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FeST

flash–Flood Event–based Spatially distributed rainfall–runoff Transformation

User's Manual

May, 2025

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FeST
flash–Flood Event–based
Spatially distributed rainfall–
runoff Transformation

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INTRODUCTION

FEST is a spatially distributed hydrological model, developed at Politecnico di Milano by the Real Time Hydrology Group (www.fest.polimi.it) since the 1990s. FEST is the acronym of "flash–Flood Event–based Spatially distributed rainfall–runoff Transformation" that denotes how the first release of the model was oriented to the simulation of rainfall-runoff transformation of single flood events. After the first version was released, the FEST model has been subjected to continuous improvement and several hydrological processes have been integrated in the original code, transforming the FEST into a continuous integrated hydrological model. Several hydrological models have been derived from FEST such as AFFDEF (Moretti and Montanari, 2007), and DIMOSOP (Ranzi et al., 2003).

The FEST model has been designed to be applied across a wide range of spatial and temporal scales. All internal state variables (discharge, soil moisture, evapotranspiration, snow water equivalent, groundwater head, etc…) can be written as output. All output can be written as time series at user-defined points or areas. The user has complete control on the saving of the output data, thus minimising any waste of disk space or CPU time.

FEST has been applied to a wide range of water resources applications such as discharge assessment for flood risk analysis (Ravazzani et al., 2014), flood forecasting, soil moisture assessment and forecasting for irrigation scheduling, impacts assessment of climate and land-use changes (Ceppi et al., 2022) on water resources availability and flood severity.

CHAPTER 1
SUPPORTED FORMATS

This section lists the file format supported by the *FeST* model.

1.1 Raster map formats

The FEST model supports natively three file formats for grid map:

- ESRI ASCII grid
- ESRI BINARY grid
- Net CDF

1.1.1 ESRI ASCII grid

The ESRI ASCII raster format file begins with header information that defines the properties of the raster such as the cell size, the number of rows and columns, and the coordinates of the origin of the raster. The header information is followed by cell value information specified in space-delimited row-major order, with each row separated by a carriage return.

The basic structure of the ESRI ASCII raster has the header information at the beginning of the file followed by the cell value data:

```
NCOLS xxx
NROWS xxx
XLLCORNER xxx
YLLCORNER xxx
CELLSIZE xxx
NODATA_VALUE xxx
    row 1
    row 2
    ...
    row n
```

WARNING
Currently the supplementary .prj file used to assign spatial reference system to the grid is not supported. Spatial reference information should be set in FEST configuration files.

Header format

The syntax of the header information is a keyword paired with the value of that keyword. The definitions of the keywords are:

Table 1.1. Definition of keywords in ESRI ASCII grid file.

Parameter	Description	Requirements
NCOLS	Number of cell columns.	Integer greater than 0.
NROWS	Number of cell rows.	Integer greater than 0.
XLLCORNER	X coordinate of the origin by lower left corner of the cell	Match with Y coordinate type.
YLLCORNER	Y coordinate of the origin by lower left corner of the cell	Match with X coordinate type.
CELLSIZE	Cell size.	Greater than 0.
NODATA_VALUE	The input values to be NoData in the output raster.	Default is -9999 but a different value can be used

Data format

The data component of the ESRI ASCII raster follows the header information.

- Cell values should be delimited by spaces.
- No carriage returns are necessary at the end of each row in the raster. The number of columns in the header determines when a new row begins.
- Row 1 of the data is at the top of the raster, row 2 is just under row 1, and so on.

1.1.2 ESRI BINARY grid

ESRI BINARY grid is similar to ESRI ASCII grid, however, there are two differences. First, in ESRI BINARY grid the gridded data values are in binary form, typically resulting in smaller files. Second, ESRI BINARY grid is a pair of files: a simple text file with extension .hdr that contains the same information as the first six lines of the equivalent ESRI ASCII grid with one additional line; and the primary content of numeric values in binary form in a file with extension .flt. The two files are associated by sharing the filename before the period, e.g., myfile.flt and myfile.hdr.

Header format

The header file defines the properties of the grid, such as the cell size, the number of rows and columns, and the coordinates of the origin of the rectangular grid. The header keywords can be in upper or lower case.

The syntax of the header information is a keyword paired with the value of that keyword. The definitions of the keywords are:

Table 1.2. Definition of keywords in ESRI BINARY header file .hdr.

Parameter	Description	Requirements
NCOLS	Number of cell columns.	Integer greater than 0.
NROWS	Number of cell rows.	Integer greater than 0.
XLLCORNER	X coordinate of the origin by lower left corner of the cell	Match with Y coordinate type.
YLLCORNER	Y coordinate of the origin by lower left corner of the cell	Match with X coordinate type.
CELLSIZE	Cell size.	Greater than 0.
NODATA_VALUE	The input values to be NoData in the output raster.	Default is -9999 but a different value can be used
BYTEORDER MSBFIRST or BYTEORDER LSBFIRST	Specifying whether the values have the most significant byte first or the least significant byte first	BYTEORDER LSBFIRST

Data format

The .flt file holds values for a single numeric measure, a value for each cell in the rectangular grid. The numeric values are in IEEE floating-point 32-bit (aka single-precision) signed binary format. The first number in the .flt file corresponds to the top left cell of the raster/grid. Going from left to right along the top row, the first 32 bits form the value for the first cell, the next 32 bits the value for the second cell, and so on, to the end of the top row. This is repeated for the second row of the raster, continuing to the lower right-hand cell.

1.1.3 NetCDF

NetCDF (network Common Data Form) is a file format for storing multidimensional scientific data (variables) such as temperature, humidity, pressure, wind speed, and direction. NetCDF file has usually extenson .nc, however different extensions may be encountered.

NetCDF data is:

- Self-Describing. A netCDF file includes information about the data it contains.
- Portable. A netCDF file can be accessed by computers with different ways of storing integers, characters, and floating-point numbers.
- Scalable. A small subset of a large dataset may be accessed efficiently.
- Appendable. Data may be appended to a properly structured netCDF file without copying the dataset or redefining its structure.
- Sharable. One writer and multiple readers may simultaneously access the same netCDF file.

The data in a netCDF file is stored in the form of arrays. For example, temperature varying over time at a location is stored as a one-dimensional array. Temperature over an area for a given time is stored as a two-dimensional array.

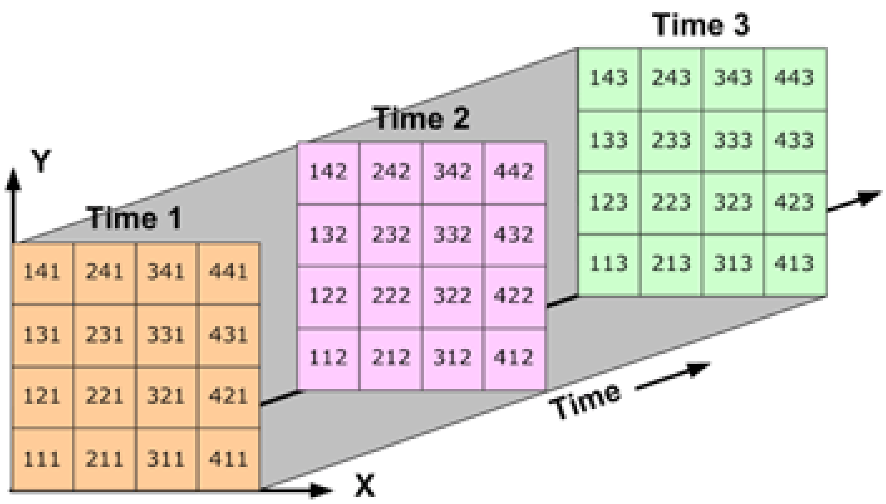

Figure 1.1 three-dimensional data: Data over an area varying with time (source: http://pro.arcgis.com/en/pro-app/help/data/multidimensional/fundamentals-of-netcdf-data-storage.htm)

Three-dimensional (3D) data, like temperature over an area varying with time, or four-dimensional (4D) data, like temperature over an area varying with time and altitude, is stored as a series of two-dimensional arrays.

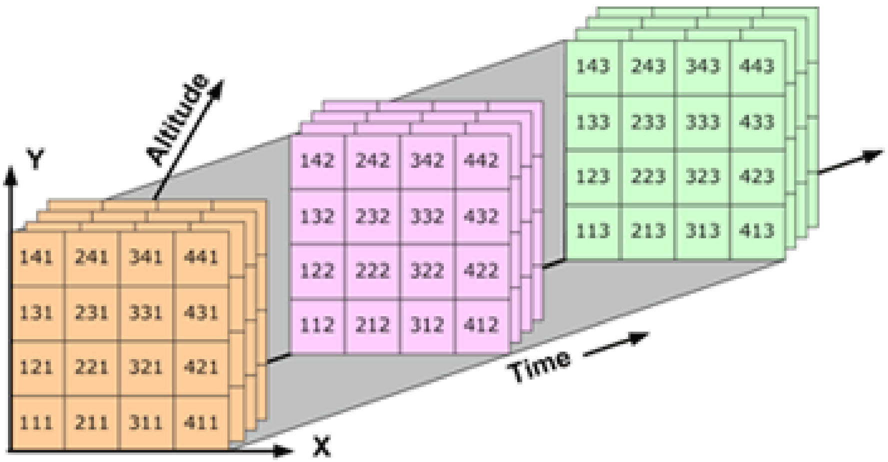

Figure 1.2 Four-dimensional data: Data over an area varying with time and altitude (source: http://pro.arcgis.com/en/pro-app/help/data/multidimensional/fundamentals-of-netcdf-data-storage.htm)

A netCDF file contains dimensions, variables, and attributes. These components are used together to capture the meaning of data and relations among data fields in an array-oriented dataset.

Many organizations and scientific groups in different countries have adopted netCDF as a standard way to represent some forms of scientific data, sometimes by defining a convention. The conventions define metadata that provides a definitive description of the data in each variable and their spatial and temporal properties. A convention helps users of data from different sources to decide which quantities are comparable. The name of the convention is presented as a global attribute in a netCDF file. Currently, the Climate and Forecast (CF) (http://cfconventions.org/) is supported.

For more information about NetCDF, visit: http://www.unidata.ucar.edu/software/netcdf/

1.2 Supported spatial reference systems

All maps of input parameters (i.e. the digital elevation model, soil saturated hydraulic conductivity, etc..) and site data (i.e. precipitation, air temperature, etc..) must be spatially referenced in either one of the supported Spatial Reference Systems.

List of supported projections:

- Geodetic
- Universal Transverse Mercator
- Transverse Mercator
- Gauss Boaga (Italy)
- Hotine Oblique Mercator
- Swiss Oblique Cylindrical

List of supported datums:

- World Geodetic System 1984
- European Datum 1950
- Monte Mario
- Swiss grid (CH1903)

Assignment of SRS is done within the input file for maps in netCDF format and site data, or through the FEST configuration files for ESRI ASCII and ESRI BINARY grids. SRS assignment is done according to EPSG (http://www.epsg.org/).

List of accepted values:

4326 GEODETIC, WGS84

4230 GEODETIC, ED50

3003 Gauss Boaga West

3004 Gauss Boaga East

21781 CH1903 Swiss topo

23028 ED50 / UTM zone 28N

23029 ED50 / UTM zone 29N

23030 ED50 / UTM zone 30N

23031 ED50 / UTM zone 31N

23032 ED50 / UTM zone 32N

23033 ED50 / UTM zone 33N

23034 ED50 / UTM zone 34N

23035 ED50 / UTM zone 35N

23036 ED50 / UTM zone 36N

23037 ED50 / UTM zone 37N

23038 ED50 / UTM zone 38N

32601 WGS 84 / UTM zone 1N

32602 WGS 84 / UTM zone 2N

32603 WGS 84 / UTM zone 3N

32604 WGS 84 / UTM zone 4N

32605 WGS 84 / UTM zone 5N

32606 WGS 84 / UTM zone 6N

32607 WGS 84 / UTM zone 7N

32608 WGS 84 / UTM zone 8N

32609 WGS 84 / UTM zone 9N

32610 WGS 84 / UTM zone 10N

32611 WGS 84 / UTM zone 11N

32612 WGS 84 / UTM zone 12N

32613 WGS 84 / UTM zone 13N

32614 WGS 84 / UTM zone 14N

32615 WGS 84 / UTM zone 15N

32616 WGS 84 / UTM zone 16N

32617 WGS 84 / UTM zone 17N

32618 WGS 84 / UTM zone 18N

32619 WGS 84 / UTM zone 19N

32620 WGS 84 / UTM zone 20N

32621 WGS 84 / UTM zone 21N

32622 WGS 84 / UTM zone 22N

32623 WGS 84 / UTM zone 23N

32624 WGS 84 / UTM zone 24N

32625 WGS 84 / UTM zone 25N

32626 WGS 84 / UTM zone 26N

32627 WGS 84 / UTM zone 27N

32628 WGS 84 / UTM zone 28N

32629 WGS 84 / UTM zone 29N

32630 WGS 84 / UTM zone 30N

32631 WGS 84 / UTM zone 31N

32632 WGS 84 / UTM zone 32N

32633 WGS 84 / UTM zone 33N

32634 WGS 84 / UTM zone 34N

32635 WGS 84 / UTM zone 35N

32636 WGS 84 / UTM zone 36N

32637 WGS 84 / UTM zone 37N

32638 WGS 84 / UTM zone 38N

32639 WGS 84 / UTM zone 39N

32640 WGS 84 / UTM zone 40N

32641 WGS 84 / UTM zone 41N

32642 WGS 84 / UTM zone 42N

32643 WGS 84 / UTM zone 43N

32644 WGS 84 / UTM zone 44N

32645 WGS 84 / UTM zone 45N

32646 WGS 84 / UTM zone 46N

32647 WGS 84 / UTM zone 47N

32648 WGS 84 / UTM zone 48N

32649 WGS 84 / UTM zone 49N

32650 WGS 84 / UTM zone 50N

32651 WGS 84 / UTM zone 51N

32652 WGS 84 / UTM zone 52N

32653 WGS 84 / UTM zone 53N

32654 WGS 84 / UTM zone 54N

32655 WGS 84 / UTM zone 55N

32656 WGS 84 / UTM zone 56N

32657 WGS 84 / UTM zone 57N

32658 WGS 84 / UTM zone 58N

32659 WGS 84 / UTM zone 59N

32660 WGS 84 / UTM zone 60N

32701 WGS 84 / UTM zone 1S

32702 WGS 84 / UTM zone 2S

32703 WGS 84 / UTM zone 3S

32704 WGS 84 / UTM zone 4S

32705 WGS 84 / UTM zone 5S

32706 WGS 84 / UTM zone 6S

32707 WGS 84 / UTM zone 7S

32708 WGS 84 / UTM zone 8S

32709 WGS 84 / UTM zone 9S

32710 WGS 84 / UTM zone 10S

32711 WGS 84 / UTM zone 11S

32712 WGS 84 / UTM zone 12S

32713 WGS 84 / UTM zone 13S

32714 WGS 84 / UTM zone 14S

32715 WGS 84 / UTM zone 15S

32716 WGS 84 / UTM zone 16S

32717 WGS 84 / UTM zone 17S

32718 WGS 84 / UTM zone 18S

32719 WGS 84 / UTM zone 19S

32720 WGS 84 / UTM zone 20S

32721 WGS 84 / UTM zone 21S

32722 WGS 84 / UTM zone 22S

32723 WGS 84 / UTM zone 23S

`32724` WGS 84 / UTM zone 24S

`32725` WGS 84 / UTM zone 25S

`32726` WGS 84 / UTM zone 26S

`32727` WGS 84 / UTM zone 27S

`32728` WGS 84 / UTM zone 28S

`32729` WGS 84 / UTM zone 29S

`32730` WGS 84 / UTM zone 30S

`32731` WGS 84 / UTM zone 31S

`32732` WGS 84 / UTM zone 32S

`32733` WGS 84 / UTM zone 33S

`32734` WGS 84 / UTM zone 34S

`32735` WGS 84 / UTM zone 35S

`32736` WGS 84 / UTM zone 36S

`32737` WGS 84 / UTM zone 37S

`32738` WGS 84 / UTM zone 38S

`32739` WGS 84 / UTM zone 39S

`32740` WGS 84 / UTM zone 40S

`32741` WGS 84 / UTM zone 41S

`32742` WGS 84 / UTM zone 42S

`32743` WGS 84 / UTM zone 43S

`32744` WGS 84 / UTM zone 44S

`32745` WGS 84 / UTM zone 45S

`32746` WGS 84 / UTM zone 46S

`32747` WGS 84 / UTM zone 47S

`32748` WGS 84 / UTM zone 48S

`32749` WGS 84 / UTM zone 49S

`32750` WGS 84 / UTM zone 50S

`32751` WGS 84 / UTM zone 51S

`32752` WGS 84 / UTM zone 52S

`32753` WGS 84 / UTM zone 53S

`32754` WGS 84 / UTM zone 54S

`32755` WGS 84 / UTM zone 55S

`32756` WGS 84 / UTM zone 56S

`32757` WGS 84 / UTM zone 57S

`32758` WGS 84 / UTM zone 58S

`32759` WGS 84 / UTM zone 59S

`32760` WGS 84 / UTM zone 60S

1.3 Date and time format

The date and time string adheres to the International Standard ISO 8601 specifications. Date and time is expressed in the form `YYYY-MM-DDThh:mm:ssTZD` where:

`YYYY` = four-digit year

`MM` = two-digit month (01=January, etc.)

`DD` = two-digit day of month (01 through 31)

`hh` = two digits of hour (00 through 23) (am/pm NOT allowed)

`mm` = two digits of minute (00 through 59)

`ss` = two digits of second (00 through 59)

`TZD` = time zone designator (`+hh:mm` or `-hh:mm`)

A time zone offset of "`+hh:mm`" indicates that the date/time uses a local time zone which is "`hh`" hours and "`mm`" minutes ahead of UTC (Coordinated Universal Time). A time zone offset of "-`hh:mm`" indicates that the date/time uses a local time zone which is "`hh`" hours and "`mm`" minutes behind UTC.

Example: `2007-03-05T01:00:00+02:00`

1.4 Time series of site data

Time series of site data, such as precipitation or air temperature data acquired by meteorological stations, are stored in plain text files. File suffix assigned to the file is usually `.fts` (fest time series), but any suffix is allowed. Every file contains data of the same variable of all available stations. So for performing an hydrological simulation you need to prepare one file with all precipitation data available, one with air temperature data, and so on. The time step must be regular along one file. Time step can be different from file to file (for example hourly precipitation and daily air temperature data are allowed).

In each file, the first 7 rows define general information of the included data in a key-value paradigm (see Chapter 2):

Table 1.3. Definition of keywords in time series of site data file.

Key	Description
`description`	Describes data included
`unit`	Unit of data included
`epsg`	EPSG code of data spatial reference system

Key	Description
`count`	Total number of stations
`dt`	Time step in second
`missing-data`	Number for missing data value
`offsetz`	Station height above terrain in meter

A section identified by the keyword `metadata` follows. It marks the beginning of the station metadata information. For each station the user must include, in the order, station name (without blank spaces), station id, easting and northing coordinate, and elevation.
A section identified by the keyword `data` follows. It marks the beginning of time series data. The first line after the `data` keyword is a comment line usually used to recall station id, but any kind of comment can be included here without compromising the simulation. The following lines after the comment line include the date and time of the data, and the list of data acquired by the stations in the same order used to list stations in the metadata section.
Note that time steps must be perfectly regular (no any gap in date and time is allowed) and no any gap (blanck space) must be present in data section. When one data is missing, it must be substituted by the missing data value code. Data and strings are separated by one or more blank spaces or tabs. A dot (.) is used as decimal separator.

The next example shows a time series file that contains air temperature data from 3 stations at hourly time step for a total of 24 hours. Coordinate reference system is Monte Mario / Italy zone 1 (epsg code 3003), value for missing data is -999.9 and station height above terrain is 2 m.

```
description = air temperature
unit = degree_Celsius
epsg = 3003
count = 3
dt = 3600 # second
missing-data = -999.9
offsetz = 2 #station height above terrain(m)

metadata
station1  id1  1520147.2  5038191.3   120.4
station2  id2  1538227.4  5003859.6   80.7
station3  id3  1520740.5  5038780.8   120.5


data
time                        id1   id2   id3
2004-03-27T00:00:00+00:00   6.1   5.7   5.8
2004-03-27T01:00:00+00:00   5.6   5.6   5.5
2004-03-27T02:00:00+00:00   5.7   5.6   5.5
2004-03-27T03:00:00+00:00   5.5   5.4   5.3
2004-03-27T04:00:00+00:00   5.3   5.2   5.2
2004-03-27T05:00:00+00:00   5.4   5.1   5.3
2004-03-27T06:00:00+00:00   5.5   4.9   5.4
2004-03-27T07:00:00+00:00   5.7  -999.9 5.4
2004-03-27T08:00:00+00:00   5.7  -999.9 5.5
2004-03-27T09:00:00+00:00   5.8   5.5   5.7
2004-03-27T10:00:00+00:00   6.6   5.7   6.3
2004-03-27T11:00:00+00:00   7.1   6.5   6.9
2004-03-27T12:00:00+00:00   7.5   7.7   7.3
2004-03-27T13:00:00+00:00   7.9   8.7   7.5
2004-03-27T14:00:00+00:00   8.5   9.3   8.5
2004-03-27T15:00:00+00:00   9.9   9.3   9.6
2004-03-27T16:00:00+00:00   9.7   9.6   9.5
2004-03-27T17:00:00+00:00   9.1   8.8   9.2
2004-03-27T18:00:00+00:00   7.9   7.5   8.4
2004-03-27T19:00:00+00:00   6.8   6.3   8.2
2004-03-27T20:00:00+00:00   6.7   6.1   7.3
2004-03-27T21:00:00+00:00   6.8   6.0   7.2
2004-03-27T22:00:00+00:00   6.9   5.9   7.1
2004-03-27T23:00:00+00:00   6.9   5.7   6.9
```

Example of time series of site data file

1.5 Time series of generic variable

Time series of generic variables, are stored in plain text files. File suffix assigned to the file is usually `.out` (generic time series output), but any suffix is allowed. One file may contain one or more variables of different kind. The time step is regular along one file.

The first lines of file contains information about file content, without a specific order or format.

A section identified by the keyword `data` follows. It marks the beginning of time series data. The first line after the `data` keyword is a comment line usually used to mark the content of each column in the file. Data are separated by one or more blank spaces or tabs. A dot (.) is used as decimal separator.

The next example shows a time series file that contains average precipitation and air temperature over the Piave river at Longarone.

```
spatial average values of meteorological variables
extent id: 01
extent name: longarone
extent area (km2):      1328.18872
number of variables:     2

data
DateTime          precipitation_mm  air-temperature_Celsius
2018-10-15T00:00:00+00:00   0.00000E+00      0.34635E+01
2018-10-15T01:00:00+00:00   0.00000E+00      0.35652E+01
2018-10-15T02:00:00+00:00   0.00000E+00      0.33697E+01
2018-10-15T03:00:00+00:00   0.00000E+00      0.35632E+01
2018-10-15T04:00:00+00:00   0.00000E+00      0.38865E+01
2018-10-15T05:00:00+00:00   0.00000E+00      0.39953E+01
2018-10-15T06:00:00+00:00   0.12359E-02      0.41558E+01
2018-10-15T07:00:00+00:00   0.13124E-02      0.46632E+01
2018-10-15T08:00:00+00:00   0.00000E+00      0.53044E+01
2018-10-15T09:00:00+00:00   0.00000E+00      0.61314E+01
2018-10-15T10:00:00+00:00   0.41156E-02      0.64432E+01
2018-10-15T11:00:00+00:00   0.18876E-01      0.67689E+01
2018-10-15T12:00:00+00:00   0.37281E-01      0.63840E+01
```

Example of generic variables time series file

1.6 Tables

Tables are used to organize information with column information in the header and one line of data per record. Tables are stored on plain text files. They are formatted according to a standard that takes inspiration from the ODT file format (*http://math.nist.gov/oommf/doc/userguide11b2/userguide/Data_table_format_ODT.html*).

Tables can be used within a *ini* configuration file (see Chapter 2) or within a file that contain only tables. In this case, it is recommended that files be given names ending in the file extension `.tab` so that table files can be easily identified. Every file can contain one or more tables. Table may contain an unlimited number of columns and lines. An header and a unit is associated to each column. Hash (#) indicates the beginning of a comment. Table may contain blank lines.

The lines of a table should be comments, data, or any of the following 5 recognized descriptor tag lines:

- `Table Start`: mandatory, used to mark the beginning of a new table.
- `Title`: optional; everything after the colon is interpreted as a title for the table.
- `Id`: mandatory; an alphanumeric string that define uniquely the table.
- `Columns`: mandatory. One parameter per column, enclosed between two square brackets `[ ]`.
- `Units`: mandatory. One parameter for each column, enclosed between two square brackets `[ ],` giving a unit label for the corresponding column.
- `Table End`: mandatory, no parameters. Should be paired with a corresponding `Table Start` record to mark the end of the table.

Data may appear anywhere after the `Units` descriptor record and before any `Table End` line, with one record per line. The data should be numeric values or string separated by whitespace.

```
Table    Start
Title:  This is a small example of table
# This is a sample comment.  You can put anything you want
# on comment lines.
Id: type here Id of table      # example of inline comment
Columns:     [header1]       [header2]          [header3]
Units:        [-]             [-]                [m3/s]
             1               name1              13.2
             2               name2              10.8
             3               name3              5.35

# this is a comment: the above line is blank
Table End
```

Example of table

CHAPTER 2
CONFIGURATION FILES: GENERAL TIPS

Configuration files are used to initialize variables, assign file names, or choose options to run hydrological simulations. Configuration files follow the INI file format. INI files are plain text files with a basic structure composed of sections and subsections, properties, and values.
The basic element contained in an INI file is the key or property. Every key has a name and a value, delimited by an equals sign (=). Order of key-value pairs is arbitrary (i.e. there’s no need to pay attention to the position of lines in a file). The name appears to the left of the equals sign:

```
name = value
```

Example of name-value pair

Keys may be grouped into arbitrarily named sections or subsections. The section name appears on a line by itself, in square brackets ([and]). All keys after the section declaration are associated with that section. The subsection name appears on a line by itself, in double square brackets ([[and]]). All keys after the subsection declaration are associated with that subsection. Properties that are declared before any section and subsection are declared are considered "global" properties.
Hash (#) at the beginning or in the middle of the line indicates a comment. Comment lines are ignored.

```
name1 = value
name2 = value
# comment
[section1]
  name1 = value # comment
  name2 = value
 [[subsection]]
   name1 = value
   name2 = value

[section2]
  name1 = value
  name2 = value
  name3 = value
```

Example of INI file with two sections and one subsection and comments.

2.1 Assigning a map as input

A common means to assign maps in FEST configuration files is by setting a section (within square brakets [ ]) or subsection (within double square brakets [[ ]]) that specifies the file to read, the format and optional properties that change according to the specified format. Supported formats are: `esri-ascii`, `esri-binary`, and `net-cdf`. For esri ascii and binary formats, spatial reference system is assigned by setting epsg property.

```
[dem]  # section named dem defining a map
    file = ./data/dem.asc
    format = esri-ascii
    epsg = 3003
```

Example of section that defines a map in esri-ascii format with spatial reference system UTM 32 north wgs84 (EPSG code 3003).

NetCdf is the preferred format when a parameter is assumed to change during simulation time span, like in the case of leaf area index for vegetation, or the snow melt coefficient. When NetCdf format is assigned as input map, different options must or can be assigned in order to properly read the map. The variable to be read can be assigned by variable name (`variable =`) or its standard name (`standard_name =`). The first map to be read can be assigned by specifying a date and time (`time = YYYY-MM-DDThh:mm:ss+hh:mm`) or setting the `sync-initial-time` option (`sync-initial-time = 1`) that automatically sets the proper map to be read according to the simulation starting date and time.

```
[lai]  # leaf area index map
    file = ./data/lai.nc
    format = net-cdf
    variable = lai
    epsg = 3003
    sync-initial-time = 1
```

Example of section that defines a map in net-cdf format with spatial reference system UTM 32 north wgs84 (EPSG code 3003), and lai as name of variable to be read. The date and time of the first map to be read is automatically assigned by the model (`sync-initial-time = 1`)

For some parameters an option to set a constant value for the entire simulation domain is to use the `scalar` keyword, as in the example below.

```
[hydraulic-conductivity]
    scalar = 0.00001
```

Example of section that defines a map with a constant value. Spatial extent and reference system is inherited from the reference ones assigned to the simulation run.

