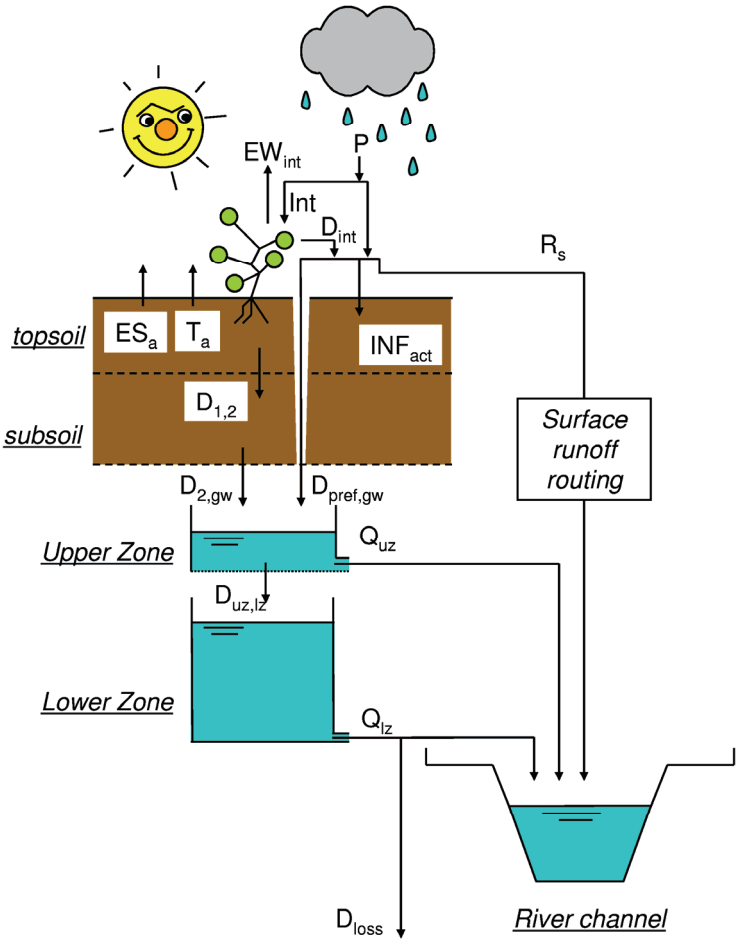
JRC Scientific and Technical Reports

LISFLOOD

Distributed Water Balance and Flood Simulation Model

Revised User Manual

Johan van der Knijff, Ad de Roo



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CONTENTS

1. Introduction

The LISFLOOD model is a hydrological rainfall-runoff model that is capable of simulating the hydrological processes that occur in a catchment. LISFLOOD has been developed by the floods group of the Natural Hazards Project of the Joint Research Centre (JRC) of the European Commission. The specific development objective was to produce a tool that can be used in large and trans-national catchments for a variety of applications, including:

- Flood forecasting
- Assessing the effects of river regulation measures
- Assessing the effects of land-use change
- Assessing the effects of climate change

Although a wide variety of existing hydrological models are available that are suitable for *each* of these individual tasks, few *single* models are capable of doing *all* these jobs. Besides this, our objective requires a model that is spatially distributed and –at least to a certain extent- physically-based. Also, the focus of our work is on European catchments. Since several databases exist that contain pan-European information on soils (King *et al.*, 1997; Wösten *et al.*, 1999), land cover (CEC, 1993), topography (Hiederer & de Roo, 2003) and meteorology (Rijks *et al.*, 1998), it would be advantageous to have a model that makes the best possible use of these data. Finally, the wide scope of our objective implies that changes and extensions to the model will be required from time to time. Therefore, it is essential to have a model code that can be easily maintained and modified. LISFLOOD has been specifically developed to satisfy these requirements. The model is designed to be applied across a wide range of spatial and temporal scales. LISFLOOD is grid-based, and applications so far have employed grid cells of as little as 100 metres for medium-sized catchments, up to 5000 metres for modelling the whole of Europe. Long-term water balance can be simulated (using a daily time step), as well as individual flood events (using hourly time intervals, or even smaller). The output of a “water balance run” can be used to provide the initial conditions of a “flood run”. Although the model’s primary output product is channel discharge, all internal rate and state variables (soil moisture, for example) can be written as output as well. In addition, all output can be written as grids, or time series at user-defined points or areas. The user has complete control over how output is written, thus minimising any waste of disk space or CPU time.

About LISFLOOD

The LISFLOOD model is implemented in the PCRaster Environmental Modelling language (Wesseling et al., 1996), wrapped in a Python based interface. PCRaster is a raster GIS environment that has its own high-level computer language, which allows the construction of iterative spatio-temporal environmental models. The Python wrapper of LISFLOOD enables the user to control the model inputs and outputs and the selection of the model modules. This approach combines the power, relative simplicity and maintainability of code written in the the PCRaster Environmental Modelling language and the flexibility of Python. LISFLOOD runs on any operating for which Python and PCRaster are available. Currently these include 32-bits Windows (e.g. Windows XP, Vista) and a number of Linux distributions.

About this User Manual

This revised User Manual documents LISFLOOD version March 31 2008, and replaces all previous documentation of the model (e.g. van der Knijff & de Roo, 2006;

de Roo *et. al.*, 2003). The scope of this document is to give model users all the information that is needed for successfully using LISFLOOD. Chapter 2 explains the theory behind the model, including all model equations. The remaining chapters cover all practical aspects of working with LISFLOOD. A series of Annexes at the end of this document describe some optional features that can be activated when running the model. Most model users will not need these features (which are disabled by default), and for the sake of clarity we therefore decided to keep their description out of the main text. The current document does not cover the calculation of the potential evapo(transpi)ration rates that are needed as input to the model. A separate pre-processor (LISVAP) exists that calculates these variables from standard (gridded) meteorological observations. LISVAP is documented in a separate volume (van der Knijff, 2006).

