically based precipitation-runoff model of a hillslope or small catchment involves specification of the governing laws of mathematical physics, the geometry of the system, sources and sinks and initial and boundary conditions. For a wide range of surface and subsurface flow processes the governing equations are law of conservation of mass (continuity equation) and a flux law (Singh and Prasana, 1999). Overland flow is modeled as broad sheet flow using the Saint-Venant equations or their kinematic wave approximations (Moore and Foster, 1990). However, natural surfaces have several small and large irregularities causing water to occur as anastomosing flow with a great variety of flow depths (Kirkby, 1988). Descriptions of overland flow assuming sheet flow over smooth surfaces are therefore at best viewed as parametric prediction models (Freeze, 1974). Both saturated and unsaturated flow within porous media are described as potential flow using Darcy's law and the continuity equation, which combine to the Richards equation. However, Darcy's law is not valid when boundary layer effects and viscous resistance retard the flow, e.g. in macropore systems (Dingman, 1984, 1994). Since water in macropores moves only under the influence of gravity, the flow can be approximated by kinematic wave theory in this case (Germann et al., 1986). Concerning infiltration and percolation through an unsaturated soil matrix, Philip's or Green and Ampt's approaches may suffice, although the underlying assumptions may be violated if large structural pores are present (Youngs, 1991). As undisturbed forest soils in general have a surface layer which can accept all rainfall or snowmelt, development of ponded infiltration theory has been ignored in most forest hydrology studies (Bonell, 1993).

Advances in computer technology and improved observational capabilities providing spatially distributed data have led to the development of physically based, distributed models which describe state variables and flow of water in three dimensions using realistic, process-based equations (Grayson et al., 1992a, 1992b; Sorooshian, 1997). Examples of these models are the Institute of Hydrology Distributed Model (IHDM) (Calver and Wood, 1995), the Système Hydrologique Européen (SHE) model (Abbot et al., 1985a, 1985b) and the ECOMAG model (Motovilov et al., 1999). Theoretically, the main advantage of physically based, distributed models is that they represent accurately the heterogeneities in space and time of various hydrological processes. However, this comes at the expense of a large number of parameters, most of which are related to a better representation of the physics involved (Sorooshian, 1997), and a high demand for data describing spatially distributed catchment characteristics and climatic input (Seyfried and Wilcox, 1995). A critique expressed against these models concerns the description of integrated areal response at the grid scale using effective parameters and equations derived from an understanding of physics at the point scale. As there is no satisfactory theory for aggregating the behaviour of hydrological processes, state variables or parameters from the point scale to the size of the selected grid elements, models which are claimed to be distributed, physically based are in reality lumped conceptual models, just with many more parameters (Blöschl and Sivapalan, 1995). Distributed models which operate on computational elements much larger than the spatial scale of the processes dominating runoff production cannot be expected to produce accurate predictions of discharge in heterogeneous terrain. In order to provide accurate descriptions of the mechanisms controlling event response within small catchments using physically based, distributed models, the size of computational elements must be small enough to represent the relevant hydrological processes and their interactions (Bronstert, 1999).

Topographical gradients control the spatial extent of runoff producing areas in the landscape through lateral fluxes and spatial redistribution of water. This has led to the development of physically based hydrological models using digital elevation models for providing an accurate representation of topographical characteristics which are fundamental for flow processes (Moore et al., 1991; Grayson et al., 1992a). These models describe saturated subsurface flow, saturation overland flow and infiltration excess overland flow, and can also account for differences in soil characteristics or vegetation (O'Loughlin, 1986). Grayson et al. (1992b) argued that topographically driven, spatially distributed process models hold the greatest potential for application to various forest land management problems related to small or medium size (less than 10 km2) headwater catchments.

2 Spatial discretisation

2.1 Model domain

If the model is to be run on a regular grid, the programs *stationMask* and *prehbv* may be used for defining the model domain, sub-catchment hierarchy and the characteristics of the landscape elements used as computational elements in the model. This requires that data defining watercourses, catchments and land surface characteristics are available as ascii/grid import/export format files used by most geographical information systems (GIS). These two programs generate a set of files which are necessary for running program *hbv* with the spatially distributed HBV model.

If the model is to be run with irregularly shaped computational elements the files defining the model domain and the characteristics of landscape elements must be produced with a text editor.

2.2 Meteorological input data

If the model is run on a regular grid, meteorological input data may also be defined on a regular grid. In this case the meteorological data are read from binary files, one file per time step for precipitation and temperature, respectively. Regardless of the spatial discretisation of the model domain, time series of meteorological input data from station points may be used for driving the model. In this case, the meteorological data are read from a text file.

2.3 Hierarchy of landscape and watercourse elements

The model can describe flow of water through the hierarchy of landscape elements, sub-catchments and the river/lake network in an implicit approach which assumes that runoff is sent from all landscape elements within a sub-catchment draining to a part of the watercourse hierarchy directly to the outlet of this sub-catchment for every timestep. Water is then routed through a simplified river/lake network where each sub-catchment corresponds to one branch in the watercourse network.

3 Program *stationMask*

Program *stationMask* defines the model domain.