Parameter map values can be modified with `scale_factor` and `offset` keywords. The keyword `scale_factor` is used to multiply all cells value by a numerical factor. The keyword `offset` is used to add (or subtract) a fixed value to all cells value. Keywords `valid_min` and `valid_max` can be used optionally to bound the resulting values to a minimum and a maximum value.

```
[hydraulic-conductivity]
    file = ./data/ksat.asc
    format = esri-ascii
    epsg = 3003
    scale_factor = 0.1
```

Example of section that defines the map of hydraulic conductivity from a file in esri-ascii format. Values are multiplies by 0.1 (one order of magnitude reduction).

```
[curve-number]
    file = ./data/cn.asc
    format = esri-ascii
    epsg = 3003
    offset = 10
    valid_max = 100
```

Example of section that defines the map of curve number from a file in esri-ascii format. The value 10 is added to all cells value. The maximum value the curve number can reach is set to 100 (`valid_max = 100`).

CHAPTER 3
THE MAIN CONFIGURATION FILE

This file sets the main parameters for running a simulation such as the starting and ending date and time, the modules to be activated, the results to be put in output files, etc.... The name of the file is chosen by user but, usually, the name `fest.ini` is assigned. The file includes a list of sections, mandatory or optional, that configure a specific module of FEST model. An example of main configuration file is shown below.

```
#set start and stop time. Always use UTC. MANDATORY
[time]
  start = 2005-01-01-00:00:00+00:00
  stop  = 2022-08-31-23:00:00+00:00

# set folder for writing results. MANDATORY
# ./folder/ example for setting a folder
# ./folder/prefix_  append a prefix (prefix_) to all output files
[result]
  folder = ./results/sim0_

# simulation mask and general domain properties. MANDATORY
[domain]
  conf-file = ./conf/domain.ini

# set morphological properties. OPTIONAL
[morphology]
  conf-file = ./conf/morphology.ini

# meteorological forcings. MANDATORY
[meteo]
  dt = 3600
  conf-file = ./conf/meteo.ini
  dt-out-spatial = 3600
  out-point-file = ./conf/point_meteo.fts

# plants simulation. OPTIONAL
[plants]
  dt = 0
  conf-file = ./conf/plants.ini

#snow accumulation and melting. OPTIONAL
[snow]
  dt = 3600
  conf-file =  ./conf/snow.ini
  dt-out-spatial = 3600

#soil balance. OPTIONAL
[soil-balance]
  dt = 3600
  conf-file = ./conf/soil-balance.ini
  dt-out-spatial = 3600

#configure spatial average output. OPTIONAL
[spatial-average]
  conf-file = ./conf/spatial_average.ini

# discharge routing on hillslope,rivers, and lakes. OPTIONAL
[discharge-routing]
  dt = 900
  conf-file = ./conf/discharge-routing.ini
  out-point-file = ./conf/discharge_out.fts
```

Example of main configuration file for running a simulation. In this example, all configuration files are stored in `conf` subfolder.

3.1 Time

This mandatory section, marked by `[time]`, sets the starting and ending date and time of simulation. Keywords to be set are listed in the following table.

Table 3.1. Definition of keywords to set simulation time.

Keyword	Description	Requirements
`[time]`	Marks the beginning line of `time` section	mandatory
`start`	Starting date and time of simulation formatted according to ISO 8601 specifications in UTC time zone.	mandatory
`stop`	Ending date and time of simulation formatted according to ISO 8601 specifications in UTC time zone.	mandatory

The following example sets the starting time of simulation at 2005-01-01-00:00:00+00:00 and ending time at 2022-08-31-23:00:00+00:00.

```
#set start and stop time. Always use UTC. MANDATORY
[time]
  start = 2005-01-01-00:00:00+00:00
  stop  = 2022-08-31-23:00:00+00:00
```

Example of `[time]` section configuration within the main configuration file

3.2 Result

This mandatory section, marked by `[result]`, sets the folder where to save output files of simulation results. Keywords to be set are listed in the following table.

Table 3.2. Definition of keywords to set result folder.

Keyword	Description	Requirements
`[result]`	Marks the beginning line of `result` section	mandatory
`folder`	Sets folder name to write results. A prefix to be appended to all files can be set as in the example: `folder = ./results/sim0_` Use `folder = ./results/` instead, to leave prefix blank	mandatory

The following example sets the folder `output` for storing result files. This example uses the relative path nomenclature to specify the result folder as a subfolder of the current directory. The prefix `sim0_` is appended at the beginning of output files. For understanding how output files are named see the specific sections.

```
# set folder for writing results. MANDATORY
# ./folder/ example for setting a folder
# ./folder/prefix_  append a prefix (prefix_) to all output files
[result]
  folder = ./output/sim0_
```

Example of `[result]` section configuration within the main configuration file

3.3 Domain

This mandatory section, marked by `[domain]`, sets the file to configure simulation domain. Keywords to be set are listed in the following table.

Table 3.3. Definition of keywords to set simulation domain configuration file.

Keyword	Description	Requirements
`[domain]`	Marks the beginning line of `domain` section	mandatory
`conf-file`	Sets the name of configuration file	mandatory

The following example sets the file `./conf/domain.ini` for configuring simulation domain.

```
# simulation mask and general domain properties. MANDATORY
[domain]
  conf-file = ./conf/domain.ini
```

Example of `[domain]` section configuration within the main configuration file

3.4 Morphology

This optional section, marked by `[morphology]`, sets the file to configure morphological properties. Keywords to be set are listed in the following table.

Table 3.4. Definition of keywords to set the file to configure morphological properties.

Keyword	Description	Requirements
`[morphology]`	Marks the beginning line of `morphology` section	optional
`conf-file`	name of configuration file	mandatory

The following example sets the file `./conf/morphology.ini` for configuring morphological properties.

```
# set morphological properties. OPTIONAL
[morphology]
  conf-file = ./conf/morphology.ini
```

Example of `[morphology]` section configuration within the main configuration file

3.5 Meteo

This mandatory section, marked by `[meteo]`, sets parameters for configuring meteorological forcings management. Keywords to be set are listed in the following table.

Table 3.5. Definition of keywords to set parameters for configuring meteorological forcings.

Keyword	Description	Requirements
`[meteo]`	Marks the beginning line of `meteo` section	mandatory
`dt`	time step for new data reading (s)	mandatory
`conf-file`	name of configuration file	mandatory
`dt-out-spatial`	Time step for writing spatial average data (s). If section is not present or `dt-out-spatial = 0`, output files are not created and data are not exported.	optional
`out-point-file`	File that contains coordinate of points for exporting site data. It is a plain text file in time series format with only the metadata section (see example below). The time step defined in the file, sets the export time step (s). If file is not assigned, data are not exported. List of	optional

Keyword	Description	Requirements
	created files in Table 3.6	

Table 3.6. Name of files created for exporting sites meteorological data. The folder assigned in `[result]` section (see 3.2) is appended to the name of file as a prefix.

Variable	File name
Precipitation	`<folder> point_precipitation.fts`
Air temperature	`<folder> point_temperature.fts`
Solar radiation	`<folder> point_radiation.fts`
Air relative humidity	`<folder> point_RH.fts`
Wind speed	`<folder> point_WS.fts`

The following example sets the file `./conf/meteo.ini` for configuring meteorological forcings, a time step for reading data = 3600, a time step for exporting spatial average data = 3600, and sets the file `./conf/point_meteo.fts` for listing the coordinate of points to export site data. A new file is created for each meteorological variable used in the simulation run with file name listed in Table 3.6

```
# meteorological forcings. MANDATORY
[meteo]
  dt = 3600
  conf-file = ./conf/meteo.ini
  dt-out-spatial = 3600
  out-point-file = ./conf/point_meteo.fts
```

Example of `[meteo]` section configuration within the main configuration file

The following is an example of `out-point-file` for exporting data in five sites with time step of 3600 s. Keywords `unit` and `offsetz` are not used by the process but they must exist for adhering to standard time series data format.

```
description = points coordinate for meteo data export
unit  =     -
epsg  =     32632
count =     5
dt    =     3600
missing-data = -999.9
offsetz = 2



metadata
site1      01  614452.00 5066300.00  0.00
site2      02  612452.00 5048300.00  0.00
site3      03  609952.00 5022550.00  0.00
site4      04  610702.00 5008550.00  0.00
site5      05  613702.00 5065550.00  0.00
```

Example of `out-point-file`

3.6 Plants

This optional section, marked by `[plants]`, sets parameters to configure plants properties and simulation. Keywords to be set are listed in the following table.

Table 3.7. Definition of keywords to set parameters to configure plants properties and simulation.

Keyword	Description	Requirements
`[plants]`	Marks the beginning line of `plants` section	optional
`dt`	time step for computation (s). If `dt = 0`, parameters are kept constant; if `dt > 0`, parameters are updated in time with a simulation.	mandatory
`conf-file`	name of configuration file	mandatory
`dt-out-spatial`	Time step for writing spatial average data (s). If section is not present or `dt-out-spatial = 0`, output files are not created and data are not exported.	optional

The following example sets the file `./conf/plants.ini` for configuring plants properties that are kept constant in time (`dt = 0`).

```
# plants simulation. OPTIONAL
[plants]
  dt = 0
  conf-file = ./conf/plants.ini
```

Example of `[plants]` section configuration within the main configuration file

3.7 Snow

This optional section, marked by `[snow]`, sets parameters for configuring snow simulation (accumulation and melting). Keywords to be set are listed in the following table.

Table 3.8. Definition of keywords to set parameters for configuring snow simulation.

Keyword	Description	Requirements
`[snow]`	Marks the beginning line of `snow` section	optional
`dt`	time step for computation (s)	mandatory
`conf-file`	name of configuration file	mandatory
`dt-out-spatial`	Time step for writing spatial average data (s). If section is not present or `dt-out-spatial = 0`, output files are not created and data are not exported.	optional
`out-point-file`	File that contains coordinate of points for exporting site snow water equivalent data. It is a plain text file in time series format with only the metadata section (see example in 3.5). The time step defined in the file, sets the export time step (s). If file is not assigned, data are not exported. Name of file created: `<folder> point_swe.fts`	optional

The following example sets the file `./conf/snow.ini` for configuring snow simulation, a time step for computing = 3600, and a time step for exporting spatial average data = 3600.

```
#snow accumulation and melting. OPTIONAL
[snow]
  dt = 3600
  conf-file =  ./conf/snow.ini
  dt-out-spatial = 3600
```

Example of `[snow]` section configuration within the main configuration file

3.8 Glacier

This optional section, marked by [glacier], sets parameters for configuring glacier simulation (accumulation and ablation). Keywords to be set are listed in the following table.

Table 3.9. Definition of keywords to set parameters for configuring glacier simulation.

Keyword	Description	Requirements
[glacier]	Marks the beginning line of snow section	optional
dt	time step for computation (s)	mandatory
conf-file	name of configuration file	mandatory
dt-out-spatial	Time step for writing spatial average data (s). If section is not present or dt-out-spatial = 0, output files are not created and data are not exported.	optional
out-point-file	File that contains coordinate of points for exporting site snow water equivalent data. It is a plain text file in time series format with only the metadata section (see example in 3.5). The time step defined in the file, sets the export time step (s). If file is not assigned, data are not exported. Name of file created: <folder> point_swe.fts	optional

The following example sets the file ./conf/glacier.ini for configuring glacier simulation, a time step for computing = 3600, and a time step for exporting spatial average data = 3600.

```
#glacier accumulation and ablation. OPTIONAL
[glacier]
  dt = 3600
  conf-file =  ./conf/glacier.ini
  dt-out-spatial = 3600
```

Example of [glacier] section configuration within the main configuration file

3.9 Soil water balance

This optional section, marked by [soil-balance], sets parameters for configuring snow water balance simulation. Keywords to be set are listed in the following table.

Table 3.10. Definition of keywords to set parameters for configuring soil water balance simulation.

Keyword	Description	Requirements
[soil-balance]	Marks the beginning line of soil-balance section	optional
dt	time step for computation (s)	mandatory
conf-file	name of configuration file	mandatory
dt-out-spatial	Time step for writing spatial average data (s). If section is not present or dt-out-spatial = 0, output files are not created and data are not exported.	optional

The following example sets the file ./conf/soil-balance.ini for configuring soil water balance simulation, a time step for computing = 3600, and a time step for exporting spatial average data = 3600.

```
#soil balance. OPTIONAL
[soil-balance]
  dt = 3600
  conf-file = ./conf/soil-balance.ini
  dt-out-spatial = 3600
```

Example of [soil-balance] section configuration within the main configuration file

3.10 Discharge routing

This optional section, marked by [discharge-routing], sets parameters for configuring discharge routing. Keywords to be set are listed in the following table.

Table 3.11. Definition of keywords to set parameters for configuring discharge routing.

Keyword	Description	Requirements
[discharge-routing]	Marks the beginning line of discharge-routing section	optional
dt	time step for computation (s)	mandatory
conf-file	name of configuration file	mandatory
out-point-file	File that contains coordinate of points for exporting river discharge data at selected sections. It is a plain text file in time series format with only the metadata section (see example in 3.5). The time step defined in the file, sets the export time step (s). If file is not	optional

Keyword	Description	Requirements
	assigned, data are not exported. Name of file created: `<folder>point_discharge.fts`	

The following example sets the file `./conf/discharge-routing.ini` for configuring discharge routing, a time step for computing = 900, and sets the file `./conf/discharge_out.fts` for listing the coordinate of points to export data at selected sections.

```
# discharge routing on hillslope, rivers, and lakes. OPTIONAL
[discharge-routing]
  dt = 900
  conf-file = ./conf/discharge-routing.ini
  out-point-file = ./conf/discharge_out.fts
```

Example of `[discharge-routing]` section configuration within the main configuration file

3.11 Groundwater

This optional section, marked by `[groundwater]`, sets parameters for configuring discharge routing. Keywords to be set are listed in the following table.

Table 3.12. Definition of keywords to set parameters for configuring groundwater.

Keyword	Description	Requirements
`[groundwater]`	Marks the beginning line of `groundwater` section	optional
`dt`	time step for computation (s)	mandatory
`conf-file`	name of configuration file	mandatory
`out-point-file`	File that contains coordinate of points for exporting groundwater head data at selected sites. It is a plain text file in time series format with only the metadata section (see example in 3.5). The time step defined in the file, sets the export time step (s). If file is not assigned, data are not exported. One file is created for each of n simulated aquifer. Name of file created: `<folder>point_aquifer_<i>.fts` with i=1,n	optional
`dt-out-aquifer`	Time step for writing average data (s). If section is not present or `dt-out-aquifer = 0,` output file are not created and data are not exported. Name of file	optional

Keyword	Description	Requirements
	created: `<folder>aquifer.out`	

The following example sets the file `./conf/groundwater.ini` for configuring groundwater simulation, a time step for computing = 3600, and sets the file `./conf/point_groundwater.fts` for listing the coordinate of points to export data at selected sites. Results are written every hour.

```
#configure groundwater simulation. OPTIONAL
[groundwater]
dt = 3600
conf-file = ./conf/groundwater.ini
out-point-file = ./conf/point_groundwater.fts
dt-out-aquifer = 3600
```

Example of `[groundwater]` section configuration within the main configuration file

3.12 Spatial average

This optional section, marked by `[spatial-average]`, sets the configuration file for exporting spatial average data. Keywords to be set are listed in the following table.

Table 3.13. Definition of keywords to set the configuration file for exporting spatial average data.

Keyword	Description	Requirements
`[spatial-average]`	Marks the beginning line of `spatial-average` section	optional
`conf-file`	name of configuration file	mandatory

The following example sets the file `./conf/spatial-average.ini` for configuring exporting of spatial average data.

```
#configure spatial average output. OPTIONAL
[spatial-average]
  conf-file = ./conf/spatial_average.ini
```

Example of `[spatial-average]` section configuration within the main configuration file

3.13 Irrigation

This optional section, marked by `[irrigation]`, sets parameters for configuring water derivation from rivers and distribution to irrigation districts. Keywords to be set are listed in the following table.

Table 3.14. Definition of keywords to set parameters for configuring irrigation.

Keyword	Description	Requirements
`[irrigation]`	Marks the beginning line of `irrigation` section	optional
`dt`	time step for updating irrigation values (s)	mandatory
`conf-file`	name of configuration file	mandatory
`dt-out`	time step for writing into output file. It must be equal to or a multiple of `dt`	mandatory

The following example sets the file `./conf/intakes.ini` for configuring irrigation, a time step for updating values to 3600 s, as well as the time step for exporting data.

```
# irrigation management. OPTIONAL
[irrigation]
  dt = 3600 # time step for new update (s)
  conf-file = ./conf/intakes.ini  #configuration file
  dt-out = 3600  # time step for exporting data (s)
```

Example of `[irrigation]` section configuration within the main configuration file

3.14 Basin average

This optional section, marked by `[basin-average]`, sets the configuration file for exporting average values over river basins given by the coordinate of outlet section. Keywords to be set are listed in the following table.

Table 3.15. Definition of keywords to set the configuration file for exporting basin average data.

Keyword	Description	Requirements
`[basin-average]`	Marks the beginning line of `basin-average` section	optional
`conf-file`	name of configuration file	mandatory
`out-`	File that contains coordinate of points for exporting basin	mandatory

Keyword	Description	Requirements
point-file	average data at selected sections. It is a plain text file in time series format with only the metadata section (see example in 3.5). The time step defined in the file, sets the export time step (s). For name of created files see Chapter 15.	

The following example sets the file `./conf/basin-average.ini` for configuring exporting of basin average data for basin outlets listed in `./conf/basin_out.fts` file.

```
#configure basin average output. OPTIONAL
[basin-average]
conf-file = ./conf/basin-average.ini
out-point-file = ./conf/basin_out.fts
```

Example of `[basin-average]` section configuration within the main configuration file

3.15 Raster exporting

This optional section, marked by `[raster-export]`, sets the configuration file for exporting raster maps of a list of variables. Keywords to be set are listed in the following table.

Table 3.16. Definition of keywords to set the configuration file for exporting raster maps.

Keyword	Description	Requirements
[raster-export]	Marks the beginning line of raster-export section	optional
conf-file	name of configuration file	mandatory

The following example sets the file `./conf/raster-export.ini` for configuring exporting of raster maps.

```
#configure variables for raster export. OPTIONAL
[raster-export]
conf-file = ./conf/raster-export.ini
```

Example of `[raster-export]` section configuration within the main configuration file

CHAPTER 4
SETTING DOMAIN PROPERTIES

This file sets general properties of analysis domain (whether a river basin, crop fields, etc..). Variables to be set are listed in the following table.

Table 4.1. Definition of keywords to set domain properties.

Keyword	Description	Requirements
`[mask]`	this map sets the domain of simulation and coordinate reference system. All new variables created at runtime use mask as reference grid. All maps must have the same extent and coordinate reference system of mask, unless differently specified.	mandatory
`[albedo]`	Ground albedo	optional
`[land-cover]`	Land cover map according to level 3 Corine project classification.	optional
`[soil-texture]`	Soil texture map according to USDA classification scheme.	optional

The following example sets mask and albedo of a river basin stored in ESRI-ASCII grid format using UTM 32N datum ED50 as coordinate reference system (epsg code `23032)`.

```
#   set domain properties

[mask]
  file = ./data/mask.asc
  format = esri-ascii
  epsg = 23032

[albedo]
  file = ./data/albedo.asc
  format = esri-ascii
  epsg = 23032
```

4.1 Land cover

Land cover assignment in *FeST* model is based on the three levels system provided by CORINE land cover program. In the early 1980's, the European Commission recognized the need for a comprehensive, detailed, and harmonized dataset on the land cover and land use of the European continent. The European Commission launched the CORINE (Coordination of Information on the Environment) program in an effort to develop a standardized methodology for producing continent-scale land cover, biotope, and air quality maps. In its current form, the CORINE Land Cover (CLC) product offers a pan-European land cover and land use inventory with 44 thematic classes, ranging from broad forested areas to individual vineyards. The classification is organized in three levels with the following main classes:

- Artificial areas
- Agricultural areas
- Forest and semi-natural areas
- Wetlands
- Water bodies

Table 4.2. Corine land cover classes.

Code CLC	Name
111	Continuous urban fabric

Code CLC	Name
112	Discontinuous urban fabric
121	Industrial or commercial units, public services and military installations
122	Road and rail networks and associated land
123	Port areas
124	Airports
131	Mineral extraction sites
132	Dump sites
133	Construction sites
141	Green urban areas
142	Sport and leisure facilities
211	Non-irrigated arable land
212	Permanently irrigated arable land
213	Rice fields
221	Vineyards
222	Fruit trees and berry plantations
223	Olive groves
231	Pastures
241	Annual crops associated with permanent crops
242	Complex cultivation patterns
243	Land principally occupied by agriculture, with significant areas of natural vegetation

Code CLC	Name
244	Agro-forestry areas
311	Broad-leaved forest
312	Coniferous forest
313	Mixed forest
321	Natural grassland
322	Moors and heathland
323	Sclerophyllous vegetation
324	Transitional woodland/shrubs
331	Beaches, dunes, and sand plains
332	Bare rock
333	Sparsely vegetated areas
334	Burnt areas
335	Glaciers and perpetual snow
411	Inland marshes
412	Peat bogs/Mires
421	Salt marshes
422	Salines
423	Intertidal flats
511	Watercourses
512	Water bodies
521	Coastal lagoons

Code CLC	Name
522	Estuaries
523	Sea and ocean

Details about Corine land cover classification can be found here: https://land.copernicus.eu/content/corine-land-cover-nomenclature-guidelines/html/.

4.2 Soil texture

Soil texture indicates the relative content of particles of various sizes that make up the mineral fraction of the soil. Soil texture focuses on the particles that are less than two millimeters in diameter which include sand, silt, and clay.

The United States Department of Agriculture (USDA) defined twelve major soil texture classes: sand, loamy sand, sandy loam, loam, silt loam, silt, sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay, and clay. Soil textures are classified by the fractions of each soil separate (sand, silt, and clay) present in a soil. Classes are typically named for the primary constituent particle size or a combination of the most abundant particles sizes, e.g. "sandy clay" or "silty clay". A fourth term, loam, is used to describe equal properties of sand, silt, and clay in a soil sample, and lends to the naming of even more classifications, e.g. "clay loam" or "silt loam".

Determining soil texture is often aided with the use of a soil texture triangle plot. One side of the triangle represents percent sand, the second side represents percent clay, and the third side represents percent silt. If the percentages of sand, clay, and silt in the soil sample are known, then the triangle can be used to determine the soil texture classification. For example, if a soil is 70 percent sand and 10 percent clay then the soil is classified as a sandy loam. The same method can be used starting on any side of the soil triangle.

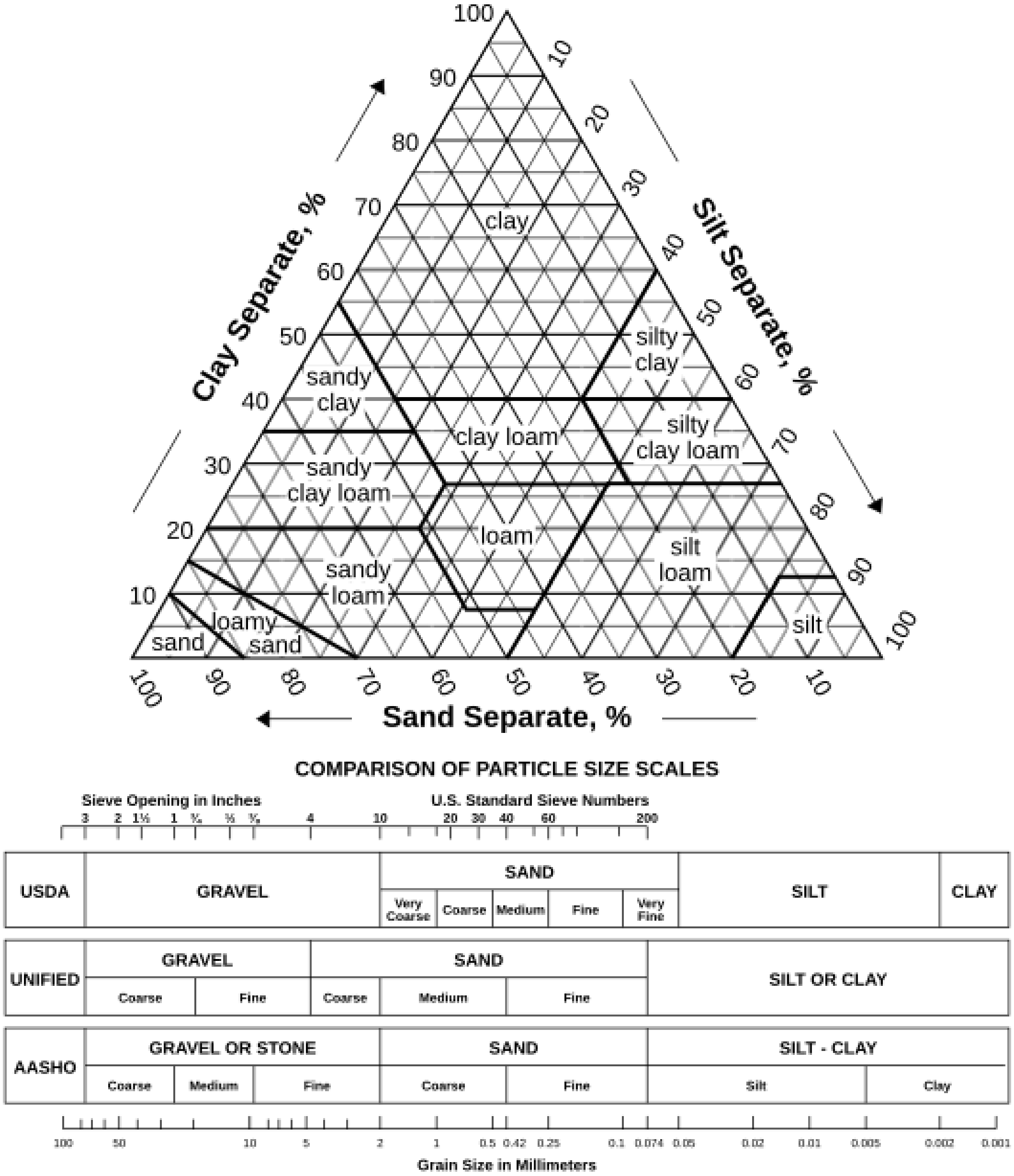

Figure 4.1 Soil texture triangle, showing the 12 major textural classes, and particle size scales as defined by the USDA (source: https://commons.wikimedia.org/wiki/File:SoilTextureTriangle.jpg)

The texture classes and the corresponding id internally used by FeST model are listed in the following table.

Table 4.3. Soil texture class and corresponding id internally used by FeST model.

Id	Soil texture class

0	Texture unknown
1	Clay
2	Silty Clay
3	Sandy Clay
4	Clay Loam
5	Silty Clay Loam
6	Sandy Clay Loam
7	Loam
8	Silty Loam
9	Sandy Loam
10	Silt
11	Loamy Sand
12	Sand

CHAPTER 5
MORPHOLOGICAL PROPERTIES

This file sets morphological properties of investigated domain. In this file the user can set 3 maps (digital elevation model, flow direction and flow accumulation) as listed in the following table. When flow direction map is assigned, the flow direction convention among ESRI and GRASS must be specified.

Table 5.1. Definition of maps to be set as morphological properties.