2. Process descriptions

Overview

Figure 2.1 gives an overview of the structure of the LISFLOOD model. Basically, the model is made up of the following components:

- a 2-layer soil water balance sub-model
- sub-models for the simulation of groundwater and subsurface flow (using 2 parallel interconnected linear reservoirs)
- a sub-model for the routing of surface runoff to the nearest river channel
- a sub-model for the routing of channel flow (not shown in the Figure)

The processes that are simulated by the model include snow melt (not shown in the Figure), infiltration, interception of rainfall, leaf drainage, evaporation and water uptake by vegetation, surface runoff, preferential flow (bypass of soil layer), exchange of soil moisture between the two soil layers and drainage to the groundwater, sub-surface and groundwater flow, and flow through river channels. Each of these processes is described in more detail in the following.

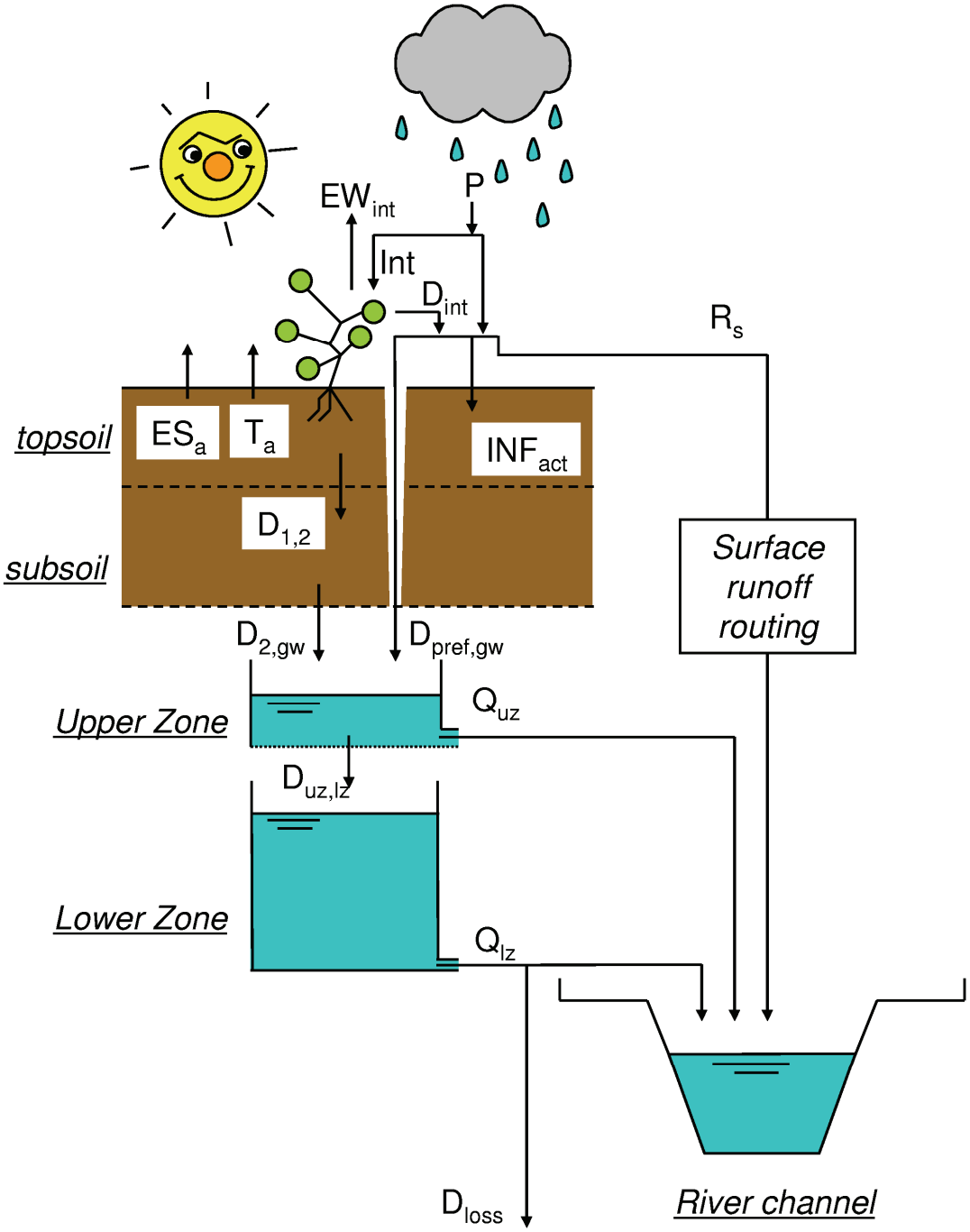


Figure 2.1 *Overview of the LISFLOOD model. P = precipitation; Int = interception; EW_{int} = evaporation of intercepted water; D_{int} = leaf drainage; ES_a = evaporation from soil surface; T_a = transpiration (water uptake by plant roots); INF_{act} = infiltration; R_s = surface runoff; $D_{1,2}$ = drainage from top- to subsoil; $D_{2,gw}$ = drainage from subsoil to upper groundwater zone; $D_{pref,gw}$ = preferential flow to upper groundwater zone; $D_{uz,lz}$ = drainage from upper- to lower groundwater zone; Q_{uz} = outflow from upper groundwater zone; Q_l = outflow from lower groundwater zone; D_{loss} = loss from lower groundwater zone. Note that snowmelt is not included in the Figure (even though it is simulated by the model).*

Treatment of meteorological input variables

The meteorological conditions provide the driving forces behind the water balance. LISFLOOD uses the following meteorological input variables:

P	:	Precipitation	[mm day^{-1}]
ET0	:	Potential (reference) evapotranspiration rate	[mm day^{-1}]
EW0	:	Potential evaporation rate from open water surface	[mm day^{-1}]
ES0	:	Potential evaporation rate from bare soil surface	[mm day^{-1}]
T_{avg}	:	Average *daily* temperature[1]	[°C]

Both precipitation and evaporation are internally converted from *intensities* [mm day^{-1}] to *quantities per time step* [mm] by multiplying them with the time step, Δt (in days). For the sake of consistency, all in- and outgoing fluxes will also be described as *quantities per time step* [mm] in the following, unless stated otherwise. *ET0*, *EW0* and *ES0* can be calculated using standard meteorological observations. To this end a dedicated pre-processing application has been developed (LISVAP), which is documented in a separate volume (van der Knijff, 2006).