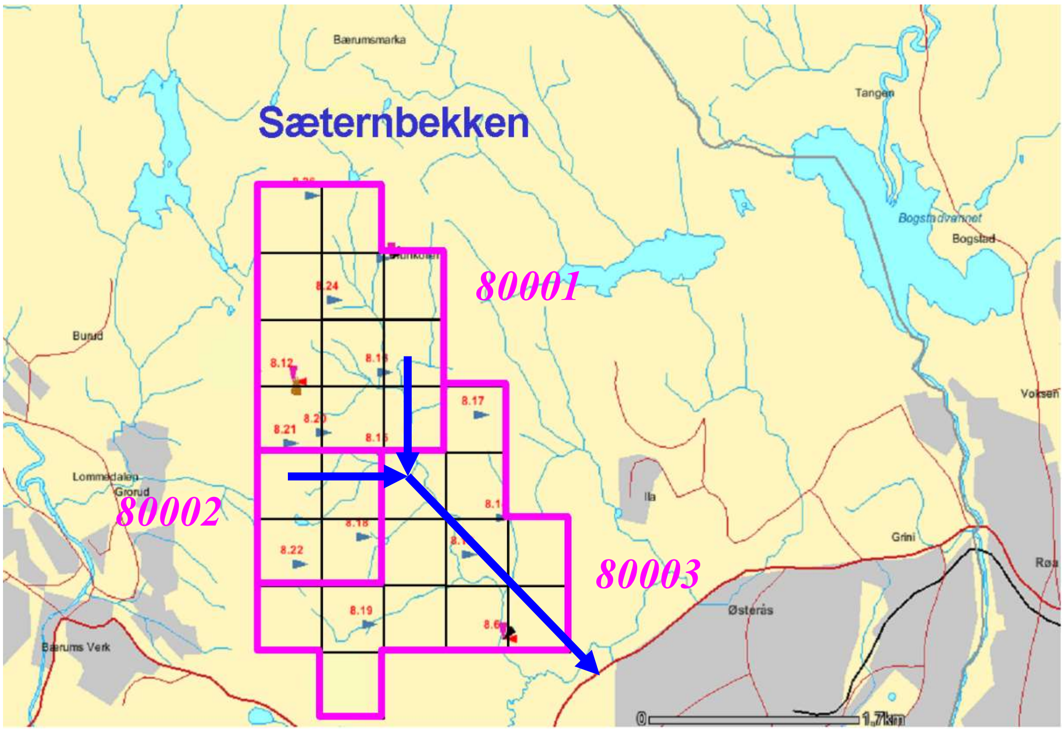
3.1 Input

Program *stationMask* requires two input files.

- Watercourse/sub-catchment hierarchy description
- Landscape elements located within each watercourse/sub-catchment

3.2 Watercourse/sub-catchment hierarchy description

The discretisation of watercourses/sub-catchments use a unique number for identifying the different elements. In the example below, these numbers are 80001, 80002 and 80003. The watercourses/sub-catchments 80001 and 80002 discharge into watercourse/sub-catchment 80003. The outlet from the model domain is located in watercourse/sub-catchment 80003. Several outlets are possible.



The watercourse/sub-catchment hierarchy is defined using a file named *watershed.txt* in this example:

```
# Number of watercourses: 3
0 :  80001    1.0    1.0
1 :  80002    1.0    1.0
2 :  80003    1.0    1.0
# Number of watercourse outlets: 1
2
# Hierarchy of watercourses
2 2 :  0 1
```

```
# Number of watercourses: <no. of watercourses/sub-catchments>
<index> : <watercourse/sub-catchment id.> <maxbas> <scale factor>
<index> : <watercourse/sub-catchment id.> <maxbas> <scale factor>
...
# Number of watercourse outlets: <no. of outlets>
<index of outlet watercourse/sub-catchment>
<index of outlet watercourse/sub-catchment>
...
# Hierarchy of watercourses
<index of downstream>  <no. of upstreams> : <indices of upstreams>
<index of downstream>  <no. of upstreams> : <indices of upstreams>
...
```

#Number of watercourses

Number of watercourses/sub-catchments.

The watercourses/sub-catchments indices start from 0. For each watercourse/sub-catchment:

- Watercourse/sub-catchment index
- Watercourse/sub-catchment identification
- Time base of triangular distribution of weights for streamflow transformation
- Scale factor for modelled watercourse/sub-catchment discharge

#Number of watercourse outlets

The watercourse/sub-catchment index of each outlet must be provided.

#Hierarchy of watercourses/sub-catchments

- Watercourse/sub-catchment index
- Number of upstream watercourses/sub-catchments
- Upstream watercourses/sub-catchments indices

3.3 Landscape elements within each watercourse/sub-catchment

The landscape elements within the regular grid are identified by an ascii/grid import/export format file. This file has grid cell identifiers that identify the watercourse/sub-catchments identifiers of the landscape elements as shown in the file named *watercourse_id.asc* in the example below. Grid cells with nodata value (-9999) will not be included in the model domain. The file *watercourse_id.asc* may include grid cells with watercourse/sub-catchments identifiers which are not included in the model domain.

```
ncols          5
nrows          8
xllcorner      0
yllcorner      0
cellsize       500
NODATA_value   -9999
80001  80001  -9999  -9999  -9999
80001  80001  80001  -9999  -9999
80001  80001  80001  -9999  -9999
80001  80001  80001  80003  -9999
80002  80002  80003  80003  -9999
80002  80002  80003  80003  80003
80003  80003  80003  80003  80003
-9999  80003  -9999  -9999  -9999
```

3.4 Output

Program *stationMask* produces one output file in ascii/grid import/export format with information about the model domain. The name of the output-file must be provided when running the model. In the example below this file is called *stations.asc*. Program *stationMask* writes the data in one column.

```
ncols          5
nrows          8
xllcorner      0
yllcorner      0
cellsize       500
NODATA_value   -9999
80001
80001
-9999
-9999
-9999
80001
80001
80001
-9999
-9999
80001
80001
80001
-9999
-9999
80001
80001
80001
80003
-9999
...
```

```
...
80002
80002
80003
80003
-9999
80002
80002
80003
80003
80003
80003
80003
80003
80003
80003
-9999
80003
-9999
-9999
-9999
```

3.5 Running *stationMask*

When *stationMask* is run on a Linux system or using a Windows console interface it is possible to read the information necessary for running the program from a text file. In the example below, the text file is called *control_mask.txt*. The model is started from the command prompt with the command:

stationMask control_mask.txt

If the executable file *stationMask* is not located in a directory in the search path of the computer session, the full or relative path to *stationMask* must be provided.