Keyword	Description	Requirements
`[dem]`	Digital elevation model map	optional
`[flow-direction]`	Flow direction map according to D8 approach (Figure 5.1)	optional
`flow-direction-convention`	Set flow direction conventions choosing among ESRI (NW=32, N=64, NE=128, W=16, E=1, SW=8, S=4, SE=2) and GRASS (NW=3, N=2, NE=1, W=4, E=8, SW=5, S=6, SE=7)	Required by `[flow-direction]`
`[flow-accumulation]`	Flow accumulation map in number of cells	optional

There are eight valid output directions relating to the eight adjacent cells into which flow could travel. This approach is commonly referred to as an eight-direction (D8) flow model and follows an approach presented in Jenson and Domingue (1988).

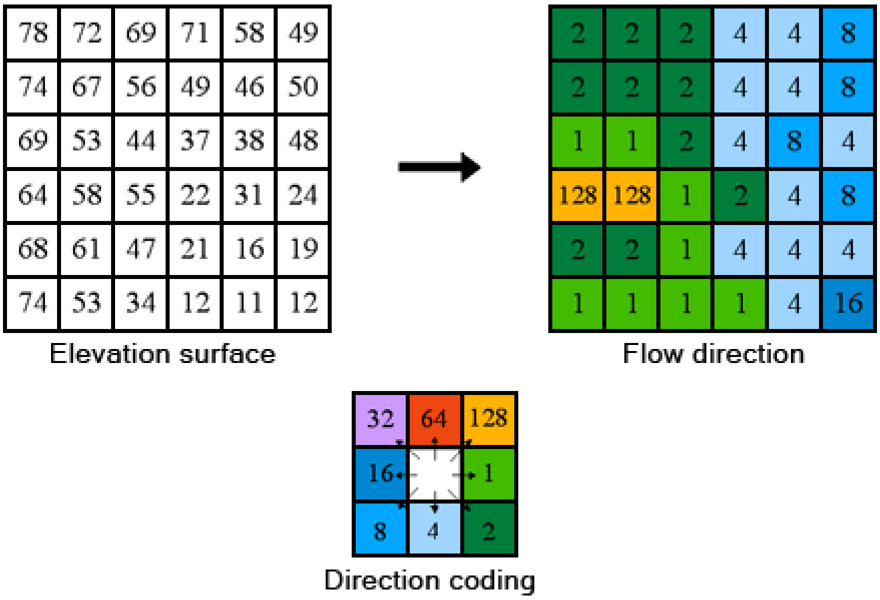

Figure 5.1 The coding of the direction of flow according to ESRI convention. (source: https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/how-flow-direction-works.htm)

When the optional section `[stream-network]` is present in the morphological properties configuration file, the topology of river network is created starting from information of elevation, and flow direction. This information is used when computation cannot be performed on a raster in arbitrary order, like for river discharge routing that requires to start from source nodes and going on till the basin outlet following the Horton stream order topology. The stream network is space filling that means that every single cell of the domain is crossed by a reach. The keywords for setting stream network delineation are listed in the following table.

Table 5.2. Keywords for setting sream network delineation.

Keyword	Description	Requirements
`[stream-network]`	marks the beginning of section	optional
`max-reach-length`	maximum rach length value [m]. When a reach longer than this value is detected it is split in sub-reaches so that they are lower than maximum	Optional. When keyword is missing, reaches are not split whatever their length is.
`negative-slope-`	While computing the reach	Optional. The correction

Keyword	Description	Requirements
`correction`	slope, when a negative slope is found, it is corrected with this value. Unit is m/m.	prevents that run-time error occurs when discharge routing is computed. When keyword is missing, negative values are left unchanged.
`file-export`	A plain text file is exported with topology information	Optional. Possible values: 1=export file, 0=do not export file. When keyword is missing file is not written.
`shp-export`	A line vector shape file is created with reaches and	Optional. Possible values: 1=export file, 0=do not export file. When keyword is missing file is not written. This option is available only on Windows operating system machines

The following example sets digital elevation model, flow direction, and flow accumulation maps stored in ESRI-ASCII grid format using UTM 32N datum ED50 as coordinate reference system (epsg code `23032).` Stream network is derived from dem and flow direction with a constraint on the maximum length of single reach of 2000 m, negative values of reach slope are corrected to 0.0005 m/m. No any files are written.

```
#   set morphological properties

[dem]
  file = ./data/dem.asc
  format = esri-ascii
  epsg = 23032

[flow-direction]
  file = ./data/flowdir.asc
  format = esri-ascii
  epsg = 23032
  flow-direction-convention = esri

[flow-accumulation]
  file = ./data/flowacc.asc
  format = esri-ascii
  epsg = 23032

[stream-network]
  max-reach-length = 2000
  negative-slope-correction = 0.0005
  file-export = 0
  shp-export = 0
```

CHAPTER 6
METEO
CONFIGURATION FILE

Two formats for input meteorological forcing time series are accepted: at site data measured by weather stations and raster dataset generally coming from weather prediction or climatic models. Variables that may be configured in meteo configuration file, and related section name, are listed as follows:

- precipitation with arbitrary time cumulation `[precipitation]`,
- daily cumulated precipitation `[precipitation-daily]`,
- subdaily air temperature averaged over arbitrary time `[temperature]`,
- daily averaged air temperature `[temperature-daily-mean]`,
- daily minimum air temperature `[temperature-daily-min]`,
- daily maximum air temperature `[temperature-daily-max]`,
- wind speed `[windspeed]`,
- solar radiation `[solar-radiation]`,
- air relative humidity `[relative-humidity]`.

When one section is missing (or commented out with `#` character) that variable is not initialized in FEST simulation run. Definition of precipitation with sub-daily or daily time cumulation in the same simulation is useful when user needs to run simulation at sub-daily time scale and, contemporary, export daily precipitation maps. In this case daily cumulated precipitation does not affect simulation results because it is only used for reporting purposes. Definition of daily and subdaily air temperature in the same simulation is useful when user needs to run simulations that require different time discretization of input temperature. For instance this is the case when user is running a simulation with snow module activated that requires subdaily time step and has chosen the Hargreaves-Samani method to compute potential evapotranspiration that requires daily time step. In this case daily maximum and minimum air temperature are required as well.

No any global properties, i.e. out of any section, are required in this file.

Some features are common to all meteorological variables. Three interpolation methods are available:

1. Thiessen polygons (id = 1)
2. Inverse distance weighting (IDW, id = 2)
3. Ordinary kriging (id = 3)

Interpolation method over a domain can be set in two ways. The first way implies to use only one method all over the domain (`interpolation-assignment = 1`). In this case, interpolation method is set by `interpolation` keyword (`interpolation = 1` for Thiessen, `interpolation = 2` for IDW, `interpolation = 3` for kriging).

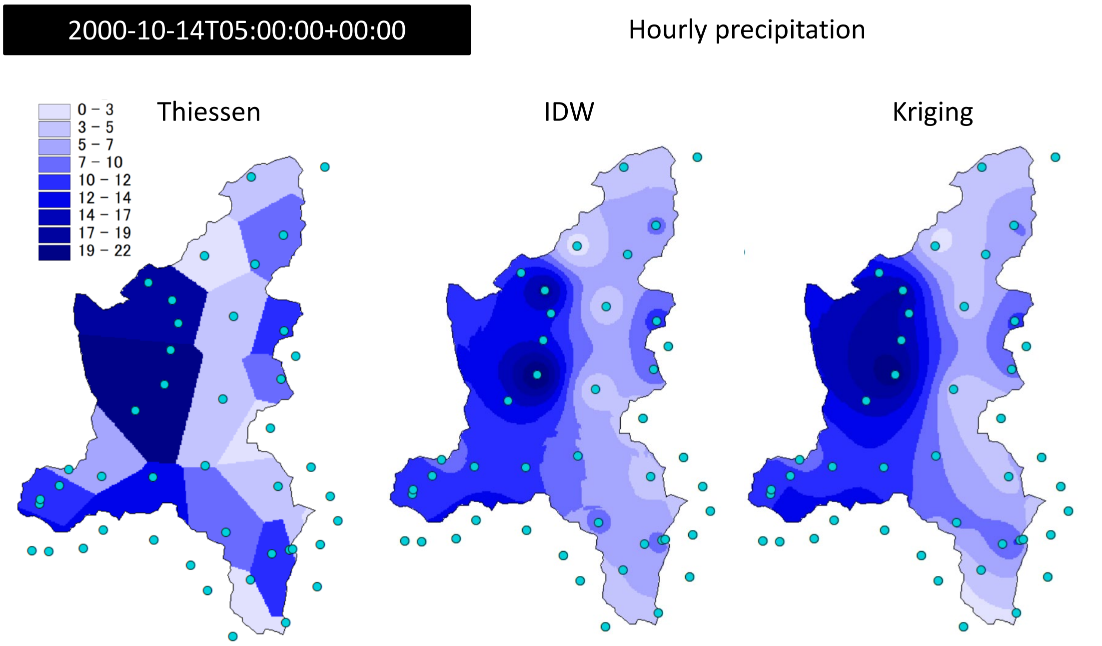

Figure 6.1 Hourly precipitation data measured on 2000-10-14T05:00:00+00:00 over the Toce river basin (Italy) interpolated with Thiessen, IDW, and Kriging methods.

A fourth option (`interpolation = 0`) is set when input data are provided in forms of netCDF maps (for example coming from weather prediction models). In this case there's no need to interpolate site data but some adjustments are applied by FEST in order to match spatial resolution and coordinate reference system of the analysis (coordinate conversion and nearest neighbours sampling are used for these purposes).

The second way to interpolate station data implies to use a different methods for each subareas of the domain (`interpolation-assignment = 2`). In this case a map is provided (set in `[[interpolation]]` sub-section) that sets for each cell the id of interpolation method among the three available (1 = Thiessen, 2 = IDW, 3 = Kriging). Virtually every cell may have an interpolation method associated that differs from the ones of the surrounding cells.

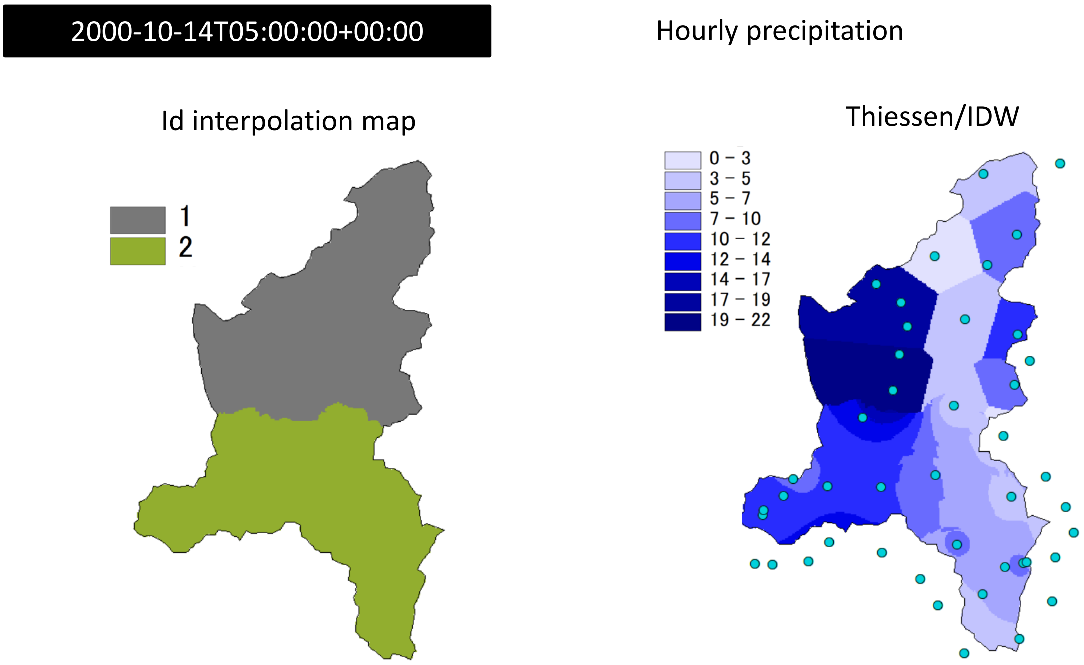

Figure 6.2 Hourly precipitation data measured on 2000-10-14T05:00:00+00:00 over the Toce river basin (Italy) interpolated with Thiessen (id = 1) and IDW (id = 2). Left map shows spatial distribution of interpolation Id.

When an interpolation method is activated, whether by an id map or by `interpolation =` keyword, specific parameters may be required or set as option by the user.

Meteorological maps can be exported to files by setting `export = 1`.

6.1 Precipitation with arbitrary time cumulation

This section is defined by `[precipitation]` in meteo configuration file. Unit of input data is mm cumulated in dt. The definitions of the keywords are reported in the Table below. Where not specified as MANDATORY, keywords are assumed to be optional.

Table 6.1. Definition of keywords in precipitation section of meteo configuration file.

Keyword	Description	Requirements
`[[interpolation]]`	map with interpolation method codes	Used when `interpolation-assignment` = 2

Keyword	Description	Requirements
[[lapse-rate-map]]	Map (or series of maps in netcdf format) used to assign lapse rate	CRS and spatial resolution must be the same of mask
dt	Cumulation time [s]	Integer greater than 0. MANDATORY
elevation-drift	Option to apply elevation based correction (lapse rate)	1 = use elevation to interpolate (requires definition of [[dem]]), 0 = no
export	activate grid exporting	1 = export interpolated grid, 0 = do not export interpolated grid MANDATORY
export-dt	time between two exportations (s)	Integer greater than 0
export-epsg	epsg of coordinate reference system of exported grid	Integer. List of accepted values in Section 1.2
export-format	1 = esri_ascii, 2 = esri_binary, 3 = netcdf	Integer among 1-3
export-path	folder where to put exported grids	string
export-start	time and date to start exporting	Date and time according to the International Standard ISO 8601 specifications
export-stop	time and date to stop exporting	Date and time according to the International Standard ISO 8601 specifications
file	File that contains data to read	MANDATORY
idw-power	power to be used with idw,	When missing, default = 2.
interpolation	Interpolation method when interpolation-assignment = 1	1 = thiessen, 2 = inverse distance weight (idw), 3 = kriging, 0 = read interpolated field
interpolation-	Defines the way of	1 = one method for the entire

Keyword	Description	Requirements
assignment	interpolation	domain, 2 = a map with interpolation method codes assigned by subsection [[interpolation]]. MANDATORY
kriging-anisotropy	Wheter to include anisotropy when fitting semivariogram model	1 = considers anisotropy, default = 0 excludes anisotropy
kriging-lags	number of lag bins for semivariogram	if undefined or set to 0 default to 15
kriging-maxlag	Limit distance (m) to be considered for semivariogram assessment	If undefined or set to 0, it is computed automatically
kriging-variance	Option to export to file variance map associated to kriging interpolation	Set to 1 to export variance, 0 to suppress it. When missing Default = 0
kriging-variogram-model	Semivariogram model to fit for kriging interpolation. When automatic fitting is chosen, the best among spherical and exponential is chosen.	1 = spherical, 2 = exponential, 3 = gaussian, 0 = automatic fitting. default to 2
lapse-rate-assignment	Method to assign lapse rate for elevation based correction	1 = one scalar for the entire domain, 2 = a map that may change in time. Requires the definition of subsection [[lapse-rate-map]]
lapse-rate-scalar	Lapse rate to use for elevation based correction (mm/m)	Real number greater than 0 when variable increase with elevation
nearest-points	number of nearest points to be considered for interpolation	Mandatory for kriging and idw
offset	Add an offset (mm)	Real number greater than zero if variable increase is required, lower than zero if

Keyword	Description	Requirements
		decrease is required.
`scale-factor`	Apply a scale factor (multiplicative). May be used for unit conversion or for model calibration. It is applied after elevation based correction	real number, optional
`standard_name`	Standard name of variable to be read in netcdf file	"`standard_name`" or "`variable`" must be defined when netcdf file is read
`valid-threshold`	minimum percentage of valid data that must be prresent to consider valid the aggregated value, when data from several time steps are read.	Percentage (0-1). When it is missing default is 1 that means that all values have to be valid to compute aggregation.
`variable`	Name of variable to be read in netcdf file	"`standard_name`" or "`variable`" must be defined when netcdf file is read

The following example uses the minimum number of mandatory keys. It sets the interpolation of data from the file precipitation.txt using thiessen polygon method without drift and grid exportation.

```
[precipitation]
  dt = 3600
  file = ./meteo/precipitation.txt
  interpolation-assignment = 1
  interpolation = 1
  elevation-drift = 0
  export = 0
```

The next example requires to interpolate data using Kriging without anisotropy. Variogram model is automatically chosen, and number of lags, and maximum distance to be considered for semi-variogram assessment are computed automatically, as well. Elevation drift is used during interpolation, with a lapse rate of 0.01 mm/h/m. Interpolated maps of precipitation and variance are exported hourly in netCDF format in subfolder

./risultati/precipitation_grid, from date 2014-07-07T00:00:00+00:00 to date 2014-07-10T00:00:00+00:00.

```
[precipitation]
  dt = 3600
  file = ./meteo/precipitation.txt
  interpolation-assignment = 1
  interpolation = 3
  kriging-variance = 1
  kriging-anisotropy = 0
  kriging-variogram-model = 0
  kriging-lags = 0
  kriging-maxlag = 0
  elevation-drift = 1
  lapse-rate-assignment = 1
  lapse-rate-scalar = 0.01
  export      = 1
  export-path = ./risultati/precipitation_grid
  export-start = 2014-07-07T00:00:00+00:00
  export-stop = 2014-07-10T00:00:00+00:00
  export-dt = 3600
  export-format = 3
  export-epsg =  3003
```

6.2 Daily precipitation

Daily precipitation properties are set in section `[precipitation-daily]`. This section is similar to `[precipitation]` section except `dt` that is not required. Having both `[precipitation]` and `[precipitation-daily]` configured in one simulation is useful when user needs to run simulation at sub-daily time scale and, at the same time, export daily precipitation maps.

6.3 Subdaily air temperature averaged over arbitrary time

This section is defined by `[temperature]` in meteo configuration file. Unit of input data is degree Celsius. Degree Kelvin data can be used as long as offset is applied in order to convert data to degree Celsius unit (see examples below). The definitions of the keywords are reported in the Table below. Where not specified as MANDATORY, keywords are assumed to be optional. Setting occurs similarly to precipitation data. A specific option of temperature data, not available in precipitation section for example, is set in order to compute vertical lapse rate from station data.

Table 6.2. Definition of keywords in temperature section of meteo configuration file.

Keyword	Description	Requirements
`[[interpolation]]`	map with interpolation method codes	Used when `interpolation-assignment` = 2
`[[lapse-rate-map]]`	Map (or series of maps in netcdf format) used to assign lapse rate	CRS and spatial resolution must be the same of mask
`dt`	Cumulation time [s]	Integer greater than 0. MANDATORY
`elevation-drift`	Option to apply elevation based correction (lapse rate)	1 = use elevation to interpolate (requires definition of `[[dem]]`), 0 = no
`export`	activate grid exporting	1 = export interpolated grid, 0 = do not export interpolated grid MANDATORY
`export-dt`	time between two exportations (s)	Integer greater than 0
`export-epsg`	epsg of coordinate reference system of exported grid	Integer. List of accepted values in Section 1.2
`export-format`	1 = esri_ascii, 2 = esri_binary, 3 = netcdf	Integer among 1-3
`export-path`	folder where to put exported grids	string
`export-start`	time and date to start exporting	Date and time according to the International Standard ISO 8601 specifications
`export-stop`	time and date to stop exporting	Date and time according to the International Standard ISO 8601 specifications
`file`	File that contains data to read	MANDATORY
`idw-power`	power to be used with idw,	When missing, default = 2.
`interpolation`	Interpolation method when interpolation-assignment = 1	1 = thiessen, 2 = inverse distance weight (idw), 3 =

Keyword	Description	Requirements
		kriging, 0 = read interpolated field
interpolation-assignment	Defines the way of interpolation	1 = one method for the entire domain, 2 = a map with interpolation method codes assigned by subsection [[interpolation]]. MANDATORY
kriging-anisotropy	Wheter to include anisotropy when fitting semivariogram model	1 = considers anisotropy, default = 0 excludes anisotropy
kriging-lags	number of lag bins for semivariogram	if undefined or set to 0 default to 15
kriging-maxlag	Limit distance (m) to be considered for semivariogram assessment	If undefined or set to 0, it is computed automatically
kriging-variance	Option to export to file variance map associated to kriging interpolation	Set to 1 to export variance, 0 to suppress it. When missing Default = 0
kriging-variogram-model	Semivariogram model to fit for kriging interpolation. When automatic fitting is chosen, the best among spherical and exponential is chosen.	1 = spherical, 2 = exponential, 3 = gaussian, 0 = automatic fitting. default to 2
lapse-rate-assignment	Method to assign lapse rate for elevation based correction	1 = one scalar for the entire domain, 2 = a map that may change in time. Requires the definition of subsection [[lapse-rate-map]]
lapse-rate-computation	Option to set wether to compute lapse rate from station data or use the assigned value	1 = compute lapse rate from data at each time step, 0 = use assigned lapse rate. Requires the definition of r2min
lapse-rate-scalar	Lapse rate to use for	Real number greater than 0

Keyword	Description	Requirements
	elevation based correction (mm/m)	when variable increase with elevation
`nearest-points`	Number of nearest points to be considered for interpolation	Mandatory for kriging and idw
`offset`	Adds an offset (degree Celsius)	Real number greater than zero if variable increase is required, lower than zero if decrease is required.
`r2min`	Value of linear regression R^2 below which value set by `lapse-rate-scalar` is used instead of computed lapse rate	Real number in the range 0-1
`scale-factor`	Apply a scale factor (multiplicative). May be used for unit conversion or for model calibration. It is applied after elevation based correction	real number, optional
`standard_name`	Standard name of variable to be read in netcdf file	"`standard_name`" or "`variable`" must be defined when netcdf file is read
`valid-threshold`	minimum percentage of valid data that must be prresent to consider valid the aggregated value, when data from several time steps are read.	Percentage (0-1). When it is missing default is 1 that means that all values have to be valid to compute aggregation.
`variable`	Name of variable to be read in netcdf file	"`standard_name`" or "`variable`" must be defined when netcdf file is read

The following example reads temperature data (unit degree Kelvin) from file `temperature.txt` in `meteo` subfolder (note the relative path notation) by averaging over 12 hours time span (`43200` s). So, assuming that data are stored in `temperature.txt` file with hourly time step, each time a new reading is performed, 12 data are read and averaged. In case nodata values are encountered, if less than 60% of data are valid numbers (`valid-threshold = 0.6`), the resulting value is set as nodata. Data are interpolated with inverse distance weighting algorithm (`interpolation = 2`) with power of distance 2 (`idw-power = 2.`) and considering 15 nearest stations (`nearest-points = 15`). An elevation drift is applied (`elevation-drift = 1`) with lapse rate computed from data (`lapse-rate-computation = 1`). If the coefficient of determination of the linear regression applied to compute the lapse rate is less than 0.6 (`r2min = 0.6`), the value -0.0065 °C/m is used as lapse rate instead (`lapse-rate-scalar = -0.0065`). An offset of -273.15 °C is applied in order to convert map from degree Kelvin to degree Celsius (`offset = -273.15`).

```
[temperature]
  dt = 43200
  file = ./meteo/temperature.txt
  valid-threshold = 0.6
  interpolation-assignment = 1
  interpolation = 2
  idw-power = 2.
  nearest-points = 15
  elevation-drift = 1
  lapse-rate-computation = 1
  r2min = 0.6
  lapse-rate-scalar = -0.0065
  offset = -273.15
  export = 0
```

6.4 Daily mean air temperature

Daily mean air temperature properties are set in section `[temperature-daily-mean]`. This section is similar to `[temperature]` section except `dt` that is not required. Having both `[temperature]` and `[temperature-daily-mean]` configured in one simulation is useful when different processes require air temperature data with different time span. For example, computation of evapotraspiration with Hargreaves-Samani equation requires daily mean, minimum and maximum air temperature, and in the same simulation hourly air temperature is required to simulate snow melt and accumulation.

6.5 Daily minimum air temperature

Daily minimum air temperature properties are set in section [temperature-daily-min]. This section is similar to [temperature] section except dt that is not required. Having both [temperature] and [temperature-daily-min] configured in one simulation is useful when different processes require air temperature data with different time span. For example, computation of evapotraspiration with Hargreaves-Samani equation requires daily mean, minimum and maximum air temperature, and in the same simulation hourly air temperature is required to simulate snow melt and accumulation.

6.6 Daily maximum air temperature

Daily maximum air temperature properties are set in section [temperature-daily-max]. This section is similar to [temperature] section except dt that is not required. Having both [temperature] and [temperature-daily-max] configured in one simulation is useful when different processes require air temperature data with different time span. For example, computation of evapotraspiration with Hargreaves-Samani equation requires daily mean, minimum and maximum air temperature, and in the same simulation hourly air temperature is required to simulate snow melt and accumulation.

6.7 Solar radiation

This section is defined by [solar-radiation] in meteo configuration file. Unit of input data is W/m². The definitions of the keywords are reported in the Table below. Where not specified as MANDATORY, keywords are assumed to be optional.

Table 6.3. Definition of keywords in radiation section of meteo configuration file.

Keyword	Description	Requirements
[[interpolation]]	map with interpolation method codes	Used when interpolation-assignment = 2
dt	Cumulation time [s]	Integer greater than 0. MANDATORY
elevation-drift	Option to apply topographic drift	1 = use elevation to interpolate, 0 = no, If missing, default = 0

Keyword	Description	Requirements
`export`	activate grid exporting	1 = export interpolated grid, 0 = do not export interpolated grid MANDATORY
`export-dt`	time between two exportations (s)	Integer greater than 0
`export-epsg`	epsg of coordinate reference system of exported grid	Integer. List of accepted values in Section 1.2
`export-format`	1 = esri_ascii, 2 = esri_binary, 3 = netcdf	Integer between 1-3
`export-path`	folder where to put exported grids	string
`export-start`	time and date to start exporting	Date and time according to the International Standard ISO 8601 specifications
`export-stop`	time and date to stop exporting	Date and time according to the International Standard ISO 8601 specifications
`file`	File that contains data to read	MANDATORY
`idw-power`	power to be used with idw,	When missing, default = 2.
`interpolation`	Interpolation method when interpolation-assignment = 1	1 = thiessen, 2 = inverse distance weight (idw), 3 = kriging, 0 = read interpolated field
`interpolation-assignment`	Defines the way of interpolation	1 = one method for the entire domain, 2 = a map with interpolation method codes assigned by subsection `[[interpolation]]`. MANDATORY
`kriging-anisotropy`	Wheter to include anisotropy when fitting semivariogram model	1 = considers anisotropy, default = 0 excludes anisotropy
`kriging-lags`	number of lag bins for	if undefined or set to 0

Keyword	Description	Requirements
	semivariogram	default to 15
`kriging-maxlag`	Limit distance (m) to be considered for semivariogram assessment	If undefined or set to 0, it is computed automatically
`kriging-variance`	Option to export to file variance map associated to kriging interpolation	Set to 1 to export variance, 0 to suppress it. When missing Default = 0
`kriging-variogram-model`	Semivariogram model to fit for kriging interpolation. When automatic fitting is chosen, the best among spherical and exponential is chosen.	1 = spherical, 2 = exponential, 3 = gaussian, 0 = automatic fitting. default to 2
`nearest-points`	number of nearest points to be considered for interpolation	Mandatory for kriging and idw
`offset`	Add an offset (mm)	Real number greater than zero if variable increase is required, lower than zero if decrease is required.
`scale-factor`	Apply a scale factor (multiplicative). May be used for unit conversion or for model calibration. It is applied after elevation based correction	real number, optional
`standard_name`	Standard name of variable to be read in netcdf file	"`standard_name`" or "`variable`" must be defined when netcdf file is read
`time-zone`	Time zone (unit = hour) of local time.	Mandatory when `elevation-drift = 1`
`valid-threshold`	minimum percentage of valid data that must be prresent to consider valid the aggregated value, when	Percentage (0-1). When it is missing default is 1 that means that all values have to be valid to compute

Keyword	Description	Requirements
	data from several time steps are read.	aggregation.
variable	Name of variable to be read in netcdf file	"standard_name" or "variable" must be defined when netcdf file is read

The next example requires to interpolate station ovservations from file RADD_2000-01-01_2011-12-31.fts using inverse distance with power 1.5 and 15 closest stations. Elevation drift is applied using 1 hour as time zone to compute local time.

```
[solar-radiation]
  dt = 3600
  file = ./meteo/RADD_2000-01-01_2011-12-31.fts
  interpolation-assignment = 1
  interpolation = 2
  idw-power = 1.5
  nearest-points = 15
  elevation-drift = 1
  time-zone = 1
  export = 0
```

6.8 Air relative humidity

This section is defined by [relative-humidity] in meteo configuration file. Unit of input data is percentage in the range 0-100. Interpolation of relative humidity data is similar to other meteorological variables except elevation drift that is not available. Definitions of keywords are reported in the Table below. Where not specified as MANDATORY, keywords are assumed to be optional.