Rain and snow

If the average temperature is below 1°C, all precipitation is assumed to be snow. A snow correction factor is used to correct for undercatch of snow precipitation. Unlike rain, snow accumulates on the soil surface until it melts. The rate of snowmelt is estimated using a simple degree-day factor method. Degree-day factor type snow melt models usually take the following form (e.g. see WMO, 1986):

$$M = C_m(T_{avg} - T_m) \tag{2-1}$$

where M is the rate of snowmelt, T_{avg} is the average daily temperature, T_m is some critical temperature and C_m is a degree-day factor [mm °C^{-1} day^{-1}]. Speers *et al.* (1979) developed an extension of this equation which accounts for accelerated snowmelt that takes place when it is raining (cited in Young, 1985):

$$M = (0.074 + 0.007 \cdot R)(T_{avg} - T_m) \tag{2-2}$$

where R is the daily rainfall and both M and R are expressed in cm (rather than mm). The equation is supposed to apply when rainfall is greater than 3 cm in 24 hours. Moreover, although the equation is reported to work sufficiently well in forested areas, it is not valid in areas that are above the tree line, where radiation is the main energy source for snowmelt). Currently LISFLOOD uses a variation on the equation of Speers *et al.* The modified equation simply assumes that for each mm of rainfall, the rate of snowmelt increases with 1% (compared to a 'dry' situation). This yields the following equation:

$$M = C_m(1 + 0.01 \cdot R\Delta t)(T_{avg} - T_m) \cdot \Delta t \tag{2-3}$$

[1] Note that the model needs *daily* average temperature values, even if the model is run on a smaller time interval (e.g. hourly). This is because the routines for snowmelt and soil freezing are use empirical relations which are based on daily temperature data. Just as an example, feeding hourly temperature data into the snowmelt routine can result in a gross overestimation of snowmelt. This is because even on a day on which the average temperature is below T_m (no snowmelt), the instantaneous (or hourly) temperature may be higher for a part of the day, leading to unrealistically high simulated snowmelt rates.

where M is the snowmelt per time step [mm], R is rainfall (not snow!) intensity [mm day^{-1}], and Δt is the time interval [days]. T_m has a value of 0 °C, and C_m is set to a default value of 4.5 mm °C^{-1} day^{-1}. However, it should be stressed that the value of C_m can actually vary greatly both in space and time (e.g. see Martinec *et al*., 1998). Therefore, in practice this parameter is often treated as a calibration constant. The amount of snowmelt can never exceed the actual snow cover that is present on the surface.

For large pixel sizes, there may be considerable sub-pixel heterogeneity in snow accumulation and melt, which is a particular problem if there are large elevation differences within a pixel. Because of this, snow melt and accumulation are modelled separately for 3 separate elevation zones, which are defined at the sub-pixel level. This is shown in Figure 2.2. The division in elevation zones is based on the maximum elevation difference within a pixel, Δz. Assuming that the cumulative elevation within each pixel follows a linear distribution, 3 elevation zones *A*, *B*, and *C* are defined. Each zone occupies one third of the pixel surface. Assuming further that T_{avg} is valid for the average pixel elevation, average temperature is extrapolated to the centroids of the lower (*A*) and upper (*C*) elevation zones, using a fixed temperature lapse rate, *L*, of 0.0065 °C per meter elevation difference. Snow, snowmelt and snow accumulation are subsequently modelled separately for each elevation zone, assuming that temperature can be approximated by the temperature at the centroid of each respective zone.

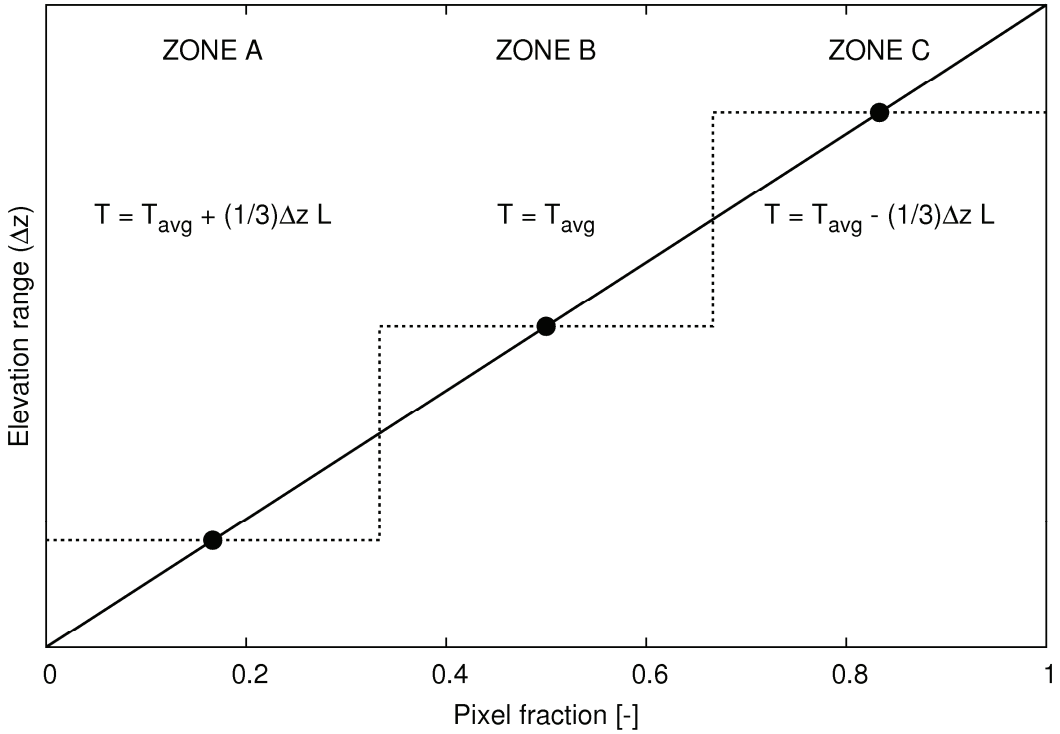


Figure 2.2 *Definition of sub-pixel elevation zones for snow accumulation and melt modelling. Snowmelt and accumulation calculations in each zone are based on elevation (and derived temperature) in centroid of each zone.* L *is the temperature lapse rate.*