File *control_mask.txt* contains the information to be supplied to the user interface of program *stationMask*. The texts in red colour are comments.

```
File with sub-catchment identifiers           : watershed.txt
         Watercourse/sub-catchment hierarchy
File with grid cell sub-catchment identifiers : watercourse_id.asc
         Landscape elements
Output file name                              : stations.asc
         Output file with model domain
```

4 Program *prehbv*

Program *prehbv* determines the characteristics of each landscape element based on ascii/grid import/export format files with information about land surface characteristics, e.g. elevation, land use, lakes, glaciers. The program also connects landscape elements to watercourse/sub-catchment elements. The information used by *prehbv* in the example below is based on data available from the Norwegian Mapping Authority including the potential tree line. This example assumes that an implicit hierarchy of landscape elements is to be used. The additional information required for running *prehbv* in case of an explicit hierarchy of landscape elements is presented in Chapter 6.

4.1 Input

Program *prehbv* requires 11 input-files.

- File with meteorological stations information
- Parameter file common for all land cover and soil/bedrock classes
- Output file from program *stationMask* with information about the model domain.
- Elevation of grid cells
- Percentage of grid cells areas covered by lakes
- Percentage of grid cells areas covered by forest
- Percentage of grid cells areas covered by bogs
- Percentage of grid cells areas covered by glaciers
- Potential tree level of grid cells
- Watercourse/sub-catchment hierarchy description (same structure as file used by program *stationMask*)
- Landscape elements located within each watercourse/sub-catchment (same structure as file used by program *stationMask*)

4.2 Meteorological stations information

Program *prehbv* determines the meteorological stations to be used for modelling precipitation and temperature in each grid cell. A file with information about the type and location of each meteorological station must be supplied. This file is called *met_stations.txt* in the example below.

```
Number of precipitation stations : 4
Number of temperature stations   : 4
P   5601         0.0         0.0  205.0         SAETERNBEKKEN
P   5602      2500.0         0.0  305.0         SAETERNBEKKEN
P   5603         0.0      4000.0  405.0         SAETERNBEKKEN
P   5604      2500.0      4000.0  505.0         SAETERNBEKKEN
T   5605         0.0         0.0  205.0         SAETERNBEKKEN
T   5606      2500.0         0.0  305.0         SAETERNBEKKEN
T   5607         0.0      4000.0  405.0         SAETERNBEKKEN
T   5608      2500.0      4000.0  505.0         SAETERNBEKKEN
```

```
Number of precipitation stations : <no. of precipitation stations>
Number of temperature stations   : <no. of temperature stations>
<station type>  <station id.>  <east coord.>  <north coord.>
         <elevation>  <station name>
<station type>  <station id.>  <east coord.>  <north coord.>
         <elevation>  <station name>
```

This file must be provided even in the case that meteorological data are to be read from binary grid files. In this case, the information is only to be considered as dummy information and the file *met_stations.txt* must contain the following data:

```
Number of precipitation stations : 1
Number of temperature stations   : 1
P   -9999  -9999  -9999  -9999
T   -9999  -9999  -9999  -9999
```

4.3 Parameter file common for all land cover and soil/bedrock classes

The file *hbv_common_parameters.txt* in the example below provides parameter values and other characteristics common to all land cover and soil/bedrock classes which are necessary for running the model. Model parameters are defined in Chapter 7.

```
Number of seconds per time step    SECONDS_TIMESTEP    : 3600
Number of precipitation series     NUM_PREC_SERIES     : 1
Number of temperature series       NUM_TEMP_SERIES     : 1
Prec. grad. low  per 100 m         PREC_GRAD_LOW       : 1.05
Prec. grad. high per 100 m         PREC_GRAD_HIGH      : 1.0
Altitude for 50 % reduction        GRAD_CHANGE_ALT     : 0
Prec. correction for rain          PREC_CORR_RAIN      : 1.0
Additional prec. corr. for snow    PREC_CORR_SNOW      : 1.0
Temp. lapse rate dry days per 100 m     LAPSE_DRY      : -.98
Temp. lapse rate wet days per 100 m     LAPSE_WET      : -.5
Lake temperature memory (days)     DAY_TEMP_MEMORY     : 30.0
Lake evaporation constant          LAKE_EPOT_PAR       : 1.0E-4
Rating curve constant              KLAKE               : .0025
Rating curve saddle point          DELTA_LEVEL         : 0.0
Rating curve exponent              NLAKE               : 1.0
Initial soil moisture        INITIAL_SOIL_MOISTURE     : 0.1
Initial upper zone           INITIAL_UPPER_ZONE        : 0.0
Initial lower zone           INITIAL_LOWER_ZONE        : .05
Initial lake temperature     INITIAL_LAKE_TEMP         : 0.0
Initial lake level           INITIAL_LAKE_LEVEL        : 0.0
Initial snow storage         INITIAL_SNOW_STORAGE      : 0.0
Initial total reservoir      INITIAL_TOTAL_RESERVOIR   : 0.0
Day no. for zero snow storage      DAY_SNOW_ZERO       : 0
```

- Number of seconds per time step is the temporal resolution of model simulations
- Number of precipitation series and number of temperature series defines the number of stations to be used for determination of meteorological input data for each grid cell. Program *prehbv* determines weights for inverse distance interpolation of meteorological data to each model grid cell using the nearest precipitation and temperature stations.
- Gradients for precipitation increase per 100 m elevation change above and below altitude **GRAD_CHANGE_ALT** must be supplied. A value of 1.0 means no change. **PREC_GRAD_HIGH** will not be used if **GRAD_CHANGE_ALT** = 0.
- Precipitation correction for rain adjusts data for gauge losses. An additional precipitation correction for snow may also be provided.