Table 6.4. Definition of keywords in relative humidity section of meteo configuration file.

Keyword	Description	Requirements
[[interpolation]]	map with interpolation method codes	Used when interpolation-assignment = 2
dt	Cumulation time [s]	Integer greater than 0. MANDATORY
export	activate grid exporting	1 = export interpolated grid,

Keyword	Description	Requirements
		0 = do not export interpolated grid MANDATORY
`export-dt`	time between two exportations (s)	Integer greater than 0
`export-epsg`	epsg of coordinate reference system of exported grid	Integer. List of accepted values in Section 1.2
`export-format`	1 = esri_ascii, 2 = esri_binary, 3 = netcdf	Integer between 1-3
`export-path`	folder where to put exported grids	string
`export-start`	time and date to start exporting	Date and time according to the International Standard ISO 8601 specifications
`export-stop`	time and date to stop exporting	Date and time according to the International Standard ISO 8601 specifications
`file`	File that contains data to read	MANDATORY
`idw-power`	power to be used with idw,	When missing, default = 2.
`interpolation`	Interpolation method when interpolation-assignment = 1	1 = thiessen, 2 = inverse distance weight (idw), 3 = kriging, 0 = read interpolated field
`interpolation-assignment`	Defines the way of interpolation	1 = one method for the entire domain, 2 = a map with interpolation method codes assigned by subsection `[[interpolation]]`. MANDATORY
`kriging-anisotropy`	Wheter to include anisotropy when fitting semivariogram model	1 = considers anisotropy, default = 0 excludes anisotropy
`kriging-lags`	number of lag bins for semivariogram	if undefined or set to 0 default to 15

Keyword	Description	Requirements
kriging-maxlag	Limit distance (m) to be considered for semivariogram assessment	If undefined or set to 0, it is computed automatically
kriging-variance	Option to export to file variance map associated to kriging interpolation	Set to 1 to export variance, 0 to suppress it. When missing Default = 0
kriging-variogram-model	Semivariogram model to fit for kriging interpolation. When automatic fitting is chosen, the best among spherical and exponential is chosen.	1 = spherical, 2 = exponential, 3 = gaussian, 0 = automatic fitting. default to 2
nearest-points	number of nearest points to be considered for interpolation	Mandatory for kriging and idw
offset	Add an offset (mm)	Real number greater than zero if variable increase is required, lower than zero if decrease is required.
scale-factor	Apply a scale factor (multiplicative). May be used for unit conversion or for model calibration. It is applied after elevation based correction	real number, optional
standard_name	Standard name of variable to be read in netcdf file	"standard_name" or "variable" must be defined when netcdf file is read
valid-threshold	minimum percentage of valid data that must be prresent to consider valid the aggregated value, when data from several time steps are read.	Percentage (0-1). When it is missing default is 1 that means that all values have to be valid to compute aggregation.
variable	Name of variable to be read	"standard_name" or

Keyword	Description	Requirements
	in netcdf file	“variable” must be defined when netcdf file is read

The next example requires to interpolate station observations from file `relative_humidity.fts` (in subfolder `meteo`) using interpolation methods defined in map `interpolation_id.asc`. Assuming id 2 and 3 are present in `interpolation_id.asc`, two interpolation methods are applied: inverse distance with power 2 and 25 closest stations, and kriging by fitting exponential semivariogram model (`kriging-variogram-model = 2`) with 15 lags (`kriging-lags = 15`) and maximum distance of 100000 m (`kriging-maxlag = 100000`). Interpolated maps are exported hourly (`export-dt = 3600`) in ESRI ASCII format (`export-format = 1`) from `2000-10-12T01:00:00+00:00` to `2000-10-16T23:00:00+00:00`. Maps are converted to Geodetic WGS84 coordinate reference system (`export-epsg = 4326`) and are saved to `./risultati/humidity` folder (`export-path = ./risultati/humidity`).

```
[relative-humidity]
  dt = 3600.
  file = ./meteo/relative_humidity.fts
  interpolation-assignment = 2
  idw-power = 2.
  kriging-anisotropy = 0
  kriging-variogram-model = 2
  kriging-lags = 15
  kriging-maxlag = 100000
  valid-threshold = 1.0
  nearest-points = 25
  export      = 1
  export-path = ./risultati/humidity
  export-start = 2000-10-12T01:00:00+00:00
  export-stop = 2000-10-16T23:00:00+00:00
  export-dt = 3600
  export-format = 1
  export-epsg =  4326
[[interpolation]]
    file = ./dati/interpolation_id.asc
    format = esri-ascii
    epsg = 23032
```

6.9 Wind speed

This section is defined by `[wind-speed]` in meteo configuration file. Unit of input data is m/s. Besides Thiessen, inverse distance and kriging methods to interpolate local measurements, two further methods are available for wind speed data: Micromet algorithm developed by Liston and Elder[1] and the method proposed by González-Longatt[2]. Both methods use topographic features like terrain elevation, slope and curvature to drift interpolated wind speed. Wind direction is required when one of these two methods is chosen. Unit of wind direction data is degree (0-360 meteorological convention, the direction from which wind originates). Definitions of keywords are reported in the Table below. Where not specified as MANDATORY, keywords are assumed to be optional.

Table 6.5. Definition of keywords in wind speed section of meteo configuration file.

Keyword	Description	Requirements
`[[interpolation]]`	map with interpolation method codes	Used when `interpolation-assignment` = 2
`dt`	Cumulation time [s]	Integer greater than 0. MANDATORY
`export`	activate grid exporting	1 = export interpolated grid, 0 = do not export interpolated grid MANDATORY
`export-dt`	time between two exportations (s)	Integer greater than 0
`export-epsg`	epsg of coordinate reference system of exported grid	Integer. List of accepted values in Section 1.2
`export-format`	1 = esri_ascii, 2 =	Integer between 1-3

[1] Liston, G. E., Elder, K., 1911. A Meteorological Distribution System for High-Resolution Terrestrial Modeling (MicroMet). Journal of Hudrometeorology, 7, 217-234.

[2] González-Longatt, F., Medina, H., Serrano González, J., Spatial interpolation and orographic correction to estimate wind energy resource in Venezuela. Renewable and Sustainable Energy Reviews, 48, 1-16, 2015.

Keyword	Description	Requirements
	esri_binary, 3 = netcdf	
`export-path`	folder where to put exported grids	string
`export-start`	time and date to start exporting	Date and time according to the International Standard ISO 8601 specifications
`export-stop`	time and date to stop exporting	Date and time according to the International Standard ISO 8601 specifications
`file`	File that contains data to read	MANDATORY
`idw-power`	power to be used with idw,	When missing, default = 2.
`interpolation`	Interpolation method when interpolation-assignment = 1	1 = thiessen, 2 = idw, 3 = kriging, 4 = micromet, 5 = gonzalez, 0 = read interpolated field
`interpolation-assignment`	Defines the way of interpolation	1 = one method for the entire domain, 2 = a map with interpolation method codes assigned by subsection `[[interpolation]]`. MANDATORY
`kriging-anisotropy`	Wheter to include anisotropy when fitting semivariogram model	1 = considers anisotropy, default = 0 excludes anisotropy
`kriging-lags`	number of lag bins for semivariogram	if undefined or set to 0 default to 15
`kriging-maxlag`	Limit distance (m) to be considered for semivariogram assessment	If undefined or set to 0, it is computed automatically
`kriging-variance`	Option to export to file variance map associated to kriging interpolation	Set to 1 to export variance, 0 to suppress it. When missing Default = 0
`kriging-variogram-model`	Semivariogram model to fit for kriging interpolation.	1 = spherical, 2 = exponential, 3 = gaussian, 0

Keyword	Description	Requirements
	When automatic fitting is chosen, the best among spherical and exponential is chosen.	= automatic fitting. default to 2
`micromet-length-scale`	Length scale [m] used to compute curvature when micromet methos is required	If undefined default to 5000 m
`micromet-slopewt`	slope weighting factor used by micromet	If undefined default value = 0.5
`micromet-curvewt`	curvature weighting factor used by micromet	If undefined default value = 0.5
`nearest-points`	number of nearest points to be considered for interpolation	Mandatory for kriging and idw
`offset`	Add an offset (mm)	Real number greater than zero if variable increase is required, lower than zero if decrease is required.
`scale-factor`	Apply a scale factor (multiplicative). May be used for unit conversion or for model calibration. It is applied after elevation based correction	real number, optional
`standard_name`	Standard name of variable to be read in netcdf file	"`standard_name`" or "`variable`" must be defined when netcdf file is read
`valid-threshold`	minimum percentage of valid data that must be prresent to consider valid the aggregated value, when data from several time steps are read.	Percentage (0-1). When it is missing default is 1 that means that all values have to be valid to compute aggregation.
`variable`	Name of variable to be read in netcdf file	"`standard_name`" or

Keyword	Description	Requirements
		"`variable`" must be defined when netcdf file is read
`wind-direction-file`	File that contains wind direction data to read	Required when Micromet or Gonzalez-Longatt methods are chosen

The next example requires to interpolate station observations from file `windspeed.fts` (in subfolder `meteo`) using interpolation methods defined in map `interpolation_wind.asc`. Assuming id 2 and 4 are present in `interpolation_wind.asc`, two interpolation methods are applied: inverse distance (id = 2) with power 2 (`idw-power = 2.`) and 5 closest stations (`nearest-points = 5`), and Micromet (id = 4) with length scale 6000 m (`micromet-length-scale = 6000.`), slope weighting factor = 0.6 (`micromet-slopewt = 0.5`) and curvature weighting factor = 0.4 (`micromet-curvewt = 0.4`).

```
[wind-speed]
  dt = 3600
  file = ./meteo/windspeed.fts
  interpolation-assignment = 2
  idw-power = 2.
  micromet-length-scale = 6000.
  micromet-slopewt = 0.5
  micromet-curvewt = 0.5
  wind-direction-file =  ./meteo/winddirection.fts
  valid-threshold = 1.0
  nearest-points = 5
  export = 0
[[interpolation]]
    file = ./dati/interpolation_wind.asc
    format = esri-ascii
    epsg = 23032
```

CHAPTER 7
SNOW ACCUMULATION AND MELTING

The *FeST* model can simulate the snow accumulation and melting. The algorithms implemented in the current version of the model are based on the air temperature. For the snow melting, the classical degree-day model is implemented. For snow accumulation, the precipitation is partitioned into liquid (rainfall) and solid (snow) components based on air temperature thresholds: a lower threshold defines the air temperature below which precipitation is totally solid, an upper threshold defines the air temperature above which precipitation is totally liquid. In between the two threshold values, a linear variation of the percentage of rainfall and snow is assumed. Snow simulation is configured through a specific file. In the configuration file the user must or can define 10 sections. Each section sets a parameter or variable that can be assigned as a scalar value or as a grid map. Some of the parameters can change within the simulation period: `[melt-coefficient]`, `[melt-threshold-temperature]`, `[partitioning-upper-temperature]`, `[partitioning-lower-temperature]`, and `[hydraulic-conductivity]`. In this case the user must use the netCDF format for the input maps that contain changing parameter values.

Two sections define initial value of state variables: `[snow-water-equivalent]`, and `[water-in-snow]`. These two sections are optional: if they are not defined, a map is created with value = 0. Two further sections are optional: `[refreezing-coefficient]`, and `[water-holding-capacity]`.

Keywords in the snow configuration file (usually named `snow.ini`) are listed and described in the following tables.

Table 7.1. Definition of `[melt-model]` section in the snow configuration file.

Keyword	Description	Requirements
`[melt-model]`	Currently only the degree-	Mandatory

Keyword	Description	Requirements
	day model based on air temperature data is implemented: 1=Degree-Day.	
`scalar`	Scalar value to be used on the entire domain	optional
`file`	Name of file of the grid map	Required when parameter values are assigned through a grid map
`format`	Input file format	Available options: esri-ascii, esri-binary, net-cdf
`epsg`	epsg coordinate reference system code.	Required when parameter values are assigned through a grid map
`variable`	Variable name in net-cdf file	Required when input map is in net-cdf format
`time`	Date and time of the first map to read from net-cdf file	optional
`sync-initial-time`	Sync the initial map with the simulation initial time.	Alternative option to `time`. Available options: 1 = map is synced, 0 = map is not synced.

Table 7.2. Definition of `[snow-water-equivalent]` section in the snow configuration file.

Keyword	Description	Requirements
`[snow-water-equivalent]`	Snow water equivalent initial value (m)	Optional. Default value = 0.
`scalar`	Scalar value to be used on the entire domain	optional
`file`	Name of file of the grid map	Required when parameter values are assigned through a grid map
`format`	Input file format	Available options: esri-ascii, esri-binary, net-cdf
`epsg`	epsg coordinate reference	Required when parameter

Keyword	Description	Requirements
	system code.	values are assigned through a grid map
`variable`	Variable name in net-cdf file	Required when input map is in net-cdf format
`time`	Date and time of the first map to read from net-cdf file	optional
`sync-initial-time`	Sync the initial map with the simulation initial time.	Alternative option to `time`. Available options: 1 = map is synced, 0 = map is not synced.

Table 7.3. Definition of `[melt-coefficient]` section in the snow configuration file.

Keyword	Description	Requirements
`[melt-coefficient]`	Snow melt coefficient (mm/day/°C)	Mandatory
`scalar`	Scalar value to be used on the entire domain	optional
`file`	Name of file of the grid map	Required when parameter values are assigned through a grid map
`format`	Input file format	Available options: esri-ascii, esri-binary, net-cdf
`epsg`	epsg coordinate reference system code.	Required when parameter values are assigned through a grid map
`variable`	Variable name in net-cdf file	Required when input map is in net-cdf format
`time`	Date and time of the first map to read from net-cdf file	optional
`sync-initial-time`	Sync the initial map with the simulation initial time.	Alternative option to `time`. Available options: 1 = map is synced, 0 = map is not synced.

Table 7.4. Definition of `[melt-threshold-temperature]` section in the snow configuration file.

Keyword	Description	Requirements
`[melt-threshold-temperature]`	air temperature above which snow melt starts (°C)	Mandatory
`scalar`	Scalar value to be used on the entire domain	optional
`file`	Name of file of the grid map	Required when parameter values are assigned through a grid map
`format`	Input file format	Available options: esri-ascii, esri-binary, net-cdf
`epsg`	epsg coordinate reference system code.	Required when parameter values are assigned through a grid map
`variable`	Variable name in net-cdf file	Required when input map is in net-cdf format
`time`	Date and time of the first map to read from net-cdf file	optional
`sync-initial-time`	Sync the initial map with the simulation initial time.	Alternative option to `time`. Available options: 1 = map is synced, 0 = map is not synced.

Table 7.5. Definition of `[partitioning-upper-temperature]` section in the snow configuration file.

Keyword	Description	Requirements
`[partitioning-upper-temperature]`	air temperature above which only rainfall occurs (°C)	Mandatory
`scalar`	Scalar value to be used on the entire domain	optional
`file`	Name of file of the grid map	Required when parameter values are assigned through a grid map
`format`	Input file format	Available options: esri-ascii, esri-binary, net-cdf

Keyword	Description	Requirements
`epsg`	epsg coordinate reference system code.	Required when parameter values are assigned through a grid map
`variable`	Variable name in net-cdf file	Required when input map is in net-cdf format
`time`	Date and time of the first map to read from net-cdf file	optional
`sync-initial-time`	Sync the initial map with the simulation initial time.	Alternative option to `time`. Available options: 1 = map is synced, 0 = map is not synced.

Table 7.6. Definition of `[partitioning-lower-temperature]` section in the snow configuration file.

Keyword	Description	Requirements
`[partitioning-lower-temperature]`	air temperature below which only snowfall occurs (°C)	Mandatory
`scalar`	Scalar value to be used on the entire domain	optional
`file`	Name of file of the grid map	Required when parameter values are assigned through a grid map
`format`	Input file format	Available options: esri-ascii, esri-binary, net-cdf
`epsg`	epsg coordinate reference system code.	Required when parameter values are assigned through a grid map
`variable`	Variable name in net-cdf file	Required when input map is in net-cdf format
`time`	Date and time of the first map to read from net-cdf file	optional
`sync-initial-time`	Sync the initial map with the simulation initial time.	Alternative option to `time`. Available options: 1 = map is synced, 0 = map is not synced.

Table 7.7. Definition of `[hydraulic-conductivity]` section in the snow configuration file.

Keyword	Description	Requirements
`[hydraulic-conductivity]`	Snow hydraulic conductivity (m/s) used to calculate intercell lateral flow	Mandatory
`scalar`	Scalar value to be used on the entire domain	optional
`file`	Name of file of the grid map	Required when parameter values are assigned through a grid map
`format`	Input file format	Available options: esri-ascii, esri-binary, net-cdf
`epsg`	epsg coordinate reference system code.	Required when parameter values are assigned through a grid map
`variable`	Variable name in net-cdf file	Required when input map is in net-cdf format
`time`	Date and time of the first map to read from net-cdf file	optional
`sync-initial-time`	Sync the initial map with the simulation initial time.	Alternative option to `time`. Available options: 1 = map is synced, 0 = map is not synced.

Table 7.8. Definition of `[water-in-snow]` section in the snow configuration file.

Keyword	Description	Requirements
`[water-in-snow]`	Liquid phase inside snowpack initial value (m)	Optional. Default value = 0.
`scalar`	Scalar value to be used on the entire domain	optional
`file`	Name of file of the grid map	Required when parameter values are assigned through a grid map

Keyword	Description	Requirements
format	Input file format	Available options: esri-ascii, esri-binary, net-cdf
epsg	epsg coordinate reference system code.	Required when parameter values are assigned through a grid map
variable	Variable name in net-cdf file	Required when input map is in net-cdf format
time	Date and time of the first map to read from net-cdf file	optional
sync-initial-time	Sync the initial map with the simulation initial time.	Alternative option to time. Available options: 1 = map is synced, 0 = map is not synced.

Table 7.9. Definition of [refreezing-coefficient] section in the snow configuration file.

Keyword	Description	Requirements
[refreezing-coefficient]	Coefficient to compute refreezing rate (-)	Optional. Default value = 0.05
scalar	Scalar value to be used on the entire domain	optional
file	Name of file of the grid map	Required when parameter values are assigned through a grid map
format	Input file format	Available options: esri-ascii, esri-binary, net-cdf
epsg	epsg coordinate reference system code.	Required when parameter values are assigned through a grid map
variable	Variable name in net-cdf file	Required when input map is in net-cdf format
time	Date and time of the first map to read from net-cdf file	optional

Table 7.10. Definition of `[water-holding-capacity]` section in the snow configuration file.

Keyword	Description	Requirements
`[water-holding-capacity]`	Water holding capacity in snow defined as a percentage of current snow water equivalent (-)	Optional. Default value = 0.1
`scalar`	Scalar value to be used on the entire domain	optional
`file`	Name of file of the grid map	Required when parameter values are assigned through a grid map
`format`	Input file format	Available options: esri-ascii, esri-binary, net-cdf
`epsg`	epsg coordinate reference system code.	Required when parameter values are assigned through a grid map
`variable`	Variable name in net-cdf file	Required when input map is in net-cdf format
`time`	Date and time of the first map to read from net-cdf file	optional

An example of `snow.ini` configuration file follows.

```
[melt-model]
   scalar = 1   # 1 = degree-day


[snow-water-equivalent]
   file = ./data/initial_snow_depth.asc
   format = esri-ascii
   epsg = 32632

[melt-coefficient]
    file = ./data/melt_factor.nc
    format = net-cdf
    variable = melt_factor
    epsg = 32632
    sync-initial-time = 1

[melt-threshold-temperature]
   scalar = 0.

[partitioning-upper-temperature]
   scalar = 1.

[partitioning-lower-temperature]
   scalar = -1.

[hydraulic-conductivity]
  scalar = 0.01

[refreezing-coefficient]
  scalar = 0.05

[water-holding-capacity]
  scalar = 0.1
```

Example of snow configuration file.

CHAPTER 8
GLACIER ACCUMULATION AND ABLATION

The FEST model can simulate the glacier accumulation and ablation. Glacier ablation is simulated by using the models implemented for snow simulation. The keyword `doy-snow-ice-transformation` defines the day of the year (1-365) in which snow water equivalent still available is transformed to ice water equivalent. In the configuration file the user must define 5 sections. Each section sets a parameter that can be assigned as a scalar value or as a grid map. Some of the parameters can change within the simulation period: `[melt-coefficient]`, `[melt-threshold-temperature]`, and `[hydraulic-conductivity]`. In this case the user must use the netCDF format for the input maps that contain changing parameter values. Keywords in the glacier configuration file (usually named `glacier.ini`) are listed and described in the following tables.

Table 8.1. Definition of `doy-snow-ice-transformation` keyword in the snow configuration file.

Keyword	Description	Requirements
`doy-snow-ice-transformation`	day of the year (1-365) in which snow water equivalent still available is transformed to ice water equivalent	Optional. If keyword is missing, or `doy-snow-ice-transformation = 0`, ice accumulation is not simulated.

Table 8.2. Definition of `[melt-model]` section in the glacier configuration file.

Keyword	Description	Requirements

Keyword	Description	Requirements
[melt-model]	Currently only the degree-day model based on air temperature data is implemented: 1=Degree-Day.	Mandatory
scalar	Scalar value to be used on the entire domain	optional
file	Name of file of the grid map	Required when parameter values are assigned through a grid map
format	Input file format	Available options: esri-ascii, esri-binary, net-cdf
epsg	epsg coordinate reference system code.	Required when parameter values are assigned through a grid map
variable	Variable name in net-cdf file	Required when input map is in net-cdf format
time	Date and time of the first map to read from net-cdf file	optional
sync-initial-time	Sync the initial map with the simulation initial time.	Alternative option to time. Available options: 1 = map is synced, 0 = map is not synced.

Table 8.3. Definition of [ice-water-equivalent] section in the glacier configuration file.

Keyword	Description	Requirements
[ice-water-equivalent]	Ice water equivalent initial value (m)	Optional. Default value = 0
scalar	Scalar value to be used on the entire domain	optional
file	Name of file of the grid map	Required when parameter values are assigned through a grid map
format	Input file format	Available options: esri-ascii, esri-binary, net-cdf

Keyword	Description	Requirements
`epsg`	epsg coordinate reference system code.	Required when parameter values are assigned through a grid map
`variable`	Variable name in net-cdf file	Required when input map is in net-cdf format
`time`	Date and time of the first map to read from net-cdf file	optional
`sync-initial-time`	Sync the initial map with the simulation initial time.	Alternative option to `time`. Available options: 1 = map is synced, 0 = map is not synced.

Table 8.4. Definition of `[melt-coefficient]` section in the glacier configuration file.

Keyword	Description	Requirements
`[melt-coefficient]`	Snow melt coefficient (mm/day/°C)	Mandatory
`scalar`	Scalar value to be used on the entire domain	optional
`file`	Name of file of the grid map	Required when parameter values are assigned through a grid map
`format`	Input file format	Available options: esri-ascii, esri-binary, net-cdf
`epsg`	epsg coordinate reference system code.	Required when parameter values are assigned through a grid map
`variable`	Variable name in net-cdf file	Required when input map is in net-cdf format
`time`	Date and time of the first map to read from net-cdf file	optional
`sync-initial-time`	Sync the initial map with the simulation initial time.	Alternative option to `time`. Available options: 1 = map is synced, 0 = map is not synced.

Table 8.5. Definition of [melt-threshold-temperature] section in the glacier configuration file.

Keyword	Description	Requirements
[melt-threshold-temperature]	air temperature above which snow melt starts (°C)	Mandatory
scalar	Scalar value to be used on the entire domain	optional
file	Name of file of the grid map	Required when parameter values are assigned through a grid map
format	Input file format	Available options: esri-ascii, esri-binary, net-cdf
epsg	epsg coordinate reference system code.	Required when parameter values are assigned through a grid map
variable	Variable name in net-cdf file	Required when input map is in net-cdf format
time	Date and time of the first map to read from net-cdf file	optional
sync-initial-time	Sync the initial map with the simulation initial time.	Alternative option to time. Available options: 1 = map is synced, 0 = map is not synced.

Table 8.6. Definition of [hydraulic-conductivity] section in the glacier configuration file.

Keyword	Description	Requirements
[hydraulic-conductivity]	Snow hydraulic conductivity (m/s) used to calculate intercell lateral flow	Mandatory
scalar	Scalar value to be used on the entire domain	optional
file	Name of file of the grid map	Required when parameter values are assigned through a grid map

Keyword	Description	Requirements
`format`	Input file format	Available options: esri-ascii, esri-binary, net-cdf
`epsg`	epsg coordinate reference system code.	Required when parameter values are assigned through a grid map
`variable`	Variable name in net-cdf file	Required when input map is in net-cdf format
`time`	Date and time of the first map to read from net-cdf file	optional
`sync-initial-time`	Sync the initial map with the simulation initial time.	Alternative option to `time`. Available options: 1 = map is synced, 0 = map is not synced.

Table 8.7. Definition of `[water-in-ice]` section in the glacier configuration file.

Keyword	Description	Requirements
`[water-in-ice]`	Liquid phase inside icepack initial value (m)	Optional. Default value = 0
`scalar`	Scalar value to be used on the entire domain	optional
`file`	Name of file of the grid map	Required when parameter values are assigned through a grid map
`format`	Input file format	Available options: esri-ascii, esri-binary, net-cdf
`epsg`	epsg coordinate reference system code.	Required when parameter values are assigned through a grid map
`variable`	Variable name in net-cdf file	Required when input map is in net-cdf format
`time`	Date and time of the first map to read from net-cdf file	optional
`sync-initial-time`	Sync the initial map with the simulation initial time.	Alternative option to `time`. Available options: 1 = map is

Keyword	Description	Requirements
		synced, 0 = map is not synced.

An example of `glacier.ini` configuration file follows.

```
doy-snow-ice-transformation = 274 # 1st October

[melt-model]
   scalar = 1   # 1 = degree-day


[melt-coefficient]
    file = ./data/melt_factor.nc
    format = net-cdf
    variable = melt_factor
    epsg = 32632
    sync-initial-time = 1

[melt-threshold-temperature]
   scalar = 0.

[hydraulic-conductivity]
  scalar = 0.01

[ice-water-equivalent]
   file = ./data/initial_ice_depth.asc
   format = esri-ascii
   epsg = 32632
```

Example of glacier configuration file.

CHAPTER 9
PLANTS

The plants module in the FEST model is used in two ways. The first way is to set plants parameters used by other processes. One example is the leaf area index, a parameter that is used by soil balance module to compute evapotranspiration using Penman-Monteith equation. When multiple values of the same parameter are available for different time, the user can pack all values in a multidimensional net-cdf file, so that the FEST model can update the parameter value when a new map supersedes the old one. The second way of using the plants module is to simulate the plants growth and mortality with a dynamic model approach. In this case, the plants parameter are treated as state variables that are updated in time by the FEST model.

The plants module is activated by filling the specific section in the main configuration file (3.6). This chapter describes the plants configuration file.

The parameters to define are listed and described in the following table.

Table 9.1. Definition of keywords in plants configuration file.