Frost index soil

When the soil surface is frozen, this affects the hydrological processes occurring near the soil surface. To estimate whether the soil surface is frozen or not, a frost

index *F* is calculated. The equation is based on Molnau & Bissell (1983, cited in Maidment 1993), and adjusted for variable time steps. The rate at which the frost index changes is given by:

$$\frac{dF}{dt} = -(1 - A_f)F - T_{av} \cdot e^{-0.04 \cdot K \cdot d_s / we_s} \qquad (2\text{-}4)$$

dF/dt is expressed in [°C day^{-1} day^{-1}]. A_f is a decay coefficient [day^{-1}], *K* is a a snow depth reduction coefficient [cm^{-1}], d_s is the (pixel-average) depth of the snow cover (expressed as mm equivalent water depth), and we_s is a parameter called snow water equivalent, which is the equivalent water depth water of a snow cover (Maidment, 1993). In LISFLOOD, A_f and *K* are set to 0.97 and 0.57 cm^{-1} respectively, and we_s is taken as 0.1, assuming an average snow density of 100 kg/m^3 (Maidment, 1993). The soil is considered frozen when the frost index rises above a critical threshold of 56. For each time step the value of *F* [°C day^{-1}] is updated as:

$$F(t) = F(t-1) + \frac{dF}{dt}\Delta t \qquad (2\text{-}5)$$

F is not allowed to become less than 0.

Interception

Interception is estimated using the following storage-based equation (Aston, 1978, Merriam, 1960):

$$Int = S_{\max} \cdot [1 - \exp(-k \cdot R\Delta t / S_{\max})] \qquad (2\text{-}6)$$

where *Int* [mm] is the interception per time step, S_{max} [mm] is the maximum interception, *R* is the rainfall intensity [mm day^{-1}] and the factor *k* accounts for the density of the vegetation. S_{max} is calculated using an empirical equation (Von Hoyningen-Huene, 1981):

$$\begin{cases} S_{\max} = 0.935 + 0.498 \cdot LAI - 0.00575 \cdot LAI^2 & [LAI > 0.1] \\ S_{\max} = 0 & [LAI \le 0.1] \end{cases} \qquad (2\text{-}7)$$

where *LAI* is the average Leaf Area Index [m^2 m^{-2}] of each model element (pixel). *k* is estimated as:

$$k = 0.046 \cdot LAI \qquad (2\text{-}8)$$

The value of *Int* can never exceed the interception storage capacity, which is defined as the difference between S_{max} and the accumulated amount of water that is stored as interception, Int_{cum}.

Evaporation of intercepted water

Evaporation of intercepted water, EW_{int}, occurs at the potential evaporation rate from an open water surface, *EW0*. The *maximum* evaporation per time step is proportional to the fraction of vegetated area in each pixel (Supit *et al.*,1994):

$$EW_{\max} = EW0 \cdot [1 - \exp(-\kappa_{gb} \cdot LAI)]\Delta t \quad (2\text{-}9)$$

where *EW0* is the potential evaporation rate from an open water surface [mm day^{-1}], and EW_{max} is in [mm] per time step. Constant κ_{gb} is the extinction coefficient for global solar radiation [-]. Since evaporation is limited by the amount of water stored on the leaves, the actual amount of evaporation from the interception store equals:

$$EW_{\text{int}} = \min(EW_{\max} \cdot \Delta t, Int_{cum}) \quad (2\text{-}10)$$

where EW_{int} is the actual evaporation from the interception store [mm] per time step, and *EW0* is the potential evaporation rate from an open water surface [mm day^{-1}]

It is assumed that on average all water in the interception store (Int_{cum}) will have evaporated or fallen to the soil surface as leaf drainage within one day. Leaf drainage is therefore modelled as a linear reservoir with a time constant (or residence time) of one day, i.e:

$$D_{\text{int}} = \frac{1}{\mathrm{T}_{\text{int}}} \cdot Int_{cum}\Delta t \quad (2\text{-}11)$$

where D_{int} is the amount of leaf drainage per time step [mm] and T_{int} is a time constant for the interception store [days], which is set to 1 day.

Treatment of built-up areas and water bodies

If (part of) a pixel is made up of built-up areas this will influence that pixel's water-balance. LISFLOOD's 'direct runoff fraction' parameter (f_{dr}) defines the fraction of a pixel that is impervious. For impervious areas, LISFLOOD assumes that:

1. Any water that reaches the surface is added directly to surface runoff
2. The storage capacity of the soil is zero (i.e. no soil moisture storage in the direct runoff fraction)
3. There is no groundwater storage

The same assumptions are made for open water bodies (e.g. lakes), which should be included in f_{dr} (large lakes that are in direct connection with major river channels can be modelled using LISFLOOD's lake option, which is described in Annex 5 of this manual). Unless stated otherwise, the description of all soil- and groundwater-related processes below (evaporation, transpiration, infiltration, preferential flow, soil moisture redistribution and groundwater flow) are valid for the permeable domain of each pixel only. However, if you activate any of LISFLOOD's options for writing these internal model fluxes to timeseries or maps (described in Chapter 8), the model will report the pixel-average fluxes, which are simply the fluxes as described in this manual, multiplied by the permeable fraction (1- f_{dr}). Figure 2.3 illustrates this, using the water uptake by plant roots as an example.