- Temperature lapse rates for dry and wet time steps (no rain or rain).
- Lake temperature memory and lake evaporation constant provide information used in a simple method for modelling lake temperature and lake evaporation.
- Rating curve parameters are used for modelling lake outflow.
- Initial value for soil moisture content in HBV elements.
- Initial values for upper and lower saturated zone water content in HBV elements.
- Initial values for lake temperature and lake water level.
- Initial value for total volume of water stored in lakes.
- Snow storage may be reduced to zero at a specified day number each year. If `DAY_SNOW_ZERO` = 0 the snow storage is not altered.

4.4 Land surface characteristics of grid cells

Program *prehbv* reads input files with land surface characteristics of the grid cells within the model domain. The information is supplied as ascii/grid import/export format files with information about elevation (metres above sea level), slope length (metres), slope angle (degrees), aspect (degrees), percentage of grid cells areas covered by lakes, percentage of grid cells areas covered by forest, percentage of grid cells areas covered by bogs, percentage of grid cells areas covered by glaciers, elevation of glacier surface, thickness of glacier ice, potential tree line of grid cells (metres above sea level) and flow direction of landscape elements. The potential tree line defines the upper margin of the subalpine forest where trees become dwarfed or are absent. The flow direction of landscape elements is not used by the program hbv in case on an implicit hierarchy of landscape elements. A file with the correct structure must be supplied, but the flow directions may hold any value, e.g. -9999 or 0. All these files have the same format. An example of the file structure is provided for grid cell elevations in file *altitude.asc*.

```
ncols         5
nrows         8
xllcorner     0
yllcorner     0
cellsize      500
NODATA_value  -9999
  410    400  -9999  -9999  -9999
  400    360    380  -9999  -9999
  300    280    300  -9999  -9999
  240    220    200    230  -9999
  280    220    200    210  -9999
  270    240    200    170    160
  280    250    210    160    120
-9999    240  -9999  -9999  -9999
```

4.5 Output

Program *prehbv* produces four output files.

- A file with control information used during model development. The name of this file must be supplied when running the model. In the example below this file is called *pre_out.txt*.
- A file with information about grid cell characteristics
- File with information about landscape elements within each watercourse/sub-catchment

- A file with coordinate indices of grid cells relative to upper left corner of rectangle with grid information.

4.6 File with information about grid cell characteristics

The file with information about characteristics for each grid cell produced by program *prehbv* describes the coordinates of each grid cell and the model structure/algorithm used for modelling hydrological processes.

Area, elevation, slope properties, lake and glacier percentage, land cover type, soil type and other land surface characteristics are described. Information about the meteorological stations and the weights to be used for interpolation of meteorological data are also provided. The file *hbv_landscape.txt* shown below presents the first lines of an output file with information about grid cell characteristics.

```
ncols         5
nrows         8
xllcorner     0
yllcorner     0
cellsize      500
NODATA_value  -9999
# Number of landscape elements :  27
0 0 250000. 410. 0.0 0.0 2 100.0 1 0.0 2 1.0 2 1.0
```

The first six lines provide information necessary for describing the coordinates of a regular grid.
Line 7 gives information about the number of landscape elements.
Starting from line 8, there is one line for each landscape element (grid cell) in the model domain with the following information.

```
Element index
Coordinate index
Area (m²)
Elevation (m)
Lake percentage (%)
Glacier percentage (%)
Land surface class 1; land cover class
Percentage of area covered by land surface class 1 (%)
Land surface class 2; land cover class
Percentage of area covered by land surface class 2 (%)
For all precipitation series:
     Precipitation station number
     Precipitation station weight
For all temperature series:
     Temperature station number
     Temperature station weight
```

4.7 File with information about landscape elements within each watercourse/sub-catchment

The landscape elements discharging to each watercourse or located within each sub-catchment are listed in file *hbv_waterland.txt* presented below.

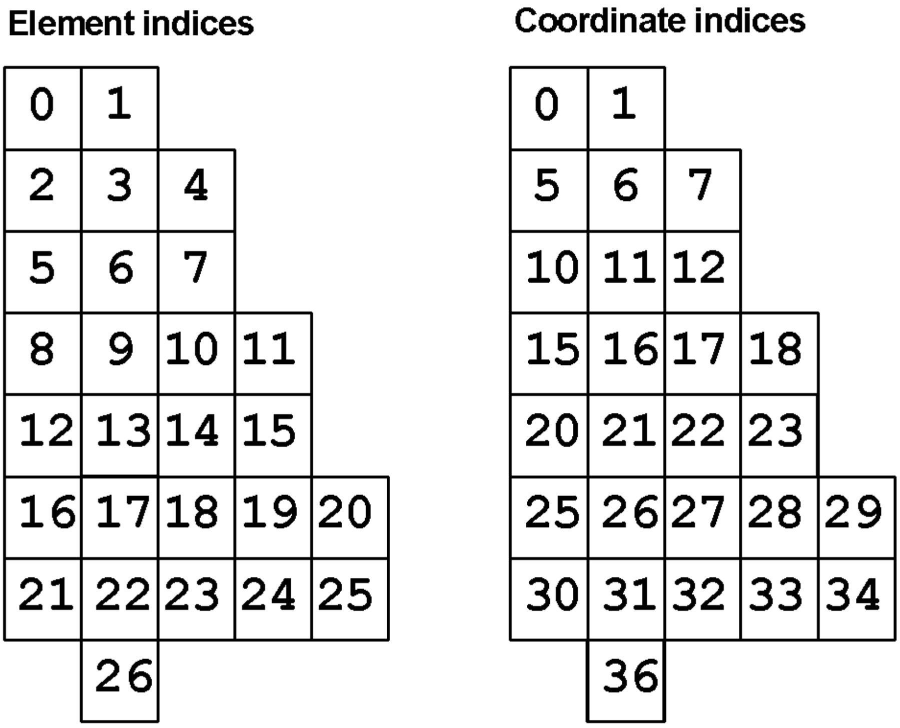
```
#  80001  #  11
0  0
1  1
2  5
3  6
4  7
5  10
6  11
7  12
8  15
9  16
10  17
#  80002  #  4
12  20
13  21
16  25
17  26
#  80003  #  12
11  18
14  22
15  23
18  27
19  28
20  29
21  30
22  31
23  32
24  33
25  34
26  36
```

The information provided for each watercourse/sub-catchment is:

```
#  <watercourse/subcathment index>  #  <no. of landscape elements>
<element index of element 1> <coordinate index of element 1>
<element index of element 2> <coordinate index of element 2>
...
```

4.8 File with coordinate indices of grid cells relative to upper left corner of rectangle with grid information

Element indices start from 0, coordinate indices are starting from 0 in the upper left corner of the regular grid. The example below shows element indices and coordinate indices for the regular grid used for landscape elements in catchment Sæternbekken.