Keyword	Description	Requirements
`plants-simulation`	Set whether to simulate plants dynamic. 0 = plants dynamic is not simulated	MANDATORY
`[vegetation-fraction]`	Map of percentage of pixel covered by vegetation. (0-1)	Optional. Required by soil balance to compute evaporation and transpiration components. It can be be set with `scalar` keyword
`[lai]`	Map of leaf area index (m^2/m^2)	Optional. Required by soil balance to compute evaporation with Penman-Monteith or energy balance

Keyword	Description	Requirements
		solving. It can be set with `scalar` keyword
`[vegetation-height]`	Map of vegetation height (m)	Optional. Required by soil balance to compute evaporation with Penman-Monteith or energy balance solving. It can be set with `scalar` keyword
`[min-stomatal-resistance]`	Map of minimum leaf stomatal resistance (s/m)	Optional. Required by soil balance to compute evaporation with Penman-Monteith. It can be set with `scalar` keyword

An example of `plants.ini` configuration file follows.

```
plants-simulation = 0

[vegetation-fraction]
  file = ./data/fv.asc
  format = esri-ascii
  epsg = 3003

[lai]
  file = ./data/lai.nc
  format = net-cdf
  variable = lai
  epsg = 3003
  sync-initial-time = 1

[vegetation-height]
  scalar = 2.3

[min-stomatal-resistance]
  scalar = 30.
```

Example of plants configuration file.

CHAPTER 10
SOIL WATER BALANCE

The soil water balance module is aimed at computing the water (and energy fluxes, optionally) and updating the soil water content. It is activated by filling the specific section in the main configuration file (3.9). This chapter describes the soil water balance configuration file.

```
threshold-storm-start = 1.
interstorm = 10.
infiltration = ./conf/infiltration.ini
evapotranspiration = ./conf/evapotranspiration.ini

[balance-id]
  file = ./data/balance_id.asc
  format = esri-ascii
  epsg = 3003

[soil-depth]
  file = ./data/sd.asc
  format = esri-ascii
  epsg = 3003

[root-zone-depth]
  scalar = 0.1

[ksat-subsurface]
  file = ./data/kprof.asc
  format = esri-ascii
  epsg = 3003

[deep-percolation-factor]
  scalar = 0.1

################################
# state variables initialization
################################

[saturation-rz]
  scalar = 0.3

[saturation-tz]
  scalar = 0.3
```

Example of soil water balance configuration file.

The parameters to define are listed and described in the following table. For setting state variables initial value see section 10.2.

Table 10.1. Definition of keywords in soil water balance configuration file.

Keyword	Description	Requirements
`threshold-storm-start`	threshold to consider storm initiated [mm/h]	MANDATORY
`interstorm`	duration of interstorm period to terminate an event [h]	MANDATORY
`infiltration`	Name of file to configure infiltration simulation. See	MANDATORY

Keyword	Description	Requirements
	10.3	
evapotranspiration	Name of file to configure infiltration simulation. See 10.4.	MANDATORY
[ksat-subsurface]	Map of saturated conductivity used to compute lateral subsurface flux (m/s)	MANDATORY. It can be be set with scalar keyword
[balance-id]	Map of balance id. 1=normal cell (hillslopes or channel); 2=lake; 3=landplain. See 10.1 for details.	MANDATORY.
[soil-depth]	Map of total soil depth (m)	MANDATORY. It can be be set with scalar keyword
[root-zone-depth]	Map of root zone depth (m)	MANDATORY. It can be be set with scalar keyword
[deep-percolation-factor]	Map of deep percolation factor, used as a limiter of deep percolation from transmission zone (-)	OPTIONAL. It can be be set with scalar keyword. Default value = 1.

10.1 Balance id

Specific scheme for solving soil balance is applied according to balance id:

- Id = 1, denotes hillslope and channel (normal) cells. Vertical and lateral flows are computed and used for updating soil moisture. When id = 1 cell bounds a id=3 cell lateral flow is passed to id = 3 cell as boundary flux condition (Neumann type boundary condition).
- Id = 2, denotes lake cells. Soil moisture is set to saturated content, evaporation is set to potential, runoff is computed as precipitation – evaporation (negative values can occur), percolation is null.
- Id = 3 denotes landplain cells that may interact with groundwater at the bottom boundary. Lateral fluxes are null, capillary rise is computed and used for

updating soil moisture. Percolation is computed and passed as source term of the underlying groundwater.

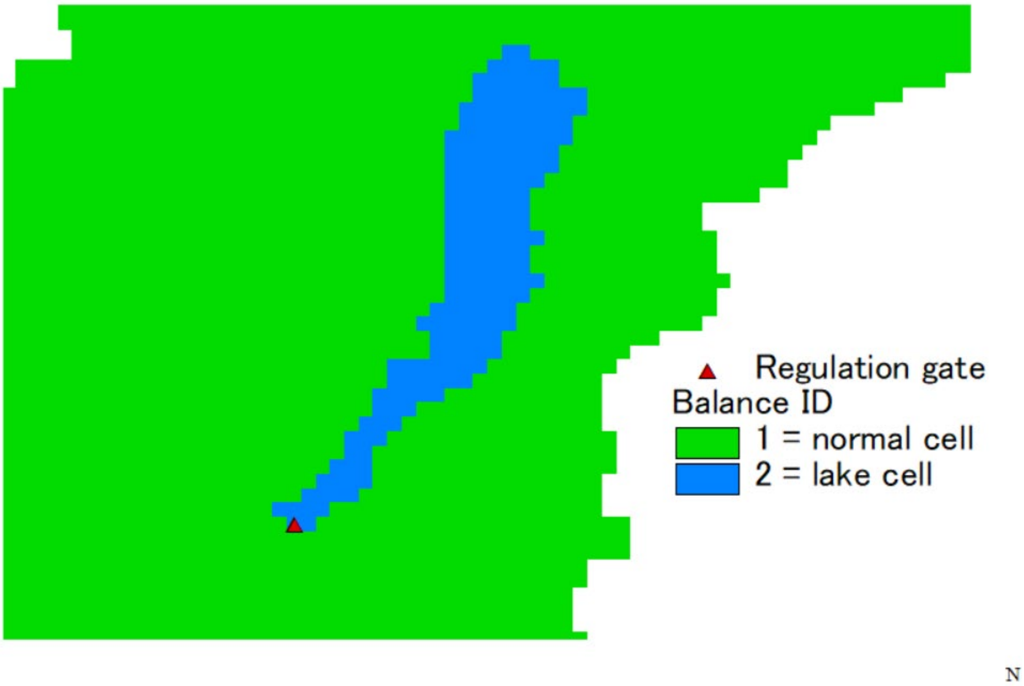

Figure 10.1 Example of Balance id map for the simulation of the Idro lake basin, in Italy. Blue cells mark lake cells. Note the location of gate that regulates outflow and lake water surface elevation.

10.2 State variables initialization

State variables must be initialized when simulation starts. Initial state can be set to an arbitrary value or to a value saved from a previous simulation run.

It is mandatory to initialize two variables: root zone soil saturation degree (`[saturation-rz]`), and transmission zone soil saturation degree (`[saturation-tz]`), either by setting a constant value (set with `scalar` keyword) or a map saved from a previous simulation run. The actual soil water content in each cell, both in root and transmission zones, is computed by the model according to the soil hydrological properties of the given cell.

Two state variables can be optionally set to an initial value: `[precipitation-status]` and `[interstorm-duration]`. Other optional state variables are required by different infiltration models (see table below). When an optional state variable is not assigned an initial value in the configuration file, the default value, 0, is assigned. A constant value can be set with `scalar` keyword.

Table 10.2. Maps to be assigned for initializing state variables.

Keyword	**Description**	**Requirements**
`saturation-rz`	Root zone soil saturation degree	Mandatory.
`saturation-tz`	Transmission zone soil saturation degree	Mandatory.
`precipitation-status`	Precipitation status. Defines if in storm or interstorm period.	Optional
`interstorm-duration`	Interstorm duration [mm]. Defines time from the end of the last precipitation event.	Optional
`cumulative-precipitation`	Cumulative precipitation since the event start [mm]	Optional. Used by SCS-CN model
`soil-retention`	Actual soil retention capacity at the beginning of precipitation [mm].	Optional. Used by SCS-CN model
`cumulative-infiltration`	Cumulative infiltration [mm]	Optional. Used by Philips and Green-Ampt infiltration models

10.3 Infiltration

Infiltration is defined as the water movement from the ground surface into the soil. Different infiltration equations have been implemented in the FEST model. It's up to the user to select the equation that he desires to use depending on required outputs and available inputs. The available infiltration models are as follows:

1. SCS-modified curve number (SCS-CN): according to the Soil Conservation Service (SCS) (1985) modified for continuous simulation (Ravazzani et al., 2015)
2. Philip: according to Philip numerical solution (1957)
3. Green and Ampt_according to Green and Ampt solution (1911)
4. Ross-Brooks and Corey: solved according to Ross (2003) fast and non-iterative solution for Richard equation using water retention curve parameters according to Brooks and Corey (1964) equation

5. Ross-Van Genuchten solved according to Ross (2003) fast and non-iterative solution for Richard equation using water retention curve parameters according to van Genuchten (1980) equation

Keywords in the infiltration configuration file (usually named `infiltration.ini`) are listed and described in the following table..

Table 10.3. Definition of keywords in infiltration configuration file.

Keyword	Description	Requirements
`model`	Infiltration model to be selected by the user: 1=SCS-CN, 2=Philip, 3=Green-Ampt, 4=Ross Brooks and Corey, 5=Ross Van Genuchten.	The user should check the available soil data before the selection of the infiltration model to be used for the simulations
`parameter-assigning-method`	Soil parameters could be assigned from single file for each parameter (method number 1) or soil parameters could be assigned from soil type map (method number 2)	For method 1 the user should provide a map for each required soil parameter, depending on the selected model. For method 2, the user should provide soil data input parameters in soil-types file.
`soil-types-file`	Soil type file used when `parameter-assigning-method = 2`	This keyword is mandatory if parameter assigning method = 2
`ross-divisions`	Number of the subdivisions of the soil layer	Required by Ross-Brooks and Corey, and Ross Van Genuchten models.
`ross-dsmax`	Refers to the maximum change in the effective saturation (S), of any unsaturated layer to aim for each time step, controls time step size. This parameter is used by Ross model.	Required by Ross-Brooks and Corey, and Ross Van Genuchten models. If not specified a default value of 0.05 is used.
`ross-hpondzero`	Refers to the bottom boundary condition for	Required by Ross-Brooks and Corey, and Ross Van

Keyword	Description	Requirements
	water; "free drainage" (means zero gradient of matric head),, "seepage", or "zero flux".	Genuchten models
[soil-type-map]	Map of soil type	this section is mandatory if parameter-assigning-method = 2
[conductivity]	Map of soil hydraulic conductivity at saturation (m/s)	Required by all infiltration models
[residual-water-content]	Map of residual water content (m^3/m^3)	Required by all infiltration models
[saturated-water-content]	Map of water content at saturation (m^3/m^3)	Required by all infiltration models
[field-capacity]	Map of field capacity (m^3/m^3)	Required by all infiltration models
[wilting-point]	Map of wilting point (m^3/m^3)	Required by all infiltration models
[pore-size-index]	Map of pore size distribution index of Brooks and Corey (-)	Required by all infiltration models
[bubble-pressure]	Map of bubbling pressure (m)	Required by all infiltration models
[curve-number]	Map of curve number (-)	Required by SCS-CN
[abstraction-ratio]	Map of abstraction ratio to compute initial loss (-). Standard value = 0.2	Required by SCS-CN
[storativity]	Map of curve number storativity (S_0) (mm). Standard value = 254	Required by SCS-CN
[front-suction-head]	Map of front suction head (m)	Required by Green-Ampt
[n-van-genuchten]	Map of *n* shape coefficient of Van Genuchten retention curve (-)	Required by Ross Van Genuchten

Keyword	Description	Requirements
[m-van-genuchten]	Map of *m* shape coefficient of Van Genuchten retention curve (-)	Required by Ross Van Genuchten
[tortuosity-index]	Map of pore tortuosity index (-)	Required by Ross Van Genuchten
[conductivity-matrix]	Map of conductivity at saturation of soil matrix (m/s)	Required by Ross Van Genuchten

In the next example, the user selected Philip equation for the simulation of the infiltration which corresponds to the method number 2. For the determination of the soil parameter the user selected the method 1 that implies assigning the soil parameters from single file for each required parameter. A `scale_factor` is applied to soil conductivity in order to convert the input map from cm/h to m/s unit.

```
model = 2 # Philip infiltration model

parameter-assigning-method = 1 # 1 = read each parameter from
single file; 2 = assign parameter from soil type map

# this keyword is mandatory if parameter-assigning-method = 2
soil-types-file = ./conf/soil-types.ini

divisions = 1 # number of subdivisions of soil layer

# max change in S (the "effective saturation") of any unsaturated
# layer to aim for each time step; controls time step size
# If not specified default value used = 0.05
# used by Ross model
dSmax = 0.05

#initial pond depth [m] if not given default to zero
# used by Ross model
hpondzero = 0.

# used by Ross model
botbc = free drainage
#botbc = zero flux
#botbc = seepage
```

Example of infiltration configuration file (part 1/2).

```
 # alternative to assign soil type map is assigning single map
for each parameter
[conductivity]
  file = ./dati/toce_kscmh.asc
  format = esri-ascii
  epsg = 23032
  scale_factor = 0.0000027777

[residual-water-content]
  file = ./dati/toce_tr_200.asc
  format = esri-ascii
  epsg = 23032

[saturated-water-content]
  file = ./dati/toce_ts_200.asc
  format = esri-ascii
  epsg = 23032

[field-capacity]
  file = ./dati/toce_fc_200.asc
  format = esri-ascii
  epsg = 23032

[wilting-point]
  file = ./dati/toce_wp_200.asc
  format = esri-ascii
  epsg = 23032

[pore-size-index]
  file = ./dati/toce_bc_200.asc
  format = esri-ascii
  epsg = 23032

[bubble-pressure]
  file = ./dati/toce_bp_200.asc
  format = esri-ascii
  epsg = 23032
```

Example of infiltration configuration file (part 2/2).

In case the user selects `parameter-assigning-method = 2` the file assigned by `soil-types-file` must be prepared together with map assigned by `[soil-type-map]` section in the infiltration configuration file. The list of parameters to be included in this files depends on the selected infiltration model previously chosen. These parameters are reported in the table below.

Table 10.4. Parameters to be included in `soil-types-file`.

Soil parameter	Definition	Unit	Model
`ksat`	Saturated hydraulic conductivity	m/s	all
`thetas`	saturated volumetric water content	m3/m3	all
`thetar`	residual volumetric water content	m3/m3	all
`fc`	Water content at field capacity	m3/m3	all
`wp`	Water content at wilting point	m3/m3	all
`smax`	maximum soil storage	m	all
`psdi`	pore-size distribution index	-	all
`cn`	Curve number	-	Curve Number
`c`	abstraction-ratio, default value=0.2	-	Curve Number
`S0`	Storativity	mm	Curve Number
`psic`	air entry value, bubbling pressure	m	Philips, ROSS-BC and ROSS-VG
`phy`	Suction head at the wetting front	m	Green and Ampt
`n`	vG retention function shape parameter	-	ROSS-VG
`m`	vG retention function shape parameter	-	ROSS-VG
`p`	tortuosity index	-	ROSS-VG
`ksat-matrix`	saturated conductivity of soil "matrix" (m/s). Different from ksat when macropores impact		ROSS-VG

The example below reports all parameters required by the Philips equation. The number of the soil types for the following example has been set to 2. So, the user in this case should include two sets of soil parameters.

```
###################################################
#                  soil types database            #
###################################################
soil-types = 2

[1] # soil type number 1
  ksat = 1.74E-05   #saturated conductivity (m/s)
  thetas =  0.462  #saturated volumetric water content (m3/m3)
  thetar =  0.01  #residual volumetric water content (m3/m3)
  psdi   =  0.288 #brooks and corey pore size distribution index (-)
  psic  = 0.00452 # air entry value, bubbling pressure (m)
  wp = 0.079  # wilting point (m3/m3)
  fc = 0.278 # field capacity (m3/m3)
  smax = 0.2 # maximum soil storage (m)

[2] # soil type number 2
  ksat = 5.48E-06   #saturated conductivity (m/s)
  thetas =  0.434  #saturated volumetric water content (m3/m3)
  thetar =  0.01  #residual volumetric water content (m3/m3)
  psdi   =  0.248 #brooks and corey pore size distribution index (-)
  psic  = 0.00488 # air entry value, bubbling pressure (m)
  wp = 0.0611  # wilting point (m3/m3)
  fc = 0.297 # field capacity (m3/m3)
  smax = 0.2 # maximum soil storage (m)
```

Example of file defined by `soil-types-file`.

10.4 Evapotranspiration

Different equations have been implemented in the FEST model for computing evapotranspiration. The available models are as follows:

1. Penman-Monteith (Allen et al., 1998);
2. Priestley and Taylor (1972);
3. Hargreaves and Samani (1982);
4. Hargreaves and Samani modified with elevation correction (Ravazzani et al., 2012);
5. FAO-56 Penman-Monteith (Allen et al., 1998);
6. Energy balance. (To be implemented in the new code)

Keywords in the evapotranspiration configuration file (usually named `evapotranspiration.ini`) are listed and described in the following table.

Table 10.5. Definition of keywords in evapotranspiration configuration file.

Keyword	Description	Requirements
`model-assignment`	1 = one method for the entire domain, 2 = a map with model codes	Mandatory
`model`	Evapotranspiration model: 1=Penman-Monteith, 2=Priestley-Taylor, 3=Hargreaves-Samani, 4= Hargreaves-Samani modified, 5=FAO-56 Penman-Monteith., 6=energy-balance	Required when `model-assignment = 1`
`dt`	Computation time step (s)	Mandatory
`use-crop-coefficient`	0 = no, 1 = yes.	Optional. If not specified crop coefficient is not applied.
`[model-map]`	map of model id (see `model`)	Required when `model-assignment = 2`

When `use-crop-coefficient = 1` the user must configure how to assign crop coefficient values in section `[crop-coefficient]`. Crop coefficient values can be assigned in two ways:

- A map of ids and a related file with crop coefficient time series value for each id in the map. When a new value of crop coefficient is read from file, the value is assigned to all cells with the same id in the map.
- A time variable map encoded in net-Cdf format.

Table 10.6. Definition of keywords for configuring crop coefficient.

Keyword	Description	Requirements
`[crop-coefficient]`	Section to configure crop coefficient use.	Required when `use-crop-coefficient = 1`
`file`	Sub-keyword in section `[crop-coefficient]` to define file with crop coefficient values in fest time	mandatory

Keyword	Description	Requirements
	series format or net-Cdf.	
`interpolation`	1 = use code-map, 0 = use netcdf grid data	mandatory
`variable`	1 = use code-map, 0 = use netcdf grid data	Required when `interpolation = 0`
`[[code-map]]`	Subsection that defines the map with id code	Required when `interpolation = 1`

In the next example, the modified Hargreaves Samani model (`model = 4`) is used to compute evapotranspiration on the entire domain (`model-assignment = 1`) at daily time scale (`dt = 86400`). Crop coefficient values are defined by reading values from `./meteo/kc.txt` (see below) file and assigned to the corresponding code in `./dati/toce_kc_code.asc` map.

```
dt = 86400 # time step computation (s)

model-assignment = 1 # one method for the entire domain

model = 4 # modified Hargreaves model

use-crop-coefficient = 1 # 0 = no, 1 = yes

[crop-coefficient]
   file = ./meteo/kc.txt #file containing crop coefficient
   interpolation = 1  # 1 = use code-map
   [[code-map]]
     file = ./dati/toce_kc_code.asc
     format = esri-ascii
     epsg = 23032
```

Example of evapotranspiration configuration file.

```
description =     crop coefficient
unit  =     -
epsg  =     23032
count =     2
dt    =     3600
missing-data      =     -999.9
offsetz     =     0

metadata
code1 1     0     0     0
code2 2     0     0     0

data
date&time   code1 code2
2000-01-01T00:00:00+01:00     0.26  1.05
2000-01-01T01:00:00+01:00     0.26  1.05
2000-01-01T02:00:00+01:00     0.26  1.05
2000-01-01T03:00:00+01:00     0.26  1.05
2000-01-01T04:00:00+01:00     0.26  1.05
2000-01-01T05:00:00+01:00     0.26  1.05
2000-01-01T06:00:00+01:00     0.26  1.05
2000-01-01T07:00:00+01:00     0.26  1.05
2000-01-01T08:00:00+01:00     0.26  1.05
2000-01-01T09:00:00+01:00     0.26  1.05
2000-01-01T10:00:00+01:00     0.26  1.05
2000-01-01T11:00:00+01:00     0.26  1.05
```

Example of file in fest time series format with crop coefficient value to assign to id map.

CHAPTER 11
DISCHARGE ROUTING

The *FeST* model can route surface runoff to compute discharge using the Muskingum-Cunge-Todini equation (Todini, 2007), following the stream network as delineated in morphological properties module. Discharge routing is activated by filling the specific section in the main configuration file (3.10). This chapter describes the discharge routing configuration file, usually named `discharge-routing.ini`.

```
export-channel-grid = 0

masks-number = 1

[reservoirs]
  file = ./conf/reservoirs.ini
  dt = 10
  dt-out = 3600

[diversions]
  file = ./conf/diversions.ini
  dt = 0
  dt-out = 3600

[discharge-in]
  scalar = 0.0


[discharge-out]
  scalar = 0.0

[discharge-lat]
  scalar = 0.0

[base-mask]
  channel-initiation-method = area
  channel-initiation-threshold = 4000000.
  hillslope-width = 200.
  hillslope-alpha = 45.
  hillslope-ks = 2.


Table Start
Title: channel properties
Id: base-mask
Columns:    [count]      [threshold]     [width]   [alpha]   [ks]
Units:        [-]           [m^2]          [m]      [deg]    [m^1/3s^-1]
            1            5000000           5         45        20
            2           10000000           7         45        25
            3           15000000          10         45        30
            4           20000000          20         45        35
            5           30000000          25         45        40
            6          100000000          35         45        45
            7          500000000          50         45        45
            8         1000000000          65         45        45
            9         2000000000          80         45        45
Table End
```

Example of discharge routing configuration file.

The parameters to define are listed and described in the following table.

Table 11.1. Definition of keywords in discharge routing configuration file.

Keyword	**Description**	**Requirements**

Keyword	Description	Requirements
`export-channel-grid`	1 = file channel.asc is written 0 = no any file is exported	MANDATORY
`masks-number`	number of masks to assign channel parameters (at least 1 for the base-mask must exist)	MANDATORY
`[reservoirs]`	Section to configure reservoirs	MANDATORY
`file`	File with information about reservoirs (see 11.1)	MANDATORY
`dt`	Computation time step (s)	MANDATORY. When `dt=0` reservoirs are not solved
`dt-out`	Time step for writing reservoirs simulation results (s).	OPTIONAL. default value = 0. When keyword is not defined or =0, files are not written
`[diversions]`	Section to configure diversions	MANDATORY
`file`	File with information about diversions (see 11.2)	MANDATORY
`dt`	Computation time step (s)	MANDATORY. When `dt=0` diversions are not solved. For every values other than 0, `dt` is set equals to discharge routing dt
`dt-out`	Time step for writing diversions simulation results (s).	OPTIONAL. default value = 0. When keyword is not defined or =0, files are not written
`[discharge-in]`	Map of input discharge initial value (m^3/s)	OPTIONAL. default value = 0. It can be set to a constant value using the `scalar` keyword
`[discharge-out]`	Map of output discharge initial value (m^3/s)	OPTIONAL. default value = 0. It can be set to a constant

Keyword	Description	Requirements
		value using the scalar keyword
[discharge-lat]	Map of lateral discharge initial value (m^3/s)	OPTIONAL. default value = 0. It can be set to a constant value using the scalar keyword
[base-mask]	Section for assigning discharge routing parameters to the entire simulation domain	MANDATORY
channel-initiation-method	Method to define channel initiation. Available methods: area = a fixed threshold area is used (m^2); ask = a threshold of the expression area*slope^k (m^2) is used, with k=1.7.	MANDATORY
channel-initiation-threshold	Threshold value to initiate channel (m^2).	MANDATORY
hillslope-width	Hillslope cross section width (m)	MANDATORY
hillslope-alpha	Hillslope slope of trapezoidal section side bank (degree)	MANDATORY.
hillslope-ks	Hillslope Strickler roughness coefficient ($m^{1/3} s^{-1}$)	MANDATORY

A table with id = base-mask is required to define routing parameters to be used on channel cells of the whole simulation domain. The user must include the same parameters specified for hillslope cells (section width, bank slope, Strickler coefficient) that can vary with basin area (m^2). The parameter values are linearly interpolated between boundary values according to the basin area of the current cell. The [count] column with an incremental counter is required in the table.

Different hillslope and channel parameters can be assigned to a specific subbasin within the simulation domain. To do so, assuming the user needs to assign parameters on *N* subbasins, new sections with name [mask*X*] must be added, with *X*= 1, *N*. The total number of masks

(`masks-number`) must be updated accordingly to account for the *base-mask* and the additional subbasins. A table with id name equals to the section name (example `mask1`) is used to assign channel parameters to the subbasin. In the following example, routing parameters are assigned to the base mask and an additional subbasin.

```
masks-number = 2

[base-mask]
  channel-initiation-method = area
  channel-initiation-threshold = 4000000.
  hillslope-width = 200.
  hillslope-alpha = 45.
  hillslope-ks = 2.

[mask1]
  file = ./data/subbasin1.asc
  format = esri-ascii
  epsg = 32633
  channel-initiation-method = area
  channel-initiation-threshold = 400000.
  hillslope-width = 200.
  hillslope-alpha = 45.
  hillslope-ks = 5.

Table Start
Title: channel properties
Id: base-mask
Columns:    [count]      [threshold]      [width]   [alpha]   [ks]
Units:        [-]            [m^2]           [m]      [deg]
[m^1/3s^-1]
            1            5000000            5         45        20
            2           10000000            7         45        25
            3           15000000           10         45        30
            4           20000000           20         45        35
Table End

Table Start
Title: channel properties
Id: mask1
Columns:    [count]      [threshold]      [width]   [alpha]   [ks]
Units:        [-]            [m^2]           [m]      [deg]
[m^1/3s^-1]
            1            3000000           10         45        10
            2           12000000           15         45        15
            3           20000000           20         45        20
            4           30000000           30         45        25
            5           40000000           40         45        30

Table End
```

Example of discharge routing configuration file with `base-mask` and the additional subbasin `mask1`.

11.1 Reservoirs

When reservoirs are activated in discharge routing configuration file, the user must provide information of reservoirs in a specific file (see example below). Two types of reservoirs are available, on-stream and off-stream reservoirs. On-stream reservoirs are the ones that are located across a river. An off-stream reservoir is a reservoir that is not located on a streambed, and is supplied by an artificial canal or pipeline. In case of off-stream reservoirs, the water stored can be released in a downstream section of the same river from which water was withdrawn, or in a different water courses.

The reservoirs configuration file contains three main keywords that configure general properties common to all reservoirs (Table below).

Table 11.2. Definition of common keywords in reservoirs configuration file.

Keyword	Description	Requirements
`nreservoirs`	Number of reservoirs to configure	MANDATORY
`epsg`	Epsg coordinate system id	MANDATORY
`path-hotstart`	Path to file saved from a previously run simulation	OPTIONAL

When `path-hotstart` is set, initial reservoir stage and discharge values in diversion channels, if present, are set to the resulting values simulated in a past *FeST* run. In this case, past values are read from tables written in the external file defined by `path-hotstart`. Example of such a file is shown as follows.

```
Table Start
Title: reservoir stage at: 2020-12-07T03:00:00+00:00
Id: reservoir stage
Columns: [id] [stage]
Units: [-] [m]
1 651.7900
2 803.0000
3 803.2100
4 640.0000
…
12 747.0000
13 382.0000
14 370.0000
Table End


Table Start
Title: diverted discharge at: 2020-12-07T03:00:00+00:00
Id: diverted discharge
Columns: [id] [Qin] [Qout]
Units: [-] [m3/s] [m3/s]
1 0.3693309 8.299407
2 2.250000 2.250000
3 9.750000 9.750000
4 6.000000 6.000000
…
10 7.831643 10.37083
Table End
```

Example of tables in file defined by `path-hotstart` to assign initial values from a past *FeST* simulation run.