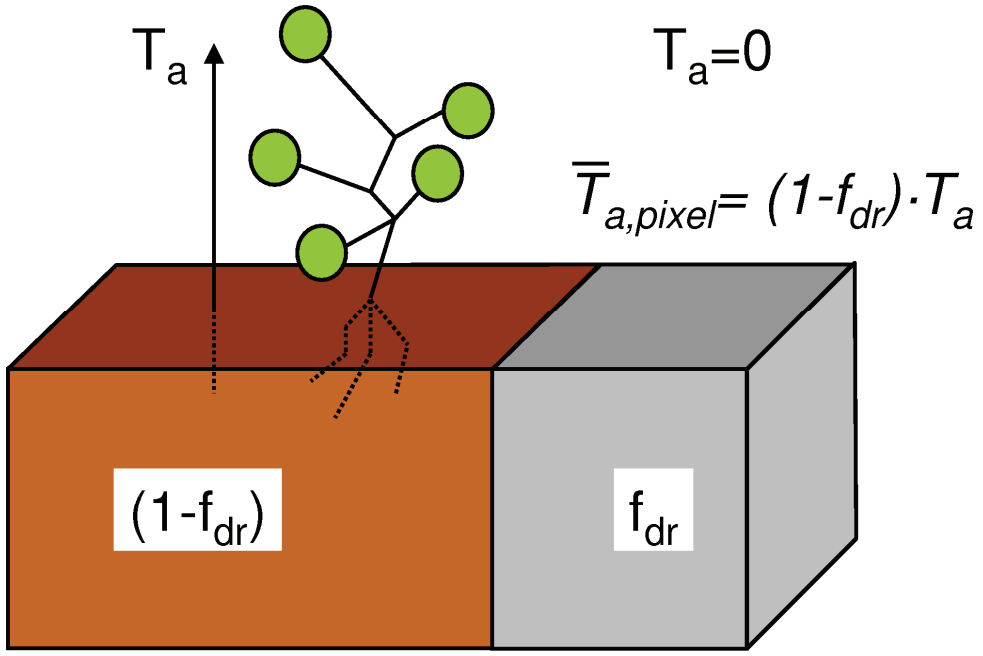


Figure 2.3 *Simulation of impermeable areas in LISFLOOD. In this example, water uptake by plant roots (transpiration, T_a) is only simulated in the permeable fraction of the pixel (1-f_{dr}), whereas it is zero in the direct runoff fraction (f_{dr}). Pixel-average fluxes (which are reported by the model as output) are calculated by multiplying by the permeable fraction.*

Water available for infiltration and direct runoff

In the permeable fraction of each pixel (1- f_{dr}), the amount of water that is available for infiltration, W_{av} [mm] equals (Supit *et al.*,1994):

$$W_{av} = R\Delta t + M + D_{\text{int}} - Int \qquad (2\text{-}12)$$

where:

R	: Rainfall [mm day^{-1}]
M	: Snow melt [mm]
D_{int}	: Leaf drainage [mm]
Int	: Interception [mm]
Δt	: time step [days]

Since no infiltration can take place in each pixel's 'direct runoff fraction', direct runoff is calculated as:

$$R_d = f_{dr} \cdot W_{av} \qquad (2\text{-}13)$$

where R_d is in [mm] per time step. Note here that W_{av} is valid for the permeable fraction only, whereas R_d is valid for the direct runoff fraction.

Water uptake by plant roots and transpiration

Water uptake and transpiration by vegetation and direct evaporation from the soil surface are modelled as two separate processes. The approach used here is largely based on Supit *et al*. (1994) and Supit & Van Der Goot (2000). The maximum transpiration per time step [mm] is given by:

$$T_{\max} = k_{crop} \cdot ET0 \cdot [1 - \exp(-\kappa_{gb} \cdot LAI)]\Delta t - EW_{\text{int}} \quad (2\text{-}14)$$

where *ET0* is the potential (reference) evapotranspiration rate [mm day^{-1}], and k_{crop} is a crop coefficient. k_{crop} is 1 for most vegetation types, except for some excessively transpiring crops like sugarcane. Note that the energy that has been 'consumed' already for the evaporation of intercepted water is simply subtracted here in order to respect the overall energy balance. The actual transpiration rate is reduced when the amount of moisture in the soil is small. In the model, a reduction factor is applied to simulate this effect:

$$r_{WS} = \frac{(w_1 - w_{wp1})}{(w_{crit1} - w_{wp1})} \quad (2\text{-}15)$$

where w_1 is the amount of moisture in the upper soil layer [mm], w_{wp1} [mm] is the amount of soil moisture at wilting point (pF 4.2) and w_{crit1} [mm] is the amount of moisture below which water uptake is reduced and plants start closing their stomata. The critical amount of soil moisture is calculated as:

$$w_{\text{crit1}} = (1 - p) \cdot (w_{fc1} - w_{wp1}) + w_{wp1} \quad (2\text{-}16)$$

where w_{fc1} [mm] is the amount of soil moisture at field capacity and p is the soil water depletion fraction. R_{WS} varies between 0 and 1: negative values and values greater than 1 are truncated to 0 and 1, respectively. p represents the fraction of soil moisture between w_{fc1} and w_{wp1} that can be extracted from the soil without reducing the transpiration rate. Its value is a function of both vegetation type and the potential evapotranspiration rate. The procedure to estimate p is described in detail in Supit & Van Der Goot (2003). Figure 2.4 further illustrates the relation between *RWS*, w, w_{crit}, w_{fc}, w_{wp} and p.