4.9 Running *prehbv*

When *prehbv* is run on a Linux system or using a Windows console interface the information necessary for running the program is read from a text file. In the example below, the text file is called *control_pre.txt*. The model is started from the command prompt with the command:

prehbv control_pre.txt

If the executable file *prehbv* is not located in a directory in the search path of the computer session, the full or relative path to *prehbv* must be provided.

File *control_pre.txt* contains the information to be supplied to the user interface of program *prehbv*. The texts in red colour are comments. Long lines in the file have been dived over two lines.

```
Output file name                                  : pre_out.txt
         Program development output file
File with meteorological stations                 : met_stations.txt
         Meteorological stations
File with common parameters               : hbv_common_parameters.txt
         Parameters for all classes
File with geographical analysis area              : stations.asc
         Model domain file
File with grid cell elevations                    : altitude.asc
         Elevation
File with lake percentage                         : lake_per.asc
         Lake percentage
File with forest percentage                       : forest_per.asc
         Forest percentage
```

```
File with bog percentage                            : bog_per.asc
         Bog percentage
File with glacier percentage                        : glacier_per.asc
         Glacier percentage
File with potential tree level                      : tree_level.asc
         Potential tree level
File with sub-catchment hierarchy                   : watershed.txt
         Watercourse/sub-catchment hierarchy
File with watercourse/sub-catchment identifiers : watercourse_id.asc
         Landscape elements located within each watercourse/sub-
         catchment
```

5 Program *hbv*

The hydrological modelling is performed by program *hbv*. Program *hbv* can be run in calibration mode or simulation mode. When the program is being run in calibration mode, a file with observed streamflow data for the calibration period is required. Program *hbv* will not perform optimization of model parameters; the only difference between the two modes is that the sum all model simulated streamflow values is written to the end of the model results files *hbv_<watercourse/sub-catchment>.var* (Chapter 6) in calibration mode. Only model results for time steps where observed data are available will be included in this sum. This model uses an implicit hierarchy of landscape elements.

5.1 Input

Input files to program *hbv* may be generated by programs *stationMask* and *prehbv* or be produced using a text editor. When the model domain is not a regular grid, input files must be produced by a text editor. In addition to the files that may be generated by programs *stationMask* and *prehbv* or be produced using a text editor, program *hbv* requires files with information about parameter values of land cover/vegetation classes and soil/bedrock classes, watercourse elements and meteorological input data. The structure of the input files is described below, or in Chaper 3. Model parameters are defined in Chapter 7.

Program *hbv* requires 10, 11 or 12 input-files.

- File with meteorological stations information
- Parameter file common for all land cover and soil/bedrock classes
- Land cover/ vegetation classes parameters
- Soil/bedrock classes parameters HBV model
- Landscape elements selected for time series output
- Landscape elements characteristics (may be generated by program *prehbv*)
- File with observed streamflow data. This file is required in calibration mode, but can be void in simulation mode. If it is void, model results will not be compared to observations. An example of this file is provided below.
- Watercourse/sub-catchment hierarchy description (same structure as file used by programs *stationMask* and *prehbv*)
- Landscape elements located within each watercourse/sub-catchment (may be generated by program *prehbv*)
- Correction of meteorological data
- Meteorological time series (only for input data in time series format)
- File with long-term mean monthly potential evaporation values named *monthlyEvaporation.txt* (only if not temperature based potential evaporation)

File with observed streamflow data named *obs_streamflow.txt* in this example:

```
#hbv_00080003.var
19960920/0000       0.011248
19960920/0100       0.011248
19960920/0200       0.011248
19960920/0300       0.011248
19960920/0400       0.011248
19960920/0500       0.011248
19960920/0600       0.011248
...
```

The first line gives the name of the model output file that observed data are to be compared to. The next lines contain observed streamflow data. This information can be repeated for each model output file that is to be compared to observed data.

5.2 When the model domain is not a regular grid

If the model domain is not a regular grid, the information in the first six lines of the file *hbv_landscape.txt* is to be considered as dummy information. It must be provided, but it will not be used by the program *hbv*.

The landscape elements discharging to each watercourse or located within each sub-catchment are read from file *hbv_waterland.txt*. In the case that the model domain is a regular grid, this file may be generated by program *prehbv*. If irregularly shaped landscape elements are used, this file must be produced using a text editor. The coordinate indices may then no longer be used for finding the location of landscape elements, and should be assigned the value of the element indices. The landscape elements discharging to each watercourse or located within each sub-catchment should then be listed as in the example below. The watercourse/sub-catchment element 80003 receives water from 10 landscape elements with indices from 0 to 9.

```
#  80003  #  10
0  0
1  1
2  2
3  3
4  4
5  5
6  6
7  7
8  8
9  9
```

5.3 Land cover classes parameters

The following land cover classes are used by program *hbv*.

- Open land: Non-forested areas below the tree line (agricultural fields, meadows etc.)
- Bog: Bogs and wetland areas
- Forest: Lowland areas with coniferous or deciduous forests
- Alpine: Areas below the tree line with subalpine forests
- Heather: Areas above the tree line with grass, heather, shrubs or dwarfed trees
- Bedrock: Areas above the tree line with extremely sparse vegetation
- Glacier: Glaciated areas covered by snow and ice

The tree line is the upper margin of the subalpine forest where trees become dwarfed or are absent.