For each reservoir the user must configure the specific section numbered from 1 to the total number of reservoirs, filling in the required information according to the reservoir type, as listed and described in the following tables.

Table 11.3. Information to provide for on-stream basin (dam, lake or flood detention basin).

Keyword	Description	Requirements
`id`	Number Id of reservoir. Integer number	MANDATORY.
`type`	available options: `on` for on-stream reservoir, `off` for off-stream reservoir, `bypass` for by-pass channel.	MANDATORY
`name`	Name of the reservoir	MANDATORY
`rk`	Runge-kutta integration order. Available options: 3, 4	MANDATORY

Keyword	Description	Requirements
`easting`	x-coordinate of reservoir	MANDATORY
`northing`	y-coordinate of reservoir	MANDATORY
`stage`	Initial water surface elevation of reservoir	MANDATORY
`stage-target-file`	The name of file of stage values in fest time series format that is treated as a target stage for on-stream reservoir, outlet discharge is adjusted to reach the target (on-stream type 2 reservoir).	OPTIONAL
`discharge-downstream-file`	The name of file of observed reservoir downstream discharge. The read value is used to overwrite the value computed by the FeST. The reservoir mass conservation equation does not change.	OPTIONAL
`discharge-diverted-file`	The name of file of observed reservoir diverted discharge. The read value is used to overwrite the value computed by the FeST. The reservoir mass conservation equation does not change.	OPTIONAL
`e-flow`	environmental flow (m^3/s), minimum value of discharge to be released from reservoir. It is used when `stage-target-file` assigns a file with reservoir stage to follow. To assign a changeable value during the year, a table on external file must be assigned (see Chapter 14)	Required to be used in combination with `stage-target-file` option

Keyword	Description	Requirements
`free-flow`	free flow discharge (m^3/s). When Qin < free flow and stage <= free flow elevation Qout = Qin	OPTIONAL. When not defined, default value = 0
`free-flow-elevation`	free flow elevation (m asl). When Qin < free flow and stage <= free flow elevation Qout = Qin	OPTIONAL. When not defined, default value = 0
`geometry`	File containing information of the stage-volume, stage-area, and stage-outlet discharge of the reservoir. See example below.	MANDATORY

An example of geometry file of a reservoir follows. Column header [1] denotes the day of year since outlet discharge is valid. When only one day (and one column) is defined, discharge is used throughout the year. A different outlet discharge column can be set for each day of the year (doy) by adding on column with the proper doy as header.

```
Table     Start
Title:  reservoir
Id: pusiano #   mandatory
Columns:     [h]      [area]     [volume]      [1]
Units:       [m]      [m2]        [m3]         [m3/s]
             200.0  5500000     77000000      0.0
             259.0  5500000     77000000      0.0
             260.05 5500000     77000000      10.0
             260.55 5500000     77000000      15.0
             261.0  5500000     77000000      20.0
             261.37 5500000     77000000      25.0
             261.65 5500000     77000000      30.0
             261.93 5500000     77000000      35.0
             262.17 5500000     77000000      40.0
Table   End
```

Example of geometry file of a reservoir

On-stream reservoirs may have two optional subsections, one to manage high flow condition, and the second one to include in the reservoir the simulation of a channel that diverts flow from the reservoir itself (like in the example of dam for hydropower production where flow is diverted to the power production plant).

Table 11.4. Optional subsections of on-stream reservoir for managing high flow condition, and flow diversion from reservoir.

Keyword	Description	Requirements
`[[manage-high-level]]`	Marks the beginning of subsection to manage high flow condition of on-stream reservoir	OPTIONAL.
`full-reservoir-level`	full reservoir level (m)	MANDATORY
`qout`	option to manage reservoir outflow. Only option available is `qin`	MANDATORY
`rising`	when `rising = 1` qout is overridden when qin is rising, when `rising = 0` qout is always overridden	MANDATORY
`[[diversion]]`	Marks the beginning of subsection to manage flow diversion from reservoir	OPTIONAL.
`weir`	File containing table of stream-diverted discharges relationship	MANDATORY
`xout`	x-coordinate corresponding to the cell where discharge is released	MANDATORY
`yout`	y-coordinate corresponding to the cell where discharge is released	MANDATORY
`e-flow`	environmental flow (m^3/s), minimum value of discharge to be released in the river downstream the diversion. To assign a changeable value during the year, a table on external file must be assigned (see Chapter 14)	OPTIONAL
`channel-lenght`	Channel length (m)	MANDATORY

Keyword	Description	Requirements
channel-slope	Channel slope (m/m)	MANDATORY
channel-manning	Channel Manning roughness coefficient (s m$^{-1/3}$)	MANDATORY
section-bottom-width	Channel section bottom width (m)	MANDATORY
section-bank-slope	Channel section bank slope (degree)	MANDATORY

```
[1]
 id = 1
 type = on # on-stream reservoir
 name = santa_caterina
 rk = 4
 easting =   305461.27
 northing = 5157052.89
 stage-target-file = ./data/santa_caterina_stage.fts
 stage = 803.
 e-flow =0.852930122 # environmental flow [m3/s]
 geometry = ./data/reservoir_geometry/santa_caterina_diga.tab
[[manage-high-level]]
   full-reservoir-level = 826.2
   qout = qin
   rising = 1
[[diversion]]
   weir = ./data/reservoir_weir/diversion-weir.tab
   xout = 304514.806 # x coordinate of outflow
   yout = 5151740.539 # y coordinate of outflow
   channel-lenght = 7200 #  [m]
   channel-slope = 0.017 #  [m/m]
   channel-manning = 0.025 #s m^-1/3
   section-bottom-width = 10 #  [m]
   section-bank-slope = 45 # [degree]
```

Example of on-stream reservoir with optional subsections for managing high flow and diversion channel

```
Table Start
Title:      weir
Id:   G_0001-      #      mandatory
      Columns:     [Qstream]    [31]        [45]        [118]
      Units:       [m3/s]       [m3/s]      [m3/s]      [m3/s]
                   0.           0.          0.          0.
                   0.853        0.          0.          0.
                   11.64        10.787      15.0        5.0
                   10000        10.787      15.0        5.0
Table End
```

Content of `diversion-weir.tab` file

Table 11.5. Information to provide for off-stream detention basin.

Keyword	Description	Requirements
`id`	Number Id of reservoir. Integer number	MANDATORY.
`type`	available options: `on` for on-stream reservoir, `off` for off-stream reservoir	MANDATORY
`name`	Name of the reservoir	MANDATORY
`rk`	Runge-kutta integration order. Available options: 3, 4	MANDATORY
`easting`	x-coordinate of reservoir	MANDATORY
`northing`	y-coordinate of reservoir	MANDATORY
`stage`	Initial water surface elevation of reservoir	MANDATORY
`stage-max`	this is the maximum stage for off-stream reservoir. When maximum stage is reached, discharge cannot enter the detention basin anymore.	MANDATORY
`geometry`	File containing information of the stage-volume, stage-area, and stage-outlet discharge of the reservoir. See example below.	MANDATORY
`weir`	File containing table of stream-diverted discharges relationship	Required when `type=off`
`xout`	x-coordinate corresponding to the cell where discharge is released	Required when `type=off`
`yout`	y-coordinate corresponding to the cell where discharge is released	Required when `type=off`

```
Table    Start
Title:   weir
Id: weir_csno    #    mandatory
Columns:      [Qstream]          [Qdiverted]
Units:        [m3/s]              [m3/s]
                 4.2                 0.2
                 5.1                 1.3
                 5.7                 2.2
                 6.4                 3.0
                 7.1                 4.0
                 7.8                 5.0
                 8.5                 5.9
                 9.2                 6.8
                 9.9                 7.7
                10.6                 8.5
                11.5                 9.4
                12.4                10.3
                13.1                11.1
Table    End
```

Some examples of the different type of reservoirs that can be simulated by the FEST model are described in the following sections.

INFO

Since version 1.5 of the Reservoirs module, reservoir volume is written to output file alongside water surface elevation.

11.1.1 Dam and lake simulation

Lake Idro or Eridio is a lake of glacial origin located in the province of Brescia on the border with Trentino, in Northern Italy. Situated at 368 meters above sea level, it is formed by the waters of the Chiese river which is also its outlet. Its surface is 10.9 km^2 and reaches a maximum depth of 122 meters.

Lake Idro is the first natural Italian lake, to have been subjected to artificial regulation. The original idea of constructing a dam dates back to 1855, but the concession was given jointly to Società Elettrica Bresciana (SEB) and the University of Naviglio Grande Bresciano in 1917 to reduce Lake Idro to a regulated reservoir, in order to produce electricity and have greater volumes of water for the summer irrigation of the Brescia and Mantua areas. The regulation work was built in the 1920s and came into operation in 1933 with a regulation which provides for a level excursion of up to 3.5 meters , later raised to 7 meters. In the period between 1950 and 1960, the company SEB (now HDE) was granted the right to build two new hydroelectric plants upstream of Lake Idro, in the Alto Chiese basin in the province of Trento, including the construction of the artificial reservoirs of Malga Bissina (1791 meters above sea level 60 million m3) and Malga Boazzo (1225 meters above sea level, 12 million m3) for a total of 72 million m3.

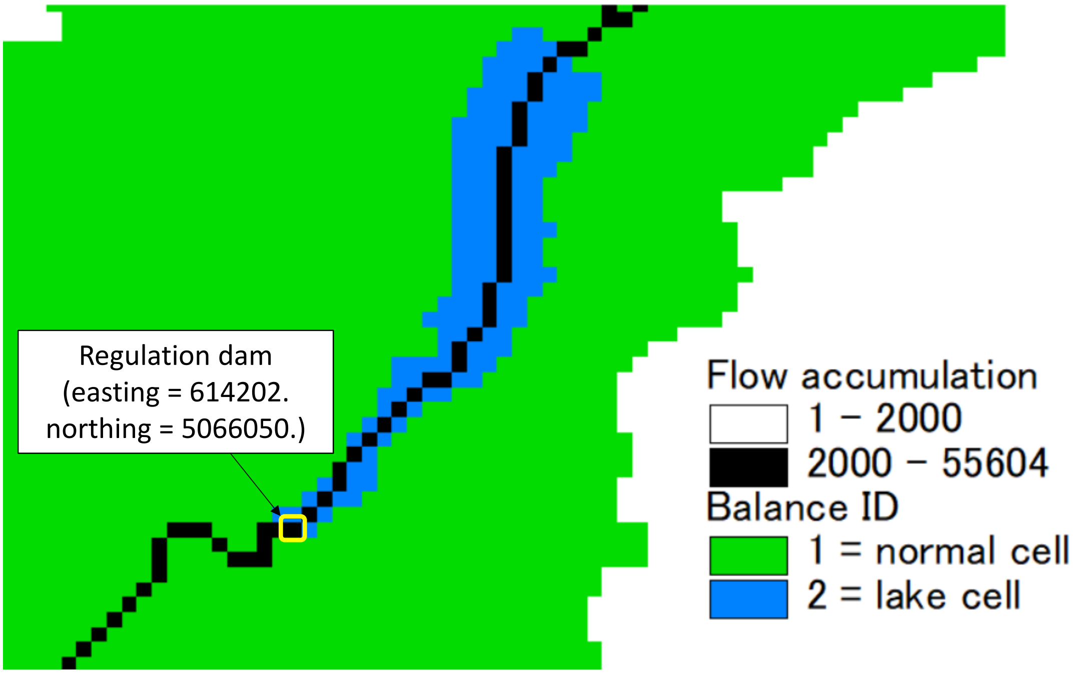

Figure 11.1 Location of the Idro lake regulation dam along the flow accumulation map of the Chiese river basin.

The `reservoirs.ini` file to include the Idro lake along the Chiese river course is shown hereafter. Coordinates of the lake match the location of the regulation dam.

```
nreservoirs = 1
epsg = 32632

[1]
  id = 1
  type = on
  name = idro
  rk = 4
  easting = 614202.
  northing = 5066050.
  stage = 366.0
  geometry = ./data/lake_idro.tab
```

The `reservoirs.ini` file to assign the Idro lake.

The `lake_idro.tab` file is shown hereafter.

```
Table   Start
Title:      reservoir
Id:   idro
      Columns:    [h]       [area]    [volume]       [1]
      Units:       [m]        [m2]        [m3]        [m3/s]
            364.00      10900000.0  1308000000.0      0.0
            364.50      10900000.0  1313450000.0      0.0
            365.00      10900000.0  1318900000.0      5.0
            365.50      10900000.0  1324350000.0      10.0
            366.00      10900000.0  1329800000.0      15.0
            366.50      10900000.0  1335250000.0      20.0
            367.00      10900000.0  1340700000.0      25.0
            367.50      10900000.0  1346150000.0      30.0
            368.00      10900000.0  1351600000.0      35.0
            368.50      10900000.0  1357050000.0      40.0
            369.00      10900000.0  1362500000.0      45.0
            369.50      10900000.0  1367950000.0      50.0
            370.00      10900000.0  1373400000.0      55.0
            370.50      10900000.0  1378850000.0      60.0
            371.00      10900000.0  1384300000.0      65.0
            371.50      10900000.0  1389750000.0      70.0
            372.00      10900000.0  1395200000.0      75.0
            372.50      10900000.0  1400650000.0      80.0
Table End
```

The `lake_idro.tab` file.

When the model runs produces a file that contains water elevation inside the basin, upstream discharge and downstream discharge as shown hereafter. Note that the upstream discharge, the one that enters the lake, when the lake surface is assigned the balanca id = 2, may be negative when the evapotranspiration is greater than runoff. This is likely to happen at initial time steps when discharge is zero and rainfall is not occurring on the basin.

```
FEST: reservoir routing
 reservoir: idro
 id:           1

 data
DateTime       h[m]           Qupstream[m3/s]     Qdownstream[m3/s]
2014-11-01T00:00:00+00:00     365.999      -0.001       14.991
2014-11-01T01:00:00+00:00     365.995      -0.001       14.954
2014-11-01T02:00:00+00:00     365.992      -0.001       14.918
2014-11-01T03:00:00+00:00     365.988      -0.001       14.881
…
2014-11-10T13:00:00+00:00     365.706       5.603       12.056
2014-11-10T14:00:00+00:00     365.703       7.105       12.032
2014-11-10T15:00:00+00:00     365.703      10.624       12.032
2014-11-10T16:00:00+00:00     365.703      14.249       12.032
2014-11-10T17:00:00+00:00     365.703      16.049       12.032
2014-11-10T18:00:00+00:00     365.703      16.914       12.032
2014-11-10T19:00:00+00:00     365.705      18.193       12.045
2014-11-10T20:00:00+00:00     365.708      20.989       12.082
2014-11-10T21:00:00+00:00     365.712      27.141       12.119
2014-11-10T22:00:00+00:00     365.719      38.665       12.185
2014-11-10T23:00:00+00:00     365.730      56.333       12.302
2014-11-11T00:00:00+00:00     365.747      71.968       12.473
2014-11-11T01:00:00+00:00     365.769      80.812       12.688
…
```

Output file.

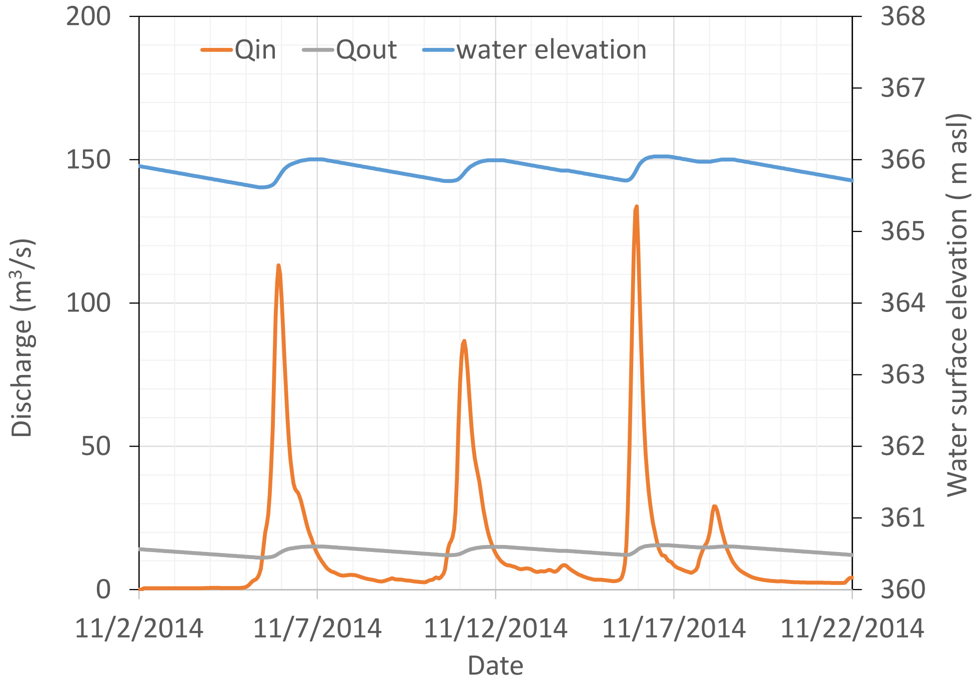

Figure 11.2 Input and output discharge and water elevation inside the Idro lake simulated by FEST model.

11.1.2 Dam with an assigned level in time

Malga Bissina dam is located in the Trento province, and in the Chiese river basin. It has a volume of about 61 milion m^3 that is used for hydropower production. In this application the purpose is to perform a simulation following a prescribed target water level that defines the usual dam regulation. The used target water levels are not real observations, they are synthetic data generated just for demonstration purposes. When a target stage is assigned in a on-stream dam, the simulation of the water surface elevation within the basin solves the mass balance equation by setting the outflow discharge as:

- When water surface is lower than target water level, outflow is computed as the minimum between the inflow discharge and the environmental flow.
- When water surface is greater than target water level, outflow is computed as the maximum between the environmental flow and the value retrieved from the dam geometry table.

Figure 11.3 The Malga Bissina dam on the Cjiese river for hydropower production. (*image source*:
https://dgdighe.mit.gov.it/categoria/articolo/_dighe_di_rilievo/diga_malga_bissina.

The `reservoirs.ini` file to include the Malga Bissina dam is shown hereafter.

```
nreservoirs = 1
epsg = 32632

[1]
  id = 2
 type = on
 name = bissina
 rk = 4
 easting = 617452.
 northing = 5101300.
 stage-target-file = ./data/bissina_stage.fts
 stage = 1779.
 e-flow = 0.08 # environmental flow [m3/s]
 geometry = ./data/bissina.tab
```

The `reservoirs.ini` file to assign the Malga Bissina dam

The `bissina.tab` file is shown hereafter.

```
Table   Start
Title:      reservoir
Id:   pusiano     #     mandatory
      Columns:    [h]        [area]    [volume]        [1]
      Units:       [m]          [m2]        [m3]         [m3/s]
              1740.0    762500.0    24400000.0        1.0
              1741.0    762500.0    25162500.0        1.0
              1742.0    762500.0    25925000.0        1.0
              1743.0    762500.0    26687500.0        1.0
              1744.0    762500.0    27450000.0        1.0
              …
              1775.0    762500.0    51087500.0        4.0
              1776.0    762500.0    51850000.0        5.0
              1777.0    762500.0    52612500.0        6.0
              1778.0    762500.0    53375000.0        7.0
              1779.0    762500.0    54137500.0        10.0
              1780.0    762500.0    54900000.0        15.0
              1781.0    762500.0    55662500.0        30.0
              1782.0    762500.0    56425000.0        50.0
              1783.0    762500.0    57187500.0        100.0
              1784.0    762500.0    57950000.0        313.69
              1785.0    762500.0    58712500.0        336.14
              1786.0    762500.0    59475000.0        393.57
              1787.0    762500.0    60237500.0        470.69
              1788.0    762500.0    61000000.0        563.22
              1789.0    762500.0    61762500.0        706.65
Table End
```

The `bissina.tab` file.

The `bissina_stage.fts` file is shown hereafter.

```
description =     water surface elevation
unit  =     m asl
epsg  =     32632
count =     1
dt    =     3600
missing-data      =     -999
offsetz     =     0



metadata
Malga_Bissina_Dam 1     0     0     0

data
DateTime    1
2003-01-01T00:00:00+01:00    1782.498
2003-01-01T01:00:00+01:00    1782.498
2003-01-01T02:00:00+01:00    1782.498
2003-01-01T03:00:00+01:00    1782.498
…
2007-04-16T20-00-00+01:00    1779.516
2007-04-16T21-00-00+01:00    1779.516
2007-04-16T22-00-00+01:00    1779.516
2007-04-16T23-00-00+01:00    1779.516
2007-04-17T00-00-00+01:00    1779.486
2007-04-17T01-00-00+01:00    1779.486
2007-04-17T02-00-00+01:00    1779.486
2007-04-17T03-00-00+01:00    1779.486
2007-04-17T04-00-00+01:00    1779.486
2007-04-17T05-00-00+01:00    1779.486
2007-04-17T06-00-00+01:00    1779.486
…
```

The `bissina_stage.fts` file.

When the model runs produces a file that contains water elevation inside the basin upstream discharge and downstream discharge as shown hereafter.

```
FEST: reservoir routing
 reservoir: bissina
 id:           2

 data
DateTime    h[m]  Qupstream[m3/s]   Qdownstream[m3/s]
2004-01-01T01:00:00+00:00    1779.000        0.000        0.000
2004-01-01T02:00:00+00:00    1779.000        0.000        0.000
2004-01-01T03:00:00+00:00    1779.000        0.000        0.000
…
2008-04-11T03:00:00+00:00    1779.574        3.675        0.020
2008-04-11T04:00:00+00:00    1779.574        3.562        0.020
2008-04-11T05:00:00+00:00    1779.574        3.197        0.020
2008-04-11T06:00:00+00:00    1779.574        2.902        0.020
2008-04-11T07:00:00+00:00    1779.574        3.572        0.020
2008-04-11T08:00:00+00:00    1779.574        8.151        0.020
2008-04-11T09:00:00+00:00    1779.575       11.380       12.873
2008-04-11T10:00:00+00:00    1779.575       10.492       12.873
2008-04-11T11:00:00+00:00    1779.574       14.306       12.872
2008-04-11T12:00:00+00:00    1779.574       12.495       12.872
2008-04-11T13:00:00+00:00    1779.575        9.716       12.874
2008-04-11T14:00:00+00:00    1779.575        8.743       12.874
2008-04-11T15:00:00+00:00    1779.575       10.809       12.874
…
```

Output file.

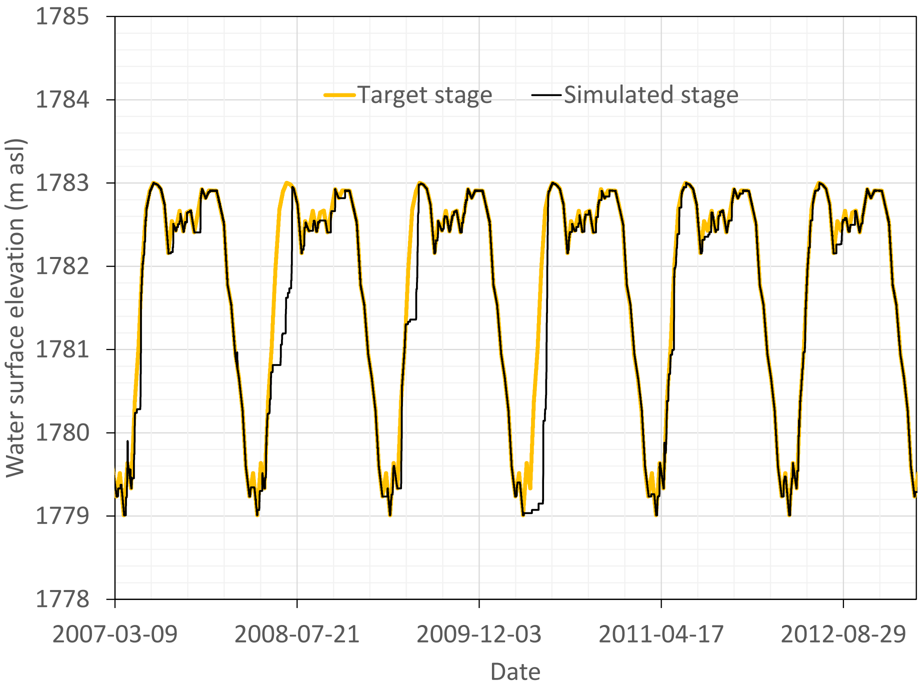

Figure 11.4 Water surface elevation simulated by FEST model and assigned as target.

11.1.3 On stream detention basin

The Gurone dam is an example of on stream detention basin that was put into operation in 2010 to mitigate flood risk on the Olona river, in northern Italy. The basin stores a total volume of 1.79 Mm^3. Two gates regulate the basin outflow to keep the maximum discharge below 36 m^3/s. When the water elevation inside the basin exceeds 289.3 m asl, water is evacuated from a 114 m length spillway with a maximum capacity of 175 m^3/s at the maximum water elevation of 290.57 m asl. The minimum water level in the basin is 278.9 m asl.

Figure 11.5 The Gurone dam on the Olona river for flood risk mitigation. (*image source*: PIANO EMERGENZA DIGA – PED DIGA DI OLONA (VA).

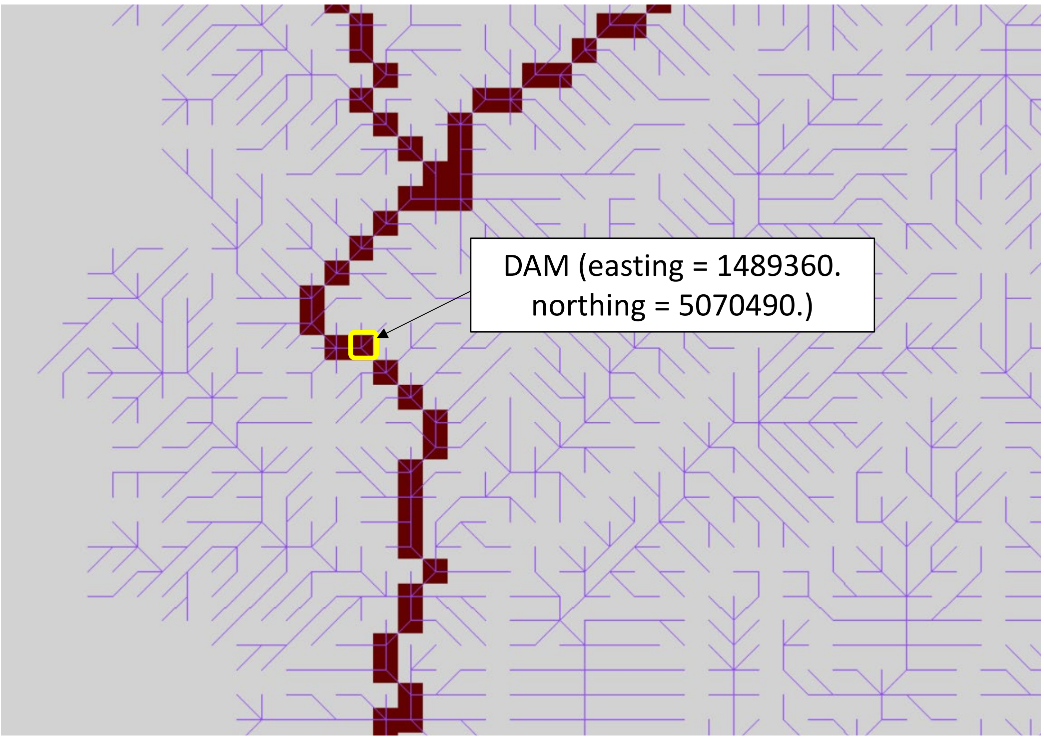

Figure 11.6 Location of the Gurone dam along the flow accumulation map of the Olona river basin.