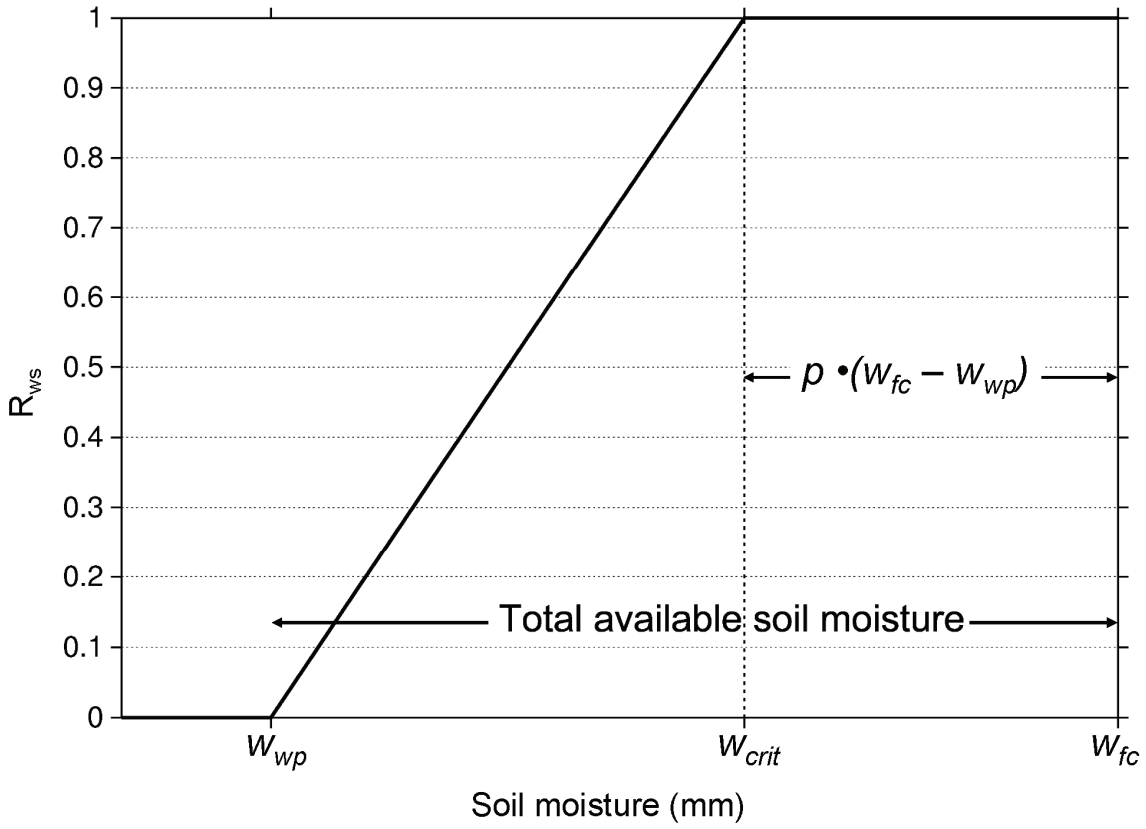


Figure 2.4 *Reduction of transpiration in case of water stress. R_{ws} decreases linearly to zero between* w_{crit} *and* w_{wp}.

The actual transpiration T_a is now calculated as:

$$T_a = r_{WS} \cdot T_{\max} \tag{2-17}$$

with T_a and T_{max} in [mm].

Transpiration is set to zero when the soil is frozen (i.e. when frost index *F* exceeds its critical threshold). The amount of moisture in the upper soil layer is updated after the transpiration calculations:

$$w_1 = w_1 - T_a \tag{2-18}$$

Direct evaporation from the soil surface

The maximum amount of evaporation from the soil surface equals the maximum evaporation from a shaded soil surface, ES_{max} [mm], which is computed as:

$$ES_{\max} = ES0 \cdot \exp(-\kappa_{gb} \cdot LAI)\Delta t \tag{2-19}$$

where *ES0* is the potential evaporation rate from bare soil surface [mm day^{-1}]. The actual evaporation from the soil mainly depends on the amount of soil moisture near the soil surface: evaporation decreases as the topsoil is drying. In the model this is simulated using a reduction factor which is a function of the number of days since the last rain storm (Stroosnijder, 1987, 1982):

$$ES_a = ES_{\max} \cdot (\sqrt{D_{slr}} - \sqrt{D_{slr} - 1}) \quad (2\text{-}20)$$

The variable D_{slr} represents the number of days since the last rain event. Its value accumulates over time: if the amount of water that is available for infiltration (W_{av}) remains below a critical threshold it increases by an amount of Δt [days] for each time step. It is reset to 1 only if the critical amount of water is exceeded[2]. The actual soil evaporation is always the smallest value out of the result of the equation above and the available amount of moisture in the soil, i.e.:

$$ES_a = \min(ES_a, w_1 - w_{res1}) \quad (2\text{-}21)$$

where w_1 [mm] is the amount of moisture in the upper soil layer and w_{res1} [mm] is the residual amount of soil moisture. Like transpiration, direct evaporation from the soil is set to zero if the soil is frozen. The amount of moisture in the upper soil layer is updated after the evaporation calculations:

$$w_1 = w_1 - ES_a \quad (2\text{-}22)$$

Infiltration capacity

The infiltration capacity of the soil is estimated using the widely-used Xinanjiang (also known as VIC/ARNO) model (e.g. Zhao & Lui, 1995; Todini, 1996). This approach assumes that the fraction of a grid cell that is contributing to surface runoff (read: saturated) is related to the total amount of soil moisture, and that this relationship can be described through a non-linear distribution function. For any grid cell, if w_1 is the total moisture storage in the upper soil layer and w_{s1} is the maximum storage, the corresponding saturated fraction A_s is approximated by the following distribution function:

$$A_s = 1 - (1 - \frac{w_1}{w_{s1}})^b \quad (2\text{-}23)$$

where w_{s1} and w_1 are the maximum and actual amounts of moisture in the upper soil layer, respectively [mm], and b is an empirical shape parameter. In the LISFLOOD implementation of the Xinanjiang model, A_s is defined as a fraction of the permeable fraction of each pixel (i.e. as a fraction of (1-d_{rf})). The infiltration capacity INF_{pot} [mm] is a function of w_s and A_s:

$$INF_{pot} = \frac{w_{s1}}{b+1} - \frac{w_{s1}}{b+1}[1 - (1 - A_s)^{\frac{b+1}{b}}] \quad (2\text{-}24)$$

Note that the shape parameter b is related to the heterogeneity within each grid cell. For a totally homogeneous grid cell b approaches zero, which reduces the above equations to a simple 'overflowing bucket' model.

[2] In the LISFLOOD settings file this critical amount is currently expressed as an *intensity* [mm day^{-1}]. This is because the equation was originally designed for a daily time step only. Because the current implementation will likely lead to *DSLR* being reset too frequently, the exact formulation may change in future versions (e.g. by keeping track of the accumulated available water of the last 24 hours).