Land cover classes parameters are read from file *hbv_landsurface_parameters.txt* below. The file has one line per land cover class, but has been divided into three parts in this example.

```
Type     no.    INTER_MAX    EPOT_PAR     WET_PER_CORR
OPEN      0     1.0E-4       9.2E-5       0.8
BOG       1     1.0E-4       0.000020     0.8
FOREST    2     1.0E-4       0.000020     0.8
ALPINE    3     0.0          0.0          0.0
HEATHER   4     1.0E-4       9.2E-5       0.8
BEDROCK   5     1.0E-4       9.2E-5       0.8
GLACIER   6     1.0E-4       9.2E-5       0.8

ACC_TEMP     MELT_TEMP    SNOW_MELT_RATE    ICE_MELT_RATE
0.0          -0.03        0.01              1.12
0.0          -0.03        0.01              1.12
0.0          -0.03        0.01              1.12
0.0          -0.03        0.01              1.12
0.0          -0.03        0.01              1.12
0.0          -0.03        0.01              1.12
0.0          -0.03        0.01              1.12

FREEZE_EFF   MAX_REL     ALBEDO     CV_SNOW
0.01         0.08        0.90       0.0
0.01         0.08        0.90       0.0
0.01         0.08        0.90       0.0
0.01         0.08        0.90       0.3
0.01         0.08        0.90       0.5
0.01         0.08        0.90       0.75
0.01         0.08        0.90       1.0
```

5.4 Soil/bedrock classes parameters

There is one soil/bedrock class corresponding to each land cover class. There is one set of soil/bedrock classes parameters for the HBV model structure.

Soil/bedrock classes parameters for the HBV model structure are read from file *hbv_soil_parameters.txt* below. The file has one line per soil/bedrock class, but has been divided into two parts in this example.

```
Type     no.      FC       FCDEL    BETA     INFMAX
OPEN      0       0.38     1.0      2.0      50.0
BOG       1       0.38     1.0      2.0      50.0
FOREST    2       0.38     1.0      2.0      50.0
ALPINE    3       0.38     1.0      2.0      50.0
HEATHER   4       0.38     1.0      2.0      50.0
BEDROCK   5       0.38     1.0      2.0      50.0
GLACIER   6       0.38     1.0      2.0      50.0

KUZ      ALFA     PERC     KLZ      DRAW
1.0      1.87     1.0E-4   0.013    0.0
1.0      1.87     1.0E-4   0.013    0.0
1.0      1.87     1.0E-4   0.013    0.0
1.0      1.87     1.0E-4   0.013    0.0
1.0      1.87     1.0E-4   0.013    0.0
1.0      1.87     1.0E-4   0.013    0.0
1.0      1.87     1.0E-4   0.013    0.0
```

5.5 Landscape elements selected for HBV time series output

State variables and fluxes for selected landscape/model elements may be written to files. The numbers of the selected landscape elements must be specified.

File *hbv_elements.txt* below shows an example for HBV model elements.

```
# Number of landscape elements selected for HBV time series
output: 3
*no.*
0
12
25
```

5.6 Correction of meteorological data

Meteorological time series are corrected for gauge losses and elevation gradients using information in the file with parameter values and other characteristics common to all land cover and soil/bedrock classes. However, these corrections will not be applied when gridded meteorological input data are used. Instead, it is possible to apply corrections to all grid cells within a sub-catchment. File *catchment_correction.txt* below shows an example.

Catchment id.	Precipitation correction	Temperature correction
80001	1.0	0.0
80002	1.0	0.0
80003	1.0	0.0

These corrections apply to all landscape elements discharging to a watercourse or contained within a sub-catchment. All precipitation values read from the grid file are multiplied by the precipitation correction, whereas the temperature correction is added to all temperature values read from the grid file. These corrections can also be applied in the case that meteorological time series are used. In this case, the precipitation and temperature corrections will be applied to the input data for all computation element of the model located within a sub-catchment.

5.7 Meteorological time series input data

Meteorological time series data are supplied in a file with one column per time series. File *input_data.txt*. below is an example.

```
*Time*         *Precip* *Precip* *Precip* *Precip* *Temp* *Temp* *Temp* *Temp*
Saeternbekken
19960820/0000  0        0        0        0        13.8   13.8   13.8   13.8
19960820/0100  0        0        0        0        13.45  13.45  13.45  13.45
19960820/0200  0        0        0        0        13.2   13.2   13.2   13.2
19960820/0300  0        0        0        0        13.65  13.65  13.65  13.65
19960820/0400  0        0        0        0        13.45  13.45  13.45  13.45
19960820/0500  0        0        0        0        13.55  13.55  13.55  13.55
19960820/0600  0.25     0.25     0.25     0.25     13.65  13.65  13.65  13.65
19960820/0700  0        0        0        0        14.1   14.1   14.1   14.1
19960820/0800  0        0        0        0        14.7   14.7   14.7   14.7
19960820/0900  0.1      0.1      0.1      0.1      17.4   17.4   17.4   17.4
19960820/1000  0        0        0        0        20.55  20.55  20.55  20.55
19960820/1100  0        0        0        0        22.6   22.6   22.6   22.6
19960820/1200  0        0        0        0        23.85  23.85  23.85  23.85
19960820/1300  0        0        0        0        24.2   24.2   24.2   24.2
19960820/1400  0        0        0        0        24.15  24.15  24.15  24.15
19960820/1500  0        0        0        0        23.65  23.65  23.65  23.65
19960820/1600  0        0        0        0        23.15  23.15  23.15  23.15
19960820/1700  0        0        0        0        21.05  21.05  21.05  21.05
19960820/1800  0        0        0        0        19.5   19.5   19.5   19.5
19960820/1900  0        0        0        0        17.7   17.7   17.7   17.7
19960820/2000  0        0        0        0        16.4   16.4   16.4   16.4
19960820/2100  0        0        0        0        15.8   15.8   15.8   15.8
19960820/2200  0        0        0        0        15.3   15.3   15.3   15.3
19960820/2300  0        0        0        0        14.55  14.55  14.55  14.55
```

Each precipitation and temperature station in file *met_stations.txt* corresponds to a column in file *input_data.txt*. Precipitation date have unit *mm/time step* and temperature data have unit ° *C* (average temperature during time step). The two first lines on the file are used for comments. Meteorological time series are corrected for gauge losses and elevation gradients using information in the file with parameter values and other characteristics common to all land cover and soil/bedrock classes.