The `reservoirs.ini` file to include the Gurone detention basin along the Olona river course is shown hereafter.

```
nreservoirs = 1
epsg = 3003

[1]
  id = 3
  type = on #on-stream
  name = gurone
  rk = 4 #runge-kutta order
  easting = 1489360.
  northing = 5070490.
  stage = 278.9 #initial stage [m asl]
  free-flow = 10. #[m3/s]
  free-flow-elevation = 278.9 #[m asl]
  geometry = ./data/gurone.tab
```

The `reservoirs.ini` file to assign the Gurone dam

The `gurone.tab` file is shown hereafter.

```
Table Start
Title:      reservoir
Id:   gurone
      Columns:    [h]         [area]      [volume]    [1]
      Units:      [m]         [m2]        [m3]        [m3/s]
                  278.9       153385      0           0
                  279.0       153385      15338.5     10
                  279.1       153385      30677       15
                  279.2       153385      46015.5     36
                  289.3       153385      1595204     36
                  290.57      153385      1790002.95  211
Table End
```

The `gurone.tab` file.

When the model runs produces a file that contains water elevation inside the basin upstream discharge and downstream discharge as shown hereafter.

```
FEST: reservoir routing
 reservoir: gurone
 id:           3

 data
#     h[m]  Qupstream[m3/s]   Qdownstream[m3/s]
2014-11-01T00:00:00+00:00     278.900       0.000          0.000
2014-11-01T01:00:00+00:00     278.900       0.000          0.000
2014-11-01T02:00:00+00:00     278.900       0.000          0.000
…
…
2014-11-10T07:00:00+00:00     279.101      15.705         15.237
2014-11-10T08:00:00+00:00     279.111      17.758         17.256
2014-11-10T09:00:00+00:00     279.122      20.046         19.684
2014-11-10T10:00:00+00:00     279.137      23.618         22.825
2014-11-10T11:00:00+00:00     279.159      28.280         27.381
2014-11-10T12:00:00+00:00     279.184      33.519         32.584
2014-11-10T13:00:00+00:00     279.198      35.738         35.513
2014-11-10T14:00:00+00:00     279.217      37.841         36.000
2014-11-10T15:00:00+00:00     279.289      39.639         36.000
2014-11-10T16:00:00+00:00     279.380      39.258         36.000
2014-11-10T17:00:00+00:00     279.481      41.277         36.000
2014-11-10T18:00:00+00:00     279.652      44.199         36.000
…
```

Output file.

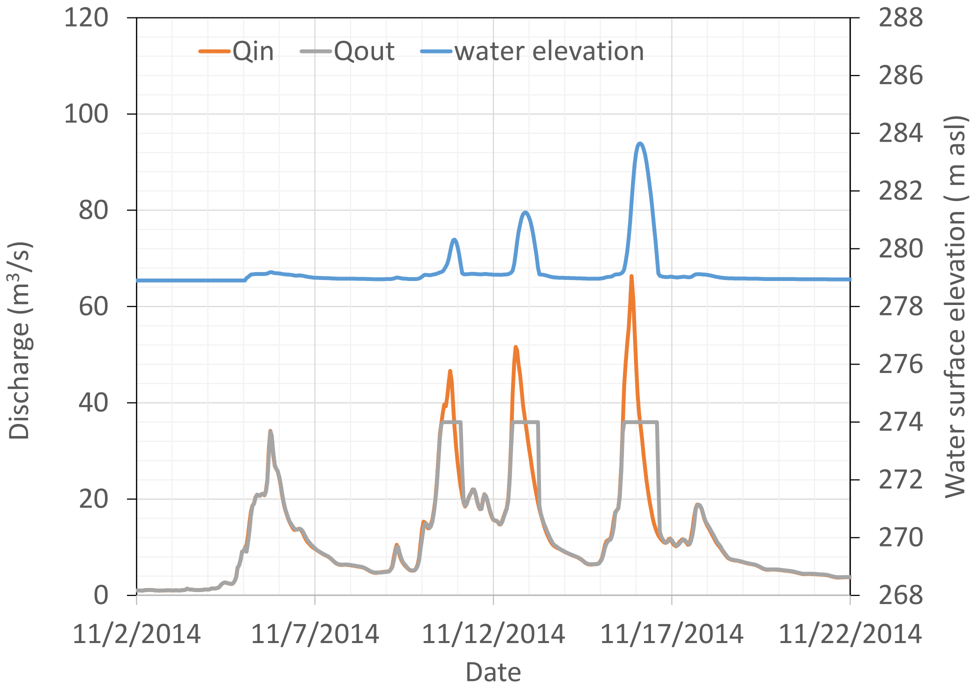

Figure 11.7 Input and output discharge and water elevation inside the basin simulated by FEST model.

11.1.4 Dam with flow diversion

Water stored within a dam is often used for hydropower generation or several further purposes such as, providing drinking water, or water for crop irrigation. To this purpose, a given amount of water is diverted from the reservoir and conveyed, in case of dam for hydropower generation, to the hydropower plant, usually located downstream in the river valley, sometimes in a different river basin.

The Santa Caterina dam, located in Auronzo di Cadore, in northern Italy, was built in 1930 and it is approximately 55m high. Water is diverted for hydropower production.

Figure 11.8 Santa Caterina dam, seen from upstream (source: https://progettodighe.it/dighe/santa-caterina/).

The `reservoirs.ini` file to include the Santa Caterina dam is shown hereafter.

```
#info to configure reservoirs
nreservoirs = 1 # number of reservoirs
hotstart = cold
epsg = 32633

[1]
 id = 1
 type = on
 name = santa_caterina
 rk = 4
 easting =   305461.273
 northing = 5157052.895
 stage-target-file = ./data/santa_caterina_stage.fts
 stage = 803
 e-flow =0.852930122
 geometry = ./data/santa_caterina.tab
[[manage-high-level]]
   full-reservoir-level = 826.2
   qout = qin
   rising = 1
[[diversion]]
   weir = ./data/weir.tab
   xout = 304514.806 # x coordinate of outflow
   yout = 5151740.539 # y coordinate of outflow
   e-flow = 0.2 # environmental flow [m3/s]
   channel-lenght = 7200 #  [m]
   channel-slope = 0.017 #  [m/m]
   channel-manning = 0.025 #s m^-1/3
   section-bottom-width = 10 #  [m]
   section-bank-slope = 45
```

The `reservoirs.ini` file to configure the Santa Caterina dam

The `santa_caterina.tab` file is shown hereafter.

```
Table     Start
Title:  Santa Caterina dam
Id: dam1
Columns:    [h]     [area]    [volume]     [1]
Units:      [m]     [m2]       [m3]        [m3/s]
793.46      1.00        0.00        0
793.50      1.30        0.05        0
794         5.00        1.64        0.85
795         14.00       11.19       0.85
796         41.00       38.82       0.85
797         78.01       98.52       0.85
798         122.01      198.75      0.85
799         188.02      354.10      0.85
800         277.03      587.07      0.85
801         407.05      929.76      0.85
802         800.10      1535.30     0.85
802.9       4991.00     4162.25     0.85
803         5456.66     4686.96     11.64
804         38893.67    27029.31    11.64
805         58570.03    75859.54    11.64
806         71119.54    140767.08   11.64
807         81790.82    217275.62   11.64
808         90933.92    303683.71   11.64
809         98855.87    398618.21   11.64
810         106459.79   501314.06   11.64
811         113556.64   611357.76   11.64
812         120569.48   728455.89   11.64
813         136478.39   857059.37   11.64
814         150338.06   1000536.89  11.64
815         170029.42   1160819.09  11.64
816         203804.48   1347904.91  11.64
817         232801.96   1566353.12  11.64
818         252030.27   1808865.38  11.64
819         280846.73   2075447.97  11.64
820         323800.89   2377986.55  11.64
821         356845.86   2718475.15  11.64
822         382726.97   3088390.97  11.64
823         409483.18   3484629.83  11.64
824         429354.57   3904148.07  11.64
825         444312.37   4341056.32  11.64
826         458461.07   4792513.78  11.64
826.1       458461.07   4838359.89  11.64
826.2       458461.07   4884206.00  11.64
826.3       458461.07   4930052.10  18.90
826.4       458461.07   4975898.21  32.71
826.5       458461.07   5021744.32  51.18
826.6       458461.07   5067590.42  73.59
826.7       458461.07   5113436.53  99.11
826.9       458461.07   5205128.74  157.87
827         458461.07   5250974.85  190.64
827.1       458461.07   5296820.96  225.35
827.2       458461.07   5342667.06  261.91
827.3       458461.07   5388513.17  300.22
827.4       458461.07   5434359.28  340.10
827.5       458461.07   5480205.38  381.48
827.6       458461.07   5526051.49  424.32
827.7       458461.07   5571897.60  468.45
Table   End
```

The `santa_caterina.tab` file.

When the model runs produces a file that contains water elevation and volume inside the reservoir, upstream and downstream discharge, and input and output discharge conveyed through the diversion, as shown hereafter.

```
FEST: reservoir routing
 reservoir: santa_caterina
 id:           1

 data
DateTime h[m] Volume[m3] Qupstream[m3/s] Qdownstream[m3/s]
QinChannel[m3/s] QoutChannel[m3/s]
2018-10-15T00:00:00+00:00  803.0    4686.9   0.0   0.0 0.0 0.0
2018-10-15T01:00:00+00:00  803.0    4686.9   0.0   0.0 0.0 0.0
2018-10-15T02:00:00+00:00  803.0    4686.9   0.0   0.0 0.0 0.0
…
…
2018-10-28T04:00:00+00:00  820.2 2458827.7  92.2   0.8 0.0 0.0
2018-10-28T05:00:00+00:00  821.2 2808854.5 100.3   0.8 0.0 0.0
2018-10-28T06:00:00+00:00  822.2 3168030.5 102.8   0.8 0.0 0.0
2018-10-28T07:00:00+00:00  823.1 3564902.5 122.7   0.8 0.0 0.0
2018-10-28T08:00:00+00:00  824.3 4058442.0 151.9   0.8 0.0 0.0
2018-10-28T09:00:00+00:00  825.7 4659342.0 178.4   0.8 0.0 0.0
2018-10-28T10:00:00+00:00  826.4 4981831.5 189.2 184.2 5.0 2.5
2018-10-28T11:00:00+00:00  826.4 4981831.5 196.6 191.6 5.0 4.9
2018-10-28T12:00:00+00:00  826.9 5226652.5 183.6 168.2 5.0 4.9
2018-10-28T13:00:00+00:00  826.9 5223965.5 165.8 166.3 5.0 5.0
2018-10-28T14:00:00+00:00  826.9 5207004.0 155.3 154.2 5.0 5.0
2018-10-28T15:00:00+00:00  826.8 5203114.0 155.0 151.5 5.0 5.0
2018-10-28T16:00:00+00:00  826.8 5202386.5 163.6 158.6 5.0 5.0
2018-10-28T17:00:00+00:00  826.9 5206052.0 157.8 152.8 5.0 5.0
2018-10-28T18:00:00+00:00  826.9 5206052.0 163.2 158.2 5.0 5.0
2018-10-28T19:00:00+00:00  826.9 5217192.0 167.6 161.4 5.0 5.0
2018-10-28T20:00:00+00:00  826.9 5205016.5 152.5 152.7 5.0 5.0
2018-10-28T21:00:00+00:00  826.8 5172475.5 126.0 131.9 5.0 5.0
2018-10-28T22:00:00+00:00  826.7 5120627.5  88.5  98.7 5.0 5.0
2018-10-28T23:00:00+00:00  826.6 5071842.0  63.7  70.9 5.0 5.0
…
```

Output file.

11.1.5 Off stream detention basin

11.2 Diversions

The diversion is an hydraulic structure that diverts water from a river section to convey it to a downstream section of the same river (bypass channel) or to a different river (diversion channel). When diversions are activated in discharge routing configuration file, the user must provide information of diversions in a specific file (see example below).
The diversions configuration file contains two main keywords that configure general properties common to all diversions (Table below).

Table 11.6. Definition of common keywords in diversions configuration file.

Keyword	Description	Requirements
`ndiversions`	Number of diversion channels to configure	MANDATORY
`epsg`	Epsg coordinate system id	MANDATORY
`path-hotstart`	file containing initial discharge for hotstart from a previous simulation	OPTIONAL

When `path-hotstart` is set, initial discharge values in diversion channels are set to the results simulated in a past *FeST* run. In this case, the discharge values are read from a table written in the external file defined by `path-hotstart`. Example of such a file is shown as follows.

```
Table Start
Title: diversion status at: 2020-12-11T00:00:00+00:00
Id: diversion status
Columns: [id] [Qin] [Qout]
Units: [-] [m3/s] [m3/s]
1 0.3693309 8.299407
2 2.250000 2.250000
3 9.750000 9.750000
4 6.000000 6.000000
5 0.2000000 0.2000000
…
10 7.831643 10.37083
Table End
```

Example of table in file defined by `path-hotstart` to assign initial discharge values from a past *FeST* simulation run.

For each diversion the user must configure the specific section numbered from 1 to the total number of diversions, filling in the required information, as listed and described in the following table.

Table 11.7. Information to provide for configuring a diversion channel.

Keyword	Description	Requirements
`id`	Number Id of diversion. Integer number.	MANDATORY.
`name`	Name of the diversion channel	MANDATORY
`easting`	x-coordinate of diversion	MANDATORY
`northing`	y-coordinate of diversion	MANDATORY
`weir`	File containing table of stream-diverted discharges relationship	MANDATORY
`e-flow`	environmental flow (m^3/s), minimum value of discharge to be released in the river downstream the diversion. To assign a changeable value during the year, a table on external file must be assigned (see Chapter 14)	OPTIONAL
`xout`	x-coordinate corresponding to the cell where discharge is released	MANDATORY
`yout`	y-coordinate corresponding to the cell where discharge is released	MANDATORY
`channel-lenght`	Channel length (m)	MANDATORY
`channel-slope`	Channel slope (m/m)	MANDATORY
`channel-manning`	Channel Manning roughness coefficient (s $m^{-1/3}$)	MANDATORY
`section-bottom-width`	Channel section bottom width (m)	MANDATORY
`section-bank-slope`	Channel section bank slope	MANDATORY

Keyword	Description	Requirements
	(degree)	

Some examples of diversion channels that can be simulated by the *FeST* model are described in the following sections.

11.2.1 Diversion channel

The Seveso river, in Northern Italy, is a small river that flows into Milan. This area is frequently hit by high rainfall intensity events that cause severe floods. The urban development after the second World War, has reduced the river basin soil infiltration capacity and exacerbated the flood occurrences. In 1980 the canale scolmatore di nord ovest (CSNO) bypass channel was put into operation to mitigate the flood risk in Milan. It is a 34 km length channel that deviates a maximum discharge of 30 m^3/s from the Seveso river to convey it into the Ticino river.

Figure 11.9 The CSNO bypass channel on the Seveso river. *Source: Stefano Stabile, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons.*

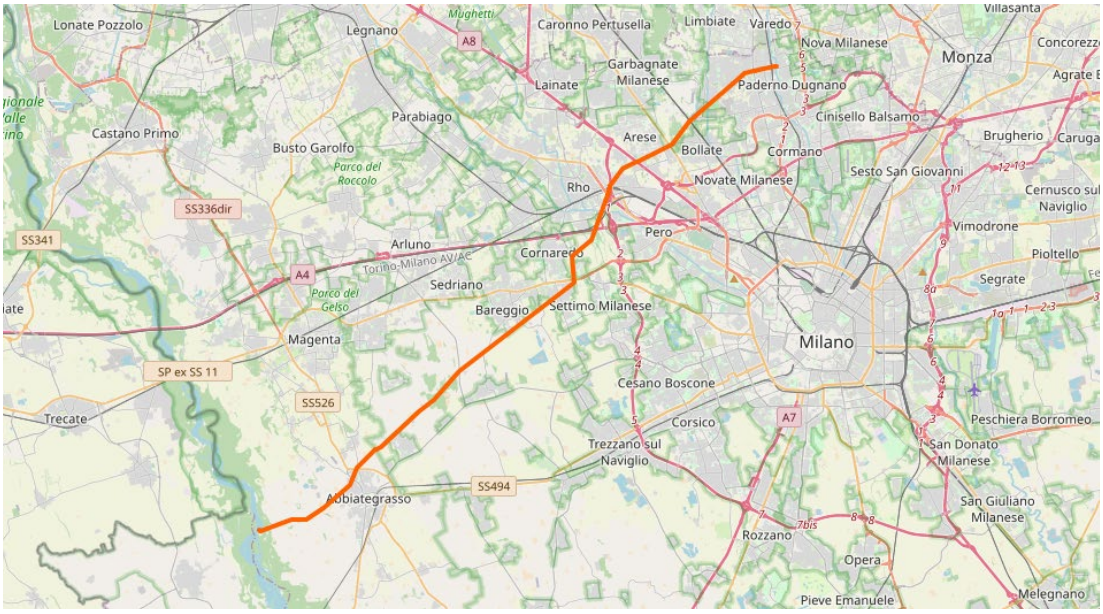

Figure 11.10 Path of the CSNO bypass channel. *Source:* https://www.openstreetmap.org/relation/4633456.

The `diversions.ini` file to include the CSNO by-pass channel along the Seveso river is shown hereafter.

```
ndiversions = 1
epsg = 3003

[1]
 id = 2
 name = csno
 easting = 1512560.
 northing  = 5047490.
 weir-change-doy = 1
 weir = ./data/weir_csno.tab
 xout = 0 # x coordinate of outflow
 yout = 0 # y coordinate of outflow
 channel-lenght = 34000 # [m]
 channel-slope = 0.001 # [m/m]
 channel-manning = 0.0222 #s m^-1/3
 section-bottom-width = 10. # [m]
```

The `diversionss.ini` file to assign the CSNO by-pass channel. Note that `xout` and `yout` are set to 0 because the outlet section of the by-pass channel is outside the simulation domain

The `weir_csno.tab` file is shown hereafter. Note that there is one column associated to doy 1. The column header name is the doy itself. A column with different discharge can be assigned for each day of the year.

```
Table Start
Title:      weir
Id:   weir_csno   #     mandatory
Columns:    [Qstream]         [1]
Units:      [m3/s]            [m3/s]
            0.0         0.0
            4.2         0.2
            5.1         1.3
            5.7         2.2
            6.4         3.0
            7.1         4.0
            7.8         5.0
            8.5         5.9
            9.2         6.8
            9.9         7.7
            10.6        8.5
            …           …
            …           …
            138.0       30.1
            139.9       30.1
            141.8       30.1
            143.8       30.1
            145.7       30.1
            147.7       30.1
            149.6       30.1
Table End
```

The `weir_csno.tab` file.

When the model runs produces a file that contains upstream and downstream discharge and input and output discharge in and from the diversion channel as shown hereafter.

```
FEST: diversion routing
diversion name: csno
diversion id:            2

 data
DateTime Qupstream[m3/s]      Qdownstream[m3/s] QinChannel[m3/s]
QoutChannel[m3/s]
2014-11-01T00:00:00+00:00      0.000      0.000     0.000     0.000
2014-11-01T01:00:00+00:00      0.000      0.000     0.000     0.000
2014-11-01T02:00:00+00:00      0.000      0.000     0.000     0.000
…
2014-11-15T13:00:00+00:00     11.319      2.100     9.219     0.054
2014-11-15T14:00:00+00:00     14.208      2.100    12.108     0.376
2014-11-15T15:00:00+00:00     18.267      2.087    16.180     0.949
2014-11-15T16:00:00+00:00     22.833      2.104    20.729     2.701
2014-11-15T17:00:00+00:00     28.560      2.781    25.779     5.741
2014-11-15T18:00:00+00:00     35.337      6.279    29.057    11.028
2014-11-15T19:00:00+00:00     40.972     10.872    30.100    17.341
2014-11-15T20:00:00+00:00     44.818     14.718    30.100    22.241
2014-11-15T21:00:00+00:00     45.403     15.303    30.100    25.306
…
```

Output file.

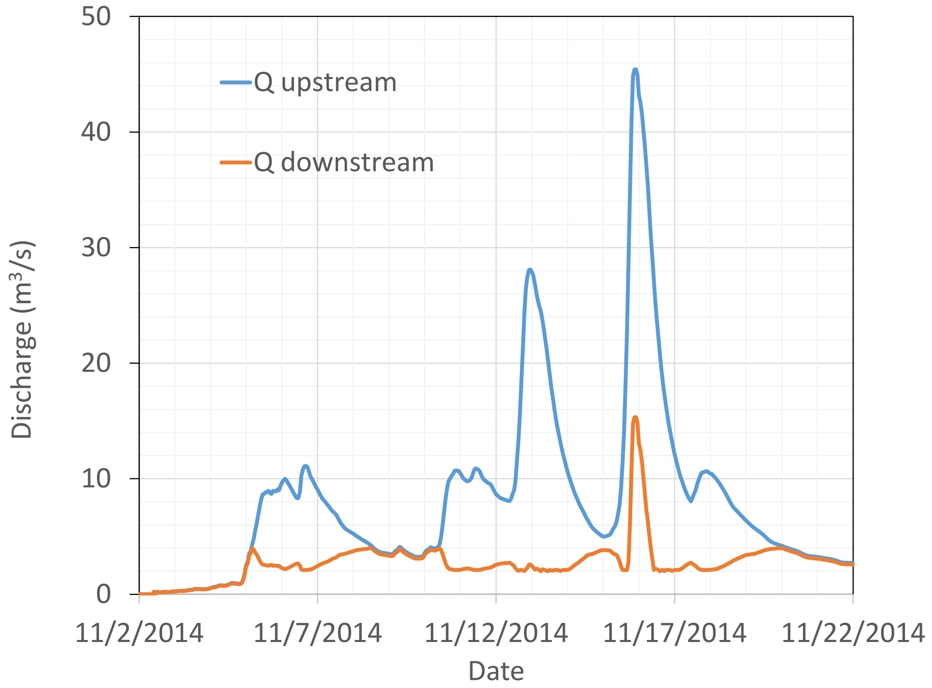

Figure 11.11 Discharge in the Seveso river upstream and downstream the diversion channel intake section.

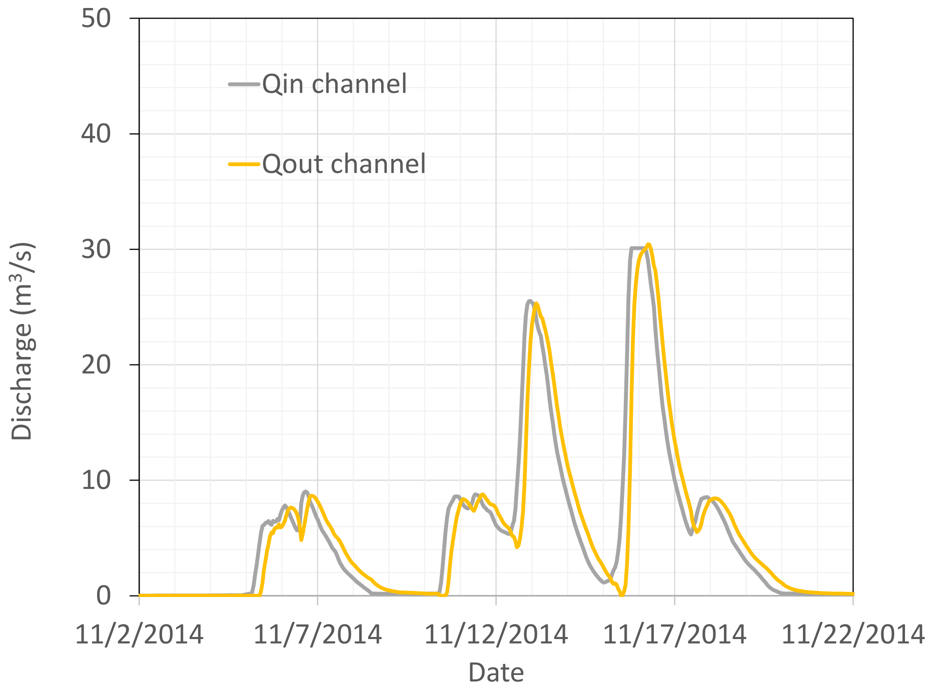

Figure 11.12 Input and output discharge in and from the CSNO diversion channel.

CHAPTER 12
GROUNDWATER

The FEST model can simulate groundwater flow with a quasi 3D scheme based on macroscopic cellular automata (Ravazzani et al., 2011). Groundwater is simulated as one or more aquifers that can interact through an aquitard. Aquitard depth is computed as the difference between bottom of upper aquifer and top of lower aquifer. Aquifers are enumerated starting from number 1 at top. At least one aquifer must be present in order to simulate groundwater. Optionally, the mutual flux exchange between river and groundwater can be simulated.

Groundwater simulation is activated by filling the specific section in the main configuration file (3.10). This chapter describes the groundwater configuration file, usually named `groundwater.ini`. Aquifers configuration is explained in Table 11.1, river-groundwater interaction is explained in Table 11.2

Table 12.1. How to configure aquifers to simulate groundwater.

Keyword	**Description**	**Requirements**
`aquifers`	Number of aquifers in the groundwater basin	Mandatory
`[aquifer_`*n*`]`	Section that configure the aquifer number *n* with *n* = 1, `aquifers`.	Mandatory
`[[boundary-condition-id]]`	Map of boundary condition and active cells definition. Available options: 1 = active cell, 2 = Dirichlet type boundary condition (assigned head), 3 =	Mandatory. The user can set a map with usual `file`, `format`, and `epsg` keywords, or he can assign a constant value using the `scalar` keyword

Keyword	Description	Requirements
	Neumann type boundary condition (flux assigned)	
`[[boundary-condition-value]]`	Map of boundary condition head values to be assigned to cells of Dirichlet type boundary condition (id = 2). For Neumann type boundary condition cells (id = 3), a flux is assigned internally at every time step from the soil water balance module.	Mandatory. The user can set a map with usual `file`, `format`, and `epsg` keywords, or he can assign a constant value using the `scalar` keyword. This map can change in time by assigning a netCDF multitemporal layer. In this case the user can set `syncinitial = 1` option to synchronize the simulation to the proper initial map
`[[top-elevation]]`	Top of the aquifer.	Mandatory. The user can set a map with usual `file`, `format`, and `epsg` keywords, or he can assign a constant value using the `scalar` keyword
`[[bottom-elevation]]`	Bottom of the aquifer	Mandatory. The user can set a map with usual `file`, `format`, and `epsg` keywords, or he can assign a constant value using the `scalar` keyword
`[[hydraulic-conductivity]]`	Aquifer hydraulic conductivity (m/s)	Mandatory. The user can set a map with usual `file`, `format`, and `epsg` keywords, or he can assign a constant value using the `scalar` keyword
`[[specific-yield]]`	Aquifer specific yield (m/m)	Mandatory. The user can set

Keyword	Description	Requirements
		a map with usual `file`, `format`, and `epsg` keywords, or he can assign a constant value using the `scalar` keyword
`[[aquitard-conductivity]]`	Aquitard hydraulic conductivity (m/s)	Required when more than one aquifer are simulated. The last (lower) aquifer does not need aquitard definition. The user can set a map with usual `file`, `format`, and `epsg` keywords, or he can assign a constant value using the `scalar` keyword

In the next example, one aquifer is configured. `boundary-condition-id`, `initial-head`, and `top-elevation`, are assigned as raster esri ascii maps. `bottom-elevation`, `hydraulic-conductivity`, and `specific-yield`, are assigned as a scalar constant. `boundary-condition-value` is assigned as a multitemporal net-cdf file with option `sync-initial-time = 1` to start from the proper initial value.

```
aquifers = 1

[aquifer_1]
   [[boundary-condition-id]]
     file = ./data/aquifer1_bc_id.asc
     format = esri-ascii
     epsg = 32632
   [[boundary-condition-value]]
     file = ./data/head_bc.nc
     format = net-cdf
     variable = head
     epsg = 32632
     sync-initial-time = 1
   [[initial-head]]
     file = ./data/dem-3m.asc
     format = esri-ascii
     epsg = 32632
   [[top-elevation]]
     file = ./data/dem.asc
     format = esri-ascii
     epsg = 32632
   [[bottom-elevation]]
     scalar = 50.
   [[hydraulic-conductivity]]
     scalar = 0.0003
   [[specific-yield]]
     scalar = 0.3
```

Example of groundwater configuration file.