Preferential bypass flow

For the simulation of preferential bypass flow –i.e. flow that bypasses the soil matrix and drains directly to the groundwater- no generally accepted equations exist. Because ignoring preferential flow completely will lead to unrealistic model behaviour during extreme rainfall conditions, a very simple approach is used in LISFLOOD. During each time step, a fraction of the water that is available for infiltration is added to the groundwater directly (i.e. without first entering the soil matrix). It is assumed that this fraction is a power function of the relative saturation of the topsoil, which results in an equation that is somewhat similar to the excess soil water equation used in the HBV model (e.g. Lindström *et al*., 1997):

$$D_{pref,gw} = W_{av}\left(\frac{w_1}{w_{s1}}\right)^{c_{pref}} \tag{2-25}$$

where $D_{pref,gw}$ is the amount of preferential flow per time step [mm], W_{av} is the amount of water that is available for infiltration, and c_{pref} is an empirical shape parameter. f_{dr} is the 'direct runoff fraction' [-], which is the fraction of each pixel that is made up by urban area and open water bodies (i.e. preferential flow is only simulated in the permeable fraction of each pixel) . The equation results in a preferential flow component that becomes increasingly important as the soil gets wetter.

Actual infiltration and surface runoff

The actual infiltration INF_{act} [mm] is now calculated as:

$$INF_{act} = \min(INF_{pot}, W_{av} - D_{pref,gw}) \tag{2-26}$$

Finally, the surface runoff R_s [mm] is calculated as:

$$R_s = R_d + (1 - f_{dr}) \cdot (W_{av} - D_{pref,gw} - INF_{act}) \tag{2-27}$$

where R_d is the direct runoff (generated in the pixel's 'direct runoff fraction'). If the soil is frozen ($F >$ critical threshold) no infiltration takes place. The amount of moisture in the upper soil layer is updated after the infiltration calculations:

$$w_1 = w_1 + INF_{act} \tag{2-28}$$

Soil moisture redistribution

The description of the moisture fluxes out of the subsoil (and also between the upper- and lower soil layer) is based on the simplifying assumption that the flow of soil moisture is entirely gravity-driven. Starting from Darcy's law for 1-D vertical flow:

$$q = -K(\theta)\left[\frac{\partial h(\theta)}{\partial z} - 1\right] \tag{2-29}$$

where q [mm day^{-1}] is the flow rate out of the soil (e.g. upper soil layer, lower soil layer); $K(\theta)$ [mm day^{-1}] is the hydraulic conductivity (as a function of the volumetric

moisture content of the soil, θ [mm^3 mm^{-3}]) and $\partial h(\theta)/\partial z$ is the matric potential gradient. If we assume a matric potential gradient of zero, the equation reduces to:

$$q = K(\theta) \tag{2-30}$$

This implies a flow that is always in downward direction, at a rate that equals the conductivity of the soil. The relationship between hydraulic conductivity and soil moisture status is described by the Van Genuchten equation (van Genuchten, 1980), here re-written in terms of mm water slice, instead of volume fractions:

$$K(w) = K_s\left(\frac{w - w_r}{w_s - w_r}\right)^{1/2}\left\{1 - \left[1 - \left(\frac{w - w_r}{w_s - w_r}\right)^{1/m}\right]^m\right\}^2 \tag{2-31}$$

where K_s is the saturated conductivity of the soil [mm day^{-1}], and w, w_r and w_s are the actual, residual and maximum amounts of moisture in the soil respectively (all in [mm]). Parameter m is calculated from the pore-size index, λ (which is related to soil texture):

$$m = \frac{\lambda}{\lambda + 1} \tag{2-32}$$

For large values of Δt (e.g. 1 day) the above equation often results in amounts of outflow that exceed the available soil moisture storage, i.e:

$$K(w)\Delta t > w - w_r \tag{2-33}$$

In order to solve the soil moisture equations correctly an iterative procedure is used. At the beginning of each time step, the conductivities for both soil layers [$K_1(w_1)$, $K_2(w_2)$] are calculated using the Van Genuchten equation. Multiplying these values with the time step and dividing by the available moisture gives a Courant-type numerical stability indicator for each respective layer:

$$C_1 = \frac{K_1(w_1)\cdot\Delta t}{w_1 - w_{r1}} \tag{2-34a}$$

$$C_2 = \frac{K_2(w_2)\cdot\Delta t}{w_2 - w_{r2}} \tag{2-34b}$$

A Courant number that is greater than 1 implies that the calculated outflow exceeds the available soil moisture, resulting in loss of mass balance. Since we need a stable solution for both soil layers, the 'overall' Courant number for the soil moisture routine is the largest value out of C_1 and C_2:

$$C_{soil} = \max(C_1, C_2) \tag{2-35}$$

In principle, rounding C_{soil} up to the nearest integer gives the number sub-steps needed for a stable solution. In practice, it is often preferable to use a critical Courant number that is lower than 1, because high values can result in unrealistic 'jumps' in the simulated soil moisture pattern when the soil is near saturation (even though mass balance is preserved). Hence, making the critical Courant number a user-defined value C_{crit}, the number of sub-steps becomes:

$$SubSteps = roundup(\frac{C_{soil}}{C_{crit}}) \quad (2\text{-}36)$$

and the corresponding sub-time-step, $\Delta' t$:

$$\Delta' t = \frac{\Delta t}{SubSteps} \quad (2\text{-}37)$$

In brief, the iterative procedure now involves the following steps. First, the number of sub-steps and the corresponding sub-time-step are computed as explained above. The amounts of soil moisture in the upper and lower layer are copied to temporary variables w'_1 and w'_2. Two variables, $D_{1,2}$ (flow from upper to lower soil layer) and $D_{2,gw}$ (flow from lower soil layer to groundwater) are initialized (set to zero). Then, for each sub-step, the following sequence of calculations is performed:

1. compute hydraulic conductivity for both layers
2. compute flux from upper to lower soil layer for this sub-step ($D'_{1,2}$, can never exceed storage capacity in lower layer):

$$D'_{1,2} = \min[K_1(w'_1)\Delta t, w'_{s2} - w'_2] \quad (2\text{-}38)$$

3. compute flux from lower soil layer to groundwater for this sub-step ($D'_{2,gw}$, can never exceed available water in lower layer):

$$D'_{2,gw} = \min[K_2(w'_2)\Delta t, w'_2 - w'_{r2}] \quad (2\text{-}39)$$

4. update w'_1 and w'_2
5. add $D'_{1,2}$ to $D_{1,2}$; add $D'_{2,gw}$ to $D_{2,gw}$