5.8 File with long-term mean monthly potential evaporation values

Long-term mean monthly potential evaporation values are supplied in file named *monthlyEvaporation.txt*.

```
Month               Potential evaporation (mm/time step)
January      :      0.1
February     :      0.2
March        :      0.3
April        :      0.4
May          :      0.7
June         :      1.0
July         :      1.0
August       :      0.7
September    :      0.4
October      :      0.3
November     :      0.2
December     :      0.1
```

5.9 Running *hbv*

When *hbv* is run on a Linux system or using a Windows console interface the information necessary for running the program is read from a text file. In the example below, the text file is called *control_hbv.txt*. The model is started from the command prompt with the command:

hbv   control_hbv.txt

If the executable file *hbv* is not located in a directory in the search path of the computer session, the full or relative path to *hbv* must be provided.

File *control_hbv.txt* contains the information to be supplied to the user interface of program *hbv*. The texts in red colour are comments. Long lines in the file have been dived over two lines.

```
Type of model run, simulation (S) or calibration (C)      : S
          Type of model run: simulation(S) or calibration (C)
Model states, not in use(N), read(R), write(W) or both read and
write(B)                                                  : N
          Read or write model state variables from or to file
Input data format, grid files (G) or time series file (T) : T
          Meteorological input data format: Time series or Grid
Potential evaporation, temperature index (T) or long-term mean
monthly values                                           : T
          Potential evaporation estimation method
Output file name                                : hbv_out.txt
          Program development output file
Start model date and time (day, month, year, hour, minute)
                                                : 20 8 1996 0 0
```

```
          Start model spin-up dd mm yyyy hh mm
Start simulation date and time (day, month, year, hour, minute)
                                                : 20 9 1996 0 0
          Start simulation dd mm yyyy hh mm
End simulation date and time (day, month, year, hour, minute)
                                                : 17 11 1996 23 0
          End simulation dd mm yyyy hh mm
File with meteorological stations     : met_stations.txt
          Meteorological stations
File with common parameters           : hbv_common_parameters.txt
          Parameters for all classes
File with land surface parameters: hbv_landsurface_parameters.txt
          Land cover/ vegetation classes parameters
File with HBV subsurface parameters   : hbv_soil_parameters.txt
          Soil/bedrock classes parameters HBV
File with landscape elements selected for time series output
                                      : hbv_elements.txt
          Landscape elements with time series output HBV
File with landscape element information    : hbv_landscape.txt
          Landscape elements characteristics
File with observed streamflow data    : obs_streamflow.txt
          Observed streamflow data
File with sub-catchment hierarchy               : watershed.txt
          Watercourse/sub-catchment hierarchy
File with information about sub-catchment elements and landscape
elements                                   : hbv_waterland.txt
          Landscape elements within each watercourse/sub-catchment
File with precipitation and temperature correction for catchments
                                      : catchment_correction.txt
          Correction of meteorological data
File with input data                  : input_data.txt
          Meteorological input data in time series format
```

6 Model results

Program *hbv* calculated input data, state variables and fluxes for each watercourse/sub-catchment. The discharge from each sub-catchment and outlet in the model domain is determined after routing water through the hierarchies of watercourses and sub-catchments.

6.1 Model results files

Program *hbv* produces the following output files.

- A file with control information used during model development. The name of this file must be supplied when running the model. In the example above this file is called *hbv_out.txt*.

For each sub-catchment the following output files are produced. The values are average for each sub-catchment area, except discharge which is the accumulated value including all upslope sub-catchment areas, glacier mass balance and glacier ice volume which are average for the glacier covered area for each sub-catchment.

- *pre_<sub-catchment>.var* precipitation (*mm/time step*)
- *tem_<sub-catchment>.var* temperature (° *C*)
- *swe_<sub-catchment>.var* snow water equivalent (*mm*)
- *gmb_<sub-catchment>.var* glacier mass balance for glacier covered area (*mm*)
- *gim_<sub-catchment>.var* glacier ice melt averaged over subcatchment area (*mm*)
- *eva_<sub-catchment>.var* evaporation (*mm/time step*)
- *ins_<sub-catchment>.var* water flowing into the soil surface (*mm/time step*)
- *hsd_<sub-catchment>.var* HBV soil moisture deficit (*mm*)
- *hsm_<sub-catchment>.var* HBV soil moisture content (*mm*)
- *hpe_<sub-catchment>.var* percolation from soil moisture zone to upper zone (*mm/time step*)
- *huz_<sub-catchment>.var* HBV upper zone (*mm*)
- *hlz_<sub-catchment>.var* HBV lower zone (*mm*)
- *hgw_<sub-catchment>.var* HBV upp. and low. zone (*mm*)
- *lak_<sub-catchment>.var* lake water level (*mm*)
- *run_<sub-catchment>.var* runoff (*mm/time step*)
- *hbv_<sub-catchment>.var* discharge (m^3/s)

For each model element selected for HBV time series output.

- *HBV_groundwater_<element>.var* groundwater table depth (*m*)

7 Model parameters

The parameters of model *hbv* are used for modifying input data and calculating state variables and fluxes for all computational elements within the model domain, both landscape elements and watercourse elements. When no unit is given the parameters have dimension 1 or alternatively, no physical dimension.