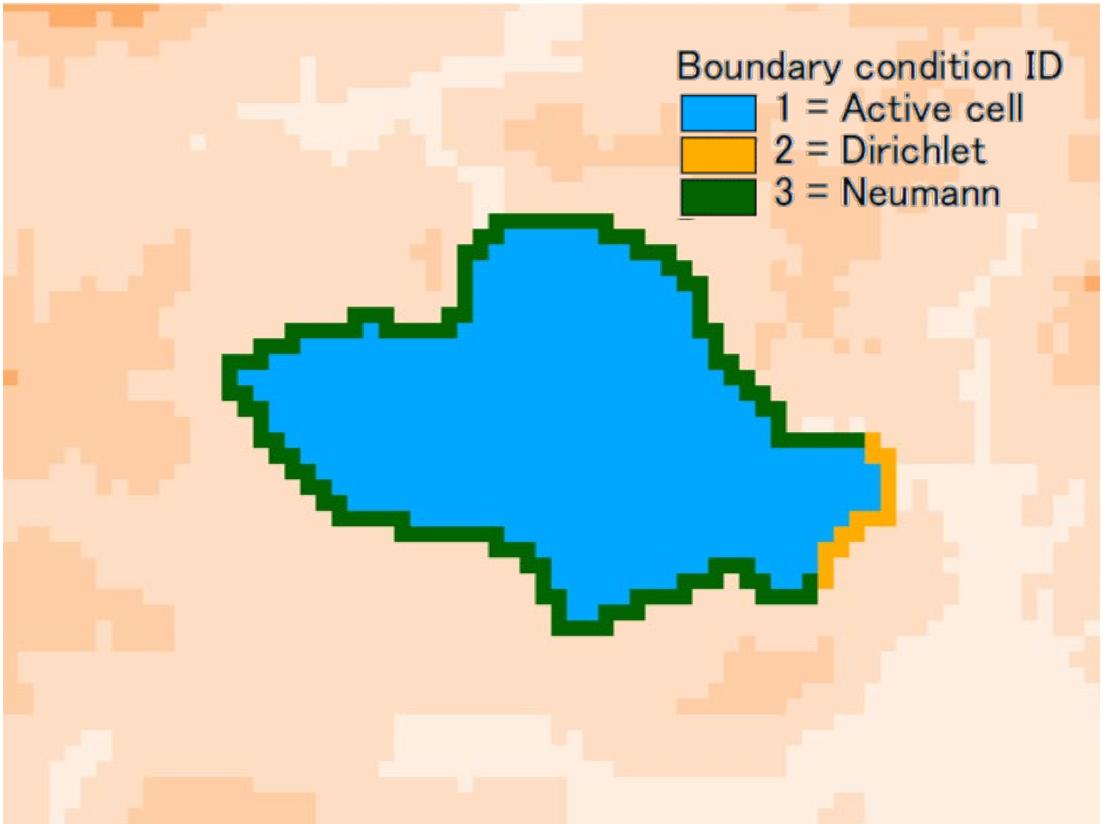

Figure 12.1 Example of map to set boundary condition and active cells.

12.1 River-groundwater flux exchange

Table 12.2. How to configure flux exchange between river and groundwater.

Keyword	Description	Requirements
`[river-groundwater]`	It starts section to configure river-groundwater interaction	Optional
`[[river-id]]`	Map that defines the cells where river-groundwater interaction is simulated. 1=river-groundwater interaction cell, nodata = no interaction.	Mandatory.
`[[river-dem]]`	Map that specifies the river	Mandatory

Keyword	Description	Requirements
	thalweg elevation. It may be different from digital elevation model assigned in Morphological properties section.	

A table with `id = river-groundwater` is required to define riverbed conductivity and thickness. In the following example two maps are assigned as `[[river-id]] and [[river-dem]]`. Table `river-groundwater` defines two ids with 0.0001 and 0.0003 m/s streambed conductivity, respectively and a streambed thichness of 1 m. `[[river-id]]` map is shown in Figure 11.2

```
[river-groundwater]
  [[river-id]]
    file = ./data/river_aquifer_id.asc
    format = esri-ascii
    epsg = 32632

  [[river-dem]]
    file = ./data/dem-5.asc
    format = esri-ascii
    epsg = 32632

Table Start
Title: river groundwater exchange parameters
Id: river-groundwater

Columns: [id]   [streambed-conductivity]  [streambed-thickness]
Units:   [-]          [m/s]                       [m]
          1          0.0001                       1.0
          2          0.0003                       1.0
Table End
```

Example of `[river-groundwater]` section in groundwater configuration file.

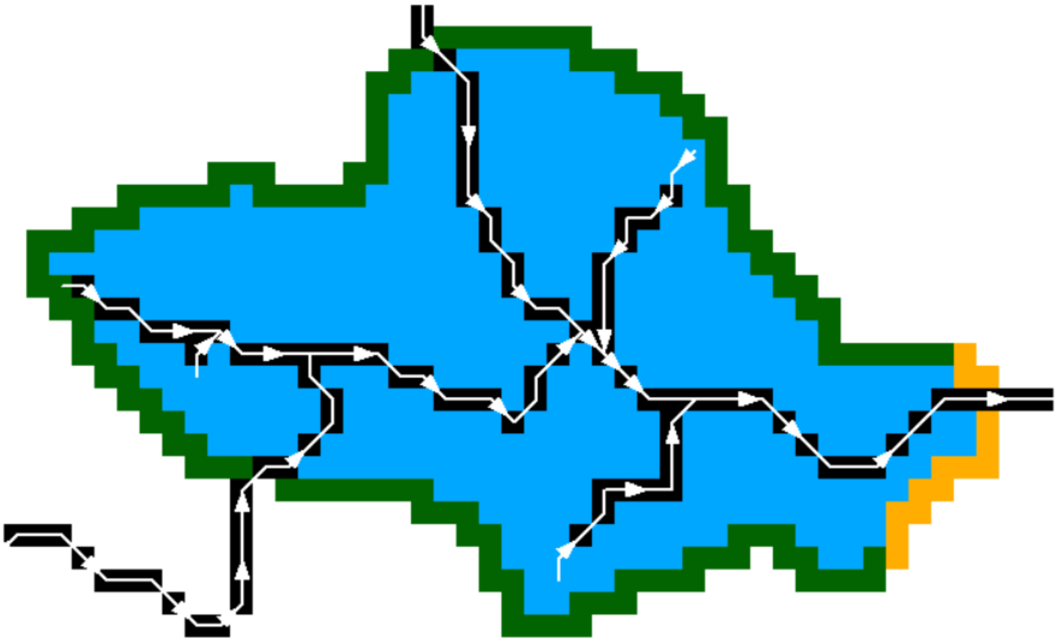

Figure 12.2 Map of flow accumulation (black cells) and river direction (white arrow) overlayed to boundary condition id map of Figure 11.1.

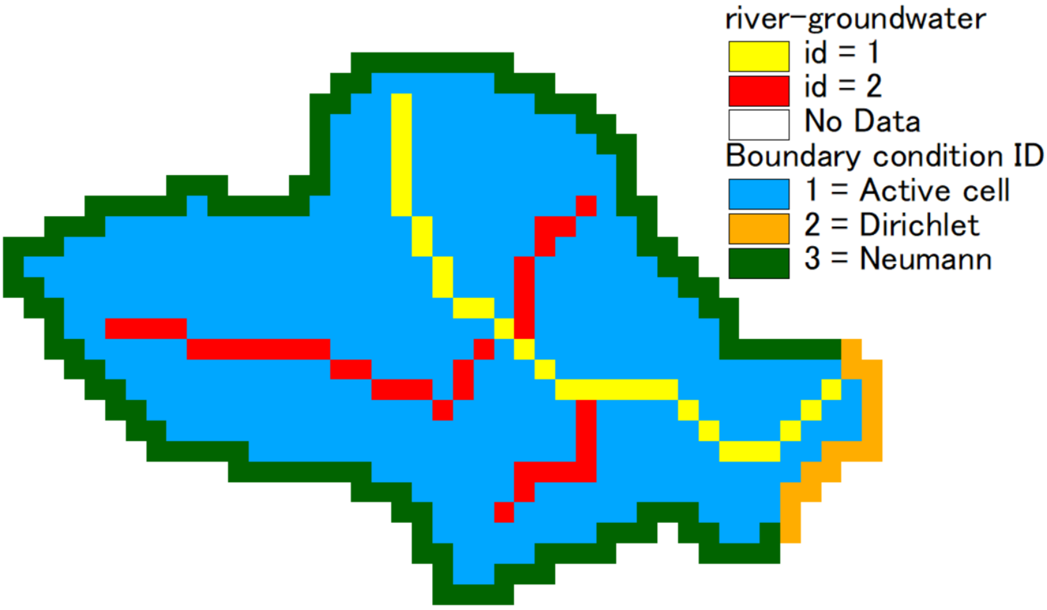

Figure 12.3 Map of flow `river-groundwater` id overlayed to boundary condition id map of Figure 11.1.

CHAPTER 13
SPATIAL AVERAGE

This file is used to write spatial average results of variables computed by the FEST model. The file contains a table of map that define the spatial extent to compute the average and the keyword `epsg` that define the reference system of maps, as in the example below.

```
epsg = 32632

Table Start
Title: mask grids for output
Id: masks
Columns:    [count]  [id]      [name]       [file]
Units:        [-]     [-]        [-]          [-]
              1       01         lago      "./bacino_lago.asc"
              2       02      gavardo      "./gavardo.asc"
              3       03      mezzane      "./bacino_mezzane.asc"
              4       04        asola      "./bacino_asola.asc"
Table End
```

Example of table of spatial extents in spatial average configuration file

For every spatial extent, the average is computed and exported on file of the variables chosen by user in the configuration file. There are specific sections for meteorological, soil balance, snow, glaciers, canopy, plants and sediment variables, as in the examples below. The value is computed for all variables marked with 1. When one variable is marked by 1 but it is not allocated because not computed by the FEST model according to options defined in the configuration files, value is not exported. For example, if user set to export wind speed in the meteorological section but wind speed is not used in the current simulation, values of wind speed are not written in the output file.

```
[meteo]
  precipitation = 1            # gross precipitation (mm)
  daily-precipitation = 0      # daily precipitation(mm)
  temperature = 1              # air temperature(°C)
  temperature-daily-mean = 1   # mean daily temperature (°C)
  temperature-daily-max = 1    # maximum daily temperature (°C)
  temperature-daily-min = 1    # minimum daily temperature (°C)
  relative-humidity = 0        # air relative humidity (% [0-1])
  solar-radiation = 0          #shortwave radiation (w/m2)
  net-radiation = 0            #net radiation (w/m2)
  wind-speed = 0               #wind speed (m/s)
  irrigation = 0               #irrigation amount (mm)
```

Example of `[meteo]` variables marked for exporting spatial average on file.

```
[soil-balance]
  soil-moisture = 1  # soil moisture(m3/m3)
  runoff = 1         # runoff(mm)
  infiltration = 1   # infiltration(mm)
  percolation = 1    # percolation(mm)
  actual-ET = 1      # actual evapotranspiration(mm)
  potential-ET = 1   # potential evapotranspiration(mm)
  capillary-rise = 0 # capillary flux(mm)
  error = 1          # balance error (mm)
```

Example of `[soil-balance]` variables marked for exporting spatial average on file.

```
[snow]
  rain = 1                    # liquid precipitation(mm)
  snow-water-equivalent = 1   # snow water equivalent(mm)
  melt-coefficient = 1        # snow melt coefficient (mm/day/°C)
  snow-covered-area = 1       # percentage of snow cover (0-1)
  water-in-snow = 1           # water in snowpack (mm)
  snow-melt = 1               # snow melt (mm)
```

Example of `[snow]` variables marked for exporting spatial average on file.

```
[glacier]
  ice-water-equivalent = 1 # snow water equivalent(mm)
  ice-covered-area = 1     # percentage of glacial cover (0-1)
  water-in-ice = 1         # water in glaciers (mm)
  ice-melt = 1             # ice melt (mm)
```

Example of [glaciers] variables marked for exporting spatial average on file.

```
[sediment]
  detachment-rate = 0  # eroded sediment amount (kg)
```

Example of [sediment] variables marked for exporting spatial average on file.

```
[canopy]
  canopy-storage = 0   # canopy water storage (mm)
  throughfall = 0      # canopy throughfall (mm)
  transpiration = 0    # canopy transpiration (mm)
```

Example of [canopy] variables marked for exporting spatial average on file.

```
[plants]
  lai = 0          # leaf area index (m2/m2)
  gpp = 0          # gross primary production (t)
  npp = 0          # net primary production (t)
  stem = 0         # stem mass (t)
  root = 0         # root mass (t)
  leaf = 0         # leaf mass (t)
  cover = 0        # canopy cover (0-1)
  dbh = 0          # plant diameter at brest height (cm)
  height = 0       # plant heigth (m)
  density = 0      # plant density (tree/hectare)
  stem-yield = 0 # stem yield (t)
```

Example of [plants] variables marked for exporting spatial average on file.

The name of output files is the concatenation of result folder defined in the main configuration file <folder>, the name of the spatial extent <name>, and the name of the process related to the variables, as listed in the following table.

Table 13.1. spatial average file name.

variables	Output file name
meteorological	<folder><name>_meteo.out
soil balance	<folder><name>_balance.out
snow	<folder><name>_snow.out
glaciers	<folder><name>_glaciers.out
sediment	<folder><name>_sediment.out
canopy	<folder><name>_canopy.out

variables	Output file name
plants	`<folder><name>_plants.out`

CHAPTER 14
IRRIGATION

The *FeST* model can simulate water derivation from rivers and distribution on irrigation districts. Irrigation simulation is activated by filling in the specific section in the main configuration file (3.13). This chapter describes the irrigation configuration file, usually named `intakes.ini`. The irrigation configuration file contains two main keywords as described in the following Table.

Table 14.1. Definition of main keywords in irrigation configuration file.

Keyword	Description	Requirements
`count`	Number of intakes to configure	MANDATORY
`epsg`	EPSG code of the coordinate reference system used for intake coordinates. It is used only to write EPSG code in output file.	MANDATORY

For each intake the user must configure the specific section numbered from 1 to the total number of intakes, filling in the required information as listed and described in the following table. Several intakes can exist at the same location and multiple intakes can discharge water to the same irrigated area.

Table 14.2. Information to provide for each intake.

Keyword	Description	Requirements
`id`	Label Id of intake.	MANDATORY.
`name`	Name of the intake	MANDATORY
`easting`	x-coordinate of intake on the watercourse	MANDATORY

Keyword	Description	Requirements
`northing`	y-coordinate of intake on the watercourse	MANDATORY
`e-flow`	environmental flow (m^3/s), minimum value of discharge to be released downstream the intake. To assign a changeable value during the year, a table on external file must be assigned (see example below)	MANDATORY
`max-discharge`	Maximum discharge (m^3/s) that can be diverted from the river. To assign a changeable value during the year, a table on external file must be assigned (see example below)	MANDATORY
`doy-start`	Day of year (1-365) when irrigation starts.	MANDATORY
`doy-stop`	Day of year (1-365) when irrigation stops.	MANDATORY
`sat-max`	Maximum mean saturation of the irrigation district above which irrigation water is not distributed (option not yet implemented in the model).	MANDATORY
`[[mask]]`	Map of the irrigation district	MANDATORY

In the following examples two intakes are configured. In the first one, maximum diverted flow and ecological flow change in time and are assigned with a table provided from external files. In the second intake, maximum flow and ecological flow are assigned as a constant value. Water diverted from both intakes is used for irrigation of the same irrigation district.

```
################################################
#       Intakes configuration file             #
################################################
count = 2
epsg = 32633

[1]
  name = intake_1
  id = 01
  easting = 301950.9
  northing = 5064960.3
  max-discharge = ./data/qmax_intake1.tab
  e-flow = ./data/eflow_intake1.tab
  doy-start =  105
  doy-stop =  258
  sat-max =  0.5
  eta = 0.6
  [[mask]] # mask of irrigated district
    file = ./data/district.asc
    format = esri-ascii
    epsg = 32633

[2]
  name = intake_2
  id = 02
  easting = 311050.9
  northing = 5065380.2
  max-discharge = 100. # [m3/s]
  e-flow = 8. # [m3/s]
  doy-start =  100
  doy-stop =  220
  sat-max =  0.5
  eta = 0.8
  [[mask]] # mask of irrigated district
    file = ./data/district.asc
    format = esri-ascii
    epsg = 32633
```

Example of intake configuration for managing irrigation.

Content of `qmax_intake1.tab` is reported as follows. In this example time span between 31 and 90 `doy` is not included in the table. In this period a value of zero is assigned to maximum flow.

```
Table     Start
Title:  Qmax intake 1
id: qmax
Columns:   [count] [doy-start]     [doy-stop]     [value]
Units:       [-]       [day]          [day]        [m3/s]
             1          1              30            15
             2         91             200            35
             3        201             365            18
Table   End
```

Content of `qmax_intake1.tab` file.

Content of `eflow_intake1.tab` is reported as follows. In this example a discharge value is assigned for each month of the year.

```
Table      Start
Title:   eflow intake 1
id: eflow
Columns:   [count] [doy-start]     [doy-stop]     [value]
Units:       [-]      [day]          [day]        [m3/s]
             1          1              31            1
             2         32              59            1.5
             3         60              90            1.6
             4         91             120            2
             5        121             151            1.8
             6        152             181            1.7
             7        182             212            1.9
             8        213             243            1.8
             9        244             273            1.5
            10        274             304            1.3
            11        305             334            1.2
            12        335             365            1
Table    End
```

Content of `eflow_intake1.tab` file.

Three output files are created and populated during simulation: `<folder>irrigation_downstream.fts` that contains river discharge downstream the intake, `<folder>irrigation_upstream.fts` that contains river discharge upstream the intake, and `<folder>irrigation_diverted.fts` that contains the diverted discharge values, where `<folder>` is the output folder (and prefix) for writing output files (see 3.2).

An example of output file for diverted discharge is reported as follows.

```
description = irrigation discharge diverted from water courses
unit = m3/s
epsg = 32633
count =           2
dt =         3600
missing-data =   -999.900
offsetz =      0.000

metadata
intake_1 01 301950.9 5064960.3 0.0
intake_2 02 311050.9 5065380.2 0.0

data
DateTime  01  02
2011-01-01T00:00:00+00:00              0.00           0.00
2011-01-01T01:00:00+00:00              0.00           0.00
2011-01-01T02:00:00+00:00              0.00           0.00
2011-01-01T03:00:00+00:00              0.00           0.00
2011-01-01T04:00:00+00:00              0.00           0.00
2011-01-01T05:00:00+00:00              0.00           0.00
2011-01-01T06:00:00+00:00              0.00           0.00
…
…
2011-05-01T00:00:00+00:00             28.18          32.01
2011-05-01T01:00:00+00:00             32.24          33.12
2011-05-01T02:00:00+00:00             34.45          34.15
2011-05-01T03:00:00+00:00             35.00          33.34
2011-05-01T04:00:00+00:00             35.00          38.10
2011-05-01T05:00:00+00:00             35.00          42.06
2011-05-01T06:00:00+00:00             35.00          44.78
```

Example of irrigation diverted discharge output file.

CHAPTER 15
BASIN AVERAGE

This file is used to write variables computed by the *FeST* model averaged over a list of river basins defined by outlet section. The file contains a list of keywords, one for each variable the user can export. The optional keyword `raster-export` set to 1 enables the *FeST* model to write basin mask in esri-ascii format (see example below).

```
raster-export = 0  # OPTIONAL default = 0
raster-export-folder = ./results/basin_mask/  # OPTIONAL

#meteo
precipitation = 1
daily-precipitation = 0
temperature = 1
temperature-daily-mean = 0
temperature-daily-max = 0
temperature-daily-min = 0
relative-humidity = 0
solar-radiation = 0
net-radiation = 0
wind-speed = 1
irrigation = 0

#snow
snow-water-equivalent = 1

#soil balance
soil-moisture = 1
delta-soil-moisture = 1
runoff = 1
infiltration = 1
percolation = 1
actual-ET = 1
potential-ET = 0
```

Example of basin-average configuration file

The optional keyword `raster-export-folder` defines the folder where to save basin mask files. When `raster-export-folder` is not set, basin mask files are saved in the current folder where the *FeST* executable is launched. Basin mask files are saved with name `basin_mask_id_<basin-id>.asc` where `<basin-id>` is the id label of river basin set in the coordinate list file.

The average value is computed for all variables marked with 1. When one variable is marked by 1 but it is not allocated because not computed by the *FeST* model according to options defined in the configuration files, value is not exported. For example, if user set to export wind-speed but windspeed is not used in the current simulation, values of windspeed are not written in the output file. One output file is created for each variable. So average temperature values for all points are written in a file, precipitation values are written in a different file, and so on.

Variables that can be exported, description, and unit are listed in the following table.

Table 15.1. basin average variable description and unit.

variable	Description	Unit
precipitation	Precipitation fallen in the current time step	mm
daily-precipitation	Precipitation fallen in 24 hours	mm
temperature	Air temperature of the current time step	Celsius degree
temperature-daily-mean	Mean daily air temperature	Celsius degree
temperature-daily-max	Maximum daily air temperature	Celsius degree
temperature-daily-min	Maximum daily air temperature	Celsius degree
relative-humidity	Air relative humidity of the current time step	% (0-100)
solar-radiation	Solar radiation of the current time step	w/m^2
net-radiation	Net radiation of the current time step	w/m^2
wind-speed	Wind speed of the current time step	m/s
irrigation	Irrigation amount of the current time step	mm
snow-water-equivalent	Snow water equivalent of the current time step	mm
soil-moisture	Soil moisture of the current time step	-

variable	Description	Unit
runoff	Runoff of the current time step	mm
infiltration	Infiltration into soil of the current time step	mm
percolation	Deep percolation out of transmission zone of the current time step	mm
actual-ET	Actual evapotranspiration of the current time step	mm
potential-ET	Potential evapotranspiration of the current time step	mm
delta-soil-moisture	Change in soil water storage of the current time step	mm

The name of output files is the concatenation of result folder name defined in the main configuration file <folder>, and a suffix that reminds the name of variable, as listed in the following table.

Table 15.2. basin average file name.

variable	Output file name
precipitation	<folder>mean_precipitation.fts
daily-precipitation	<folder>mean_pdaily.fts
temperature	<folder>mean_temperature.fts
temperature-daily-mean	<folder>mean_tmean.fts
temperature-daily-max	<folder>mean_tmax.fts
temperature-daily-min	<folder>mean_tmin.fts
relative-humidity	<folder>mean_rh.fts
solar-radiation	<folder>mean_rad.fts
net-radiation	<folder>mean_netrad.fts
wind-speed	<folder>mean_windspeed.fts
irrigation	<folder>mean_irrigation.fts
snow-water-equivalent	<folder>mean_swe.fts
soil-moisture	<folder>mean_soil-moisture.fts
runoff	<folder>mean_runoff.fts
infiltration	<folder>mean_infiltration.fts
percolation	<folder>mean_percolation.fts

variable	Output file name
actual-ET	`<folder>mean_et.fts`
potential-ET	`<folder>mean_pet.fts`
delta-soil-moisture	`<folder>mean_delta-soil-moisture.fts`

CHAPTER 16
RASTER EXPORTING

This file is used to write raster of variables computed by the *FeST*. The file contains a list of keywords, one for each variable the user can export. The keyword `time` set times when raster maps are written to output in folder specified by `folder` keyword. The section `[map-template]` (optional) allows to re-mapping raster maps to a given map template before files are written to output folder. This allows to change map extent, spatial resolution or spatial reference system. (see example below).

```
# configure variables for raster export

time = 0 0,12 * * *

folder = ./results/raster_maps/

 [map-template]
  file = ./data/template_wgs84.asc
  format = esri-ascii
  epsg = 4326

[soil-balance]
 soil-moisture = 0
 runoff = 0
 infiltration = 0
 percolation = 0
 actual-ET = 0
 potential-ET = 0

[meteo]
 precipitation = 1
 temperature = 1
 relative-humidity = 0
 solar-radiation = 0
 net-radiation = 0
 wind-speed = 0

[snow]
 snow-water-equivalent = 0
```

Example of `raster-export` configuration file

The raster map is computed and written to output folder for all variables marked with 1. When one variable is marked by 1 but it is not allocated because not computed by the *FeST* model according to options defined in the configuration files, file is not exported. For example, if user set to export wind-speed but windspeed is not used in the current simulation, map of windspeed is not written to output folder. Currently maps are exported in `esri-ascii` format, one map for each variable and for each time step. Raster maps are processed before being written to output file in order to compute the average value or the cumulated value between to time steps, according to the specific variable (see table below).
Exporting time steps are assigned with a string that mimics the cron-table syntax on Linux operating systems, a configuration file that specifies shell commands to run periodically on a given schedule.
The syntax expects a string made of five fields which represent the time to write files to output folder, as described below:

```
┌───────────── minute (0-59)
│ ┌───────────── hour (0-23)
│ │ ┌───────────── day of the month (1-31)
│ │ │ ┌───────────── month (1-12)
│ │ │ │ ┌───────────── day of the week (0-6) (Sunday to Saturday)
│ │ │ │ │
│ │ │ │ │
│ │ │ │ │
* * * * *
```

Description of the string to configure time to export maps.

Some examples:

`0 * * * *` once an hour at the beginning of the hour

`0 0 * * *` once a day at midnight

`0 0 * * 0` once a week at midnight on Sunday

`0 0 1 * *` once a month at midnight of the first day of the month

`0 0 1 1 *` once a year at midnight of 1 January

Specifying multiple specific time intervals can be done with commas (e.g., `1,2,3`) or with hyphen to assign a range of values (e.g. `7-10`).
Variables that can be exported, description, and unit are listed in the following table.

Table 16.1. raster variables that can be exported: description and unit.

variable	Description	Unit
precipitation	Precipitation fallen in the time step	mm

variable	Description	Unit
	(cumulated)	
temperature	Air temperature (average)	Celsius degree
relative-humidity	Air relative humidity (average)	% (0-100)
solar-radiation	Solar radiation (average)	w/m^2
net-radiation	Net radiation (average)	w/m^2
wind-speed	Wind speed (average)	m/s
snow-water-equivalent	Snow water equivalent (average)	mm
soil-moisture	Soil moisture (average)	-
runoff	Runoff (cumulated)	mm
infiltration	Infiltration (cumulated)	mm
percolation	Deep percolation out of transmission zone (cumulated)	mm
actual-ET	Actual evapotranspiration (cumulated)	mm
potential-ET	Potential evapotranspiration (cumulated)	mm

The name of output files is the concatenation of folder name defined in the configuration file `<folder>`, a suffix in the form `YYYY-MM-DDThh-mm` that reminds date and time of the current time step `<time>`, and a suffix that reminds the name of variable, as listed in the following table.

Table 16.2. raster file name.

variable	Output file name
precipitation	`<folder><time>_precipitation.asc`
temperature	`<folder><time>_temperature.asc`
relative-humidity	`<folder><time>_rh.asc`
solar-radiation	`<folder><time>_rad.asc`
net-radiation	`<folder><time>_netrad.asc`
wind-speed	`<folder><time>_windspeed.asc`
snow-water-equivalent	`<folder><time>_swe.asc`
soil-moisture	`<folder><time>_soil-moisture.asc`
runoff	`<folder><time>_runoff.asc`
infiltration	`<folder><time>_infiltration.asc`

variable	Output file name
percolation	`<folder><time>_percolation.asc`
actual-ET	`<folder><time>_et.asc`
potential-ET	`<folder><time>_pet.asc`

References

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