If the soil is frozen (F > critical threshold), both $D_{1,2}$ and $D_{2,gw}$ are set to zero. After the iteration loop, the amounts of soil moisture in both layers are updated as follows:

$$w_1 = w_1 - D_{1,2} \quad (2\text{-}40)$$

$$w_2 = w_2 + D_{1,2} - D_{2,gw} \quad (2\text{-}41)$$

Groundwater

Groundwater storage and transport are modelled using two parallel linear reservoirs, similar to the approach used in the HBV-96 model (Lindström et al., 1997). The upper zone represents a quick runoff component, which includes fast groundwater and subsurface flow through macro-pores in the soil. The lower zone represents the slow groundwater component that generates the base flow. The outflow from the upper zone to the channel, Q_{uz} [mm] equals:

$$Q_{uz} = \frac{1}{\mathrm{T_{uz}}} \cdot UZ\,\Delta t \quad (2\text{-}42)$$

where T_{uz} is a reservoir constant [days] and *UZ* is the amount of water that is stored in the upper zone [mm. Similarly, the outflow from the lower zone is given by:

$$Q_{lz} = \frac{1}{\mathrm{T}_{\mathrm{lz}}} \cdot LZ \; \Delta t \tag{2-43}$$

Here, T_{lz} is again a reservoir constant [days], and *LZ* is the amount of water that is stored in the lower zone [mm]. The values of both T_{uz} and T_{lz} are obtained by calibration. The upper zone also provides the inflow into the lower zone. For each time step, a fixed amount of water percolates from the upper to the lower zone:

$$D_{uz,lz} = \min(GW_{perc} \cdot \Delta t, UZ) \tag{2-44}$$

Here, GW_{perc} [mm day^{-1}] is a user-defined value that can be used as a calibration constant. For many catchments it is quite reasonable to treat the lower groundwater zone as a system with a closed lower boundary (i.e. water is either stored, or added to the channel). However, in some cases the closed boundary assumption makes it impossible to obtain realistic simulations. Because of this, it is possible to treat of fixed fraction of Q_{lz} as a loss, D_{loss}, out of the lower zone, i.e.:

$$D_{loss} = f_{loss} \cdot Q_{lz} \tag{2-45}$$

The loss fraction, f_{loss} [-], equals 0 for a completely closed lower boundary. If f_{loss} is set to 1, all outflow from the lower zone is treated as a loss. Water that flows out of the lower zone through D_{loss} is quite literally 'lost' forever. Physically, the loss term could represent water that is either lost to deep groundwater systems (that do not necessarily follow catchment boundaries), or even groundwater extraction wells. When using the model, it is suggested to use f_{oss} with some care; start with a value of zero, and only use any other value if it is impossible to get satisfactory results by adjusting the other calibration parameters.

At each time step, the amounts of water in the upper and lower zone are updated for the in- and outgoing fluxes, i.e.:

$$UZ_t = UZ_{t-1} + D_{2,gw} - D_{uz,lz} - Q_{uz} \tag{2-46}$$

$$LZ_t = LZ_{t-1} + D_{uz,lz} - Q_{lz} \tag{2-47}$$

Note that these equations are again valid for the permeable fraction of the pixel only: storage in the direct runoff fraction equals 0 for both *UZ* and *LZ*.

Routing of surface runoff to channel

Surface runoff is routed to the nearest downstream channel using a 4-point implicit finite-difference solution of the kinematic wave equations (Chow, 1988). The basic equations used are the equations of continuity and momentum. The continuity equation is:

$$\frac{\partial Q_{sr}}{\partial x} + \frac{\partial A_{sr}}{\partial t} = q_{sr} \tag{2-48}$$

where Q_{sr} is the surface runoff [$m^3\ s^{-1}$], A_{sr} is the cross-sectional area of the flow [m^2] and q_{sr} is the amount of lateral inflow per unit flow length [$m^2\ s^{-1}$]. The momentum equation is defined as:

$$\rho g A_{sr}(S_0 - S_f) = 0 \qquad (2\text{-}49)$$

where ρ is the density of the flow [$kg\ m^{-3}$], g is the gravity acceleration [$m\ s^{-2}$], S_0 is the topographical gradient and S_f is the friction gradient. From the momentum equation it follows that $S_0 = S_f$, which means that for the kinematic wave equations it is assumed that the water surface is parallel to the topographical surface. The continuity equation can also be written in the following finite-difference form (please note that for the sake of readability the 'sr' subscripts are omitted here from Q, A and q):

$$\frac{Q_{i+1}^{j+1} - Q_i^{j+1}}{\Delta x} + \frac{A_{i+1}^{j+1} - A_{i+1}^{j}}{\Delta t} = \frac{q_{i+1}^{j+1} - q_{i+1}^{j}}{2} \qquad (2\text{-}50)$$

where j is a time index and i a space index (such that $i=1$ for the most upstream cell, $i=2$ for its downstream neighbour, etcetera). The momentum equation can also be expressed as (Chow et al., 1988):

$$A_{sr} = \alpha_{k,sr} \cdot Q_{sr}^{\ \beta_k} \qquad (2\text{-}51)$$

Substituting the right-hand side of this expression in the finite-difference form of the continuity equation gives a nonlinear implicit finite-difference solution of the kinematic wave:

$$\frac{\Delta t}{\Delta x} Q_{i+1}^{j+1} + \alpha_k (Q_{i+1}^{j+1})^{\beta_k} = \frac{\Delta t}{\Delta x} Q_i^{j+1} + \alpha_k (Q_{i+1}^{j})^{\beta_k} + \Delta t \left(\frac{q_{i+1}^{j+1} + q_{i+1}^{j}}{2}\right) \qquad (2\text{-}52)$$

If $\alpha_{k,sr}$ and β_k are known, this non-linear equation can be solved for each pixel and during each time step using an iterative procedure. This numerical solution scheme is available as a built-in function in the PCRaster software. The coefficients $\alpha_{k,sr}$ and β_k are calculated by substituting Manning's equation in the right-hand side of Equation 2-51:

$$A_{sr} = \left(\frac{n \cdot P_{sr}^{2/3}}{\sqrt{S_0}}\right)^{3/5} \cdot Q_{sr}^{3/5} \qquad (2\text{-}53)$$

where n is Manning's roughness coefficient and