7.1 Parameters common for all land cover and soil/bedrock classes

- **`PREC_GRAD_LOW, PREC_GRAD_HIGH:`** Gradients for precipitation increase per 100 m elevation change below and above elevation **`GRAD_CHANGE_ALT`**. A value of 1.0 means no change. A value of 1.1 means 10 % increase per 100 m elevation change. **`PREC_GRAD_HIGH`** will not be used if **`GRAD_CHANGE_ALT`** = 0.
- **`PREC_CORR_RAIN:`** Precipitation correction for rain (gauge undercatch).
- **`PREC_CORR_SNOW:`** Additional precipitation correction for snow(gauge undercatch).
- **`LAPSE_DRY, LAPSE_WET:`** Temperature lapse rates for dry and wet time steps (no rain or rain) per 100 m elevation change (˚C).
- **`DAY_TEMP_MEMORY:`** Temperature memory for lakes used in a simple method for modelling lake temperature (TimeStep).
- **`LAKE_EPOT_PAR:`** Controls lake evaporation rate (m/(TimeStep·˚C)).
- **`KLAKE:`** The constant of the rating curve of lakes (m).
- **`DELTA_LEVEL:`** The zero point of the rating curve of the lakes (m).
- **`NLAKE:`** Exponent of the rating curve of the lakes.
- **`INITIAL_SOIL_MOISTURE:`** Initial water content in soil moisture zone in HBV model elements (m).
- **`INITIAL_UPPER_ZONE:`** Initial water content in upper zone in HBV model elements (m).
- **`INITIAL_LOWER_ZONE:`** Initial water content in lower zone in HBV model elements (m).
- **`INITIAL_LAKE_TEMP:`** Initial temperature of lake elements (˚C).
- **`INITIAL_LAKE_LEVEL:`** Initial water level of lake elements (m).
- **`INITIAL_SNOW_STORAGE:`** Initial snow storage (m).
- **`INITIAL_TOTAL_RESERVOIR:`** Initial volume of water stored in lakes (m^3)
- **`DAY_SNOW_ZERO:`** Allows snow storage to be set to zero at the specified day of the year. If **`DAY_SNOW_ZERO`**= 0 the snow storage is not changed.

7.2 Land cover parameters

The parameters for land cover/vegetation are unique for each class.

- **`INTER_MAX:`** Maximum interception storage (m).
- **`EPOT_PAR:`** Controls potential evaporation rate (m/(TimeStep·˚C)).
- **`WET_PER_CORR:`** Controls reduction of ground evapotranspiration when intercepted water is stored on vegetation..
- **`ACC_TEMP:`** Threshold temperature for snow accumulation (˚C).
- **`MELT_TEMP:`** Threshold temperature for snow melt (˚C).

- **SNOW_MELT_RATE:** Controls snow melt rate (m/(TimeStep·˚C)).
- **ICE_MELT_RATE:** Controls ice melt rate for glaciers by multiplication with **SNOW_MELT_RATE**.
- **FREEZE_EFF:** Controls refreeze rate of liquid meltwater in snow by multiplication with **SNOW_MELT_RATE**.
- **MAX_REL:** Meltwater is retained in the snow until the amount of liquid water reaches the relative fraction of snowpack water equivalent given by **MAX_REL**.
- **ALBEDO:** Snow surface albedo.
- **CV_SNOW:** Coefficient of variation for lognormal distribution of snowfall.

7.3 HBV soil/bedrock parameters

The parameters for soil/bedrock are unique for each class.

- **FC:** Field capacity (m).
- **FCDEL:** Fraction of field capacity where reduction of evapotranspiration below potential level starts.
- **BETA:** Controls distribution function of soil moisture.
- **INFMAX:** Maximum infiltration rate (m/TimeStep).
- **KUZ:** Upper zone response coefficient.
- **ALFA:** Controls increase of upper zone response with increasing water content.
- **PERC:** Percolation from upper to lower zone (m/TimeStep).
- **KLZ:** Lower zone response coefficient.
- **DRAW:** Rate of draw up from lower zone to soil moisture zone (m/TimeStep).

7.4 Streamflow routing parameter

The time base of the triangular distribution, streamflow transformation function is given by the parameter **MAXBAS** in the file with watercourse/sub-catchment hierarchy description (same structure as file used by programs *stationMask*, *prehbv* and *hbv*).

8 HBV model algorithms

8.1 Vegetation

The vegetation cover is described as a lumped reservoir. Intercepted water stored on vegetation evaporates at the potential rate. As long as intercepted water is present, the fraction of the time step when actual evapotranspiration from the ground takes place is reduced according to:

$$DryPeriod = TimeStep - WetPeriod \cdot WET\_PER\_CORR$$

- *DryPeriod* is the fraction of *TimeStep* when evapotranspiration from the ground occurs.
- *TimeStep* is the time resolution of the model run.
- *WetPeriod* is the fraction of *TimeStep* when evaporation of intercepted water occurs at the potential rate.
- $0 \leq WET\_PER\_CORR \leq 1$

8.2 HBV model structure

The HBV model algorithms of program *hbv* are based on the Nordic HBV model (Sælthun, 1996), with some exceptions. One important difference is that the response function of the upper groundwater reservoir is based on the principle described by Lindström et al. (1997) where no threshold is applied. Runoff from the upper groundwater zone is given by:

$$Q_U = KUZ \cdot UZ^{ALFA}$$

- $ALFA > 1.0$

8.3 Streamflow routing

The streamflow generated from the response function of the model is routed through a transformation function in order to obtain a correct shape of the hydrograph at the outlet of the sub-catchments. This transformation function is a simple filter technique with a triangular distribution of the weights, as described by Lindström et al. (1997). The time base of the triangular distribution is given by the parameter *maxbas* which is set individually for each watershed/sub-catchment.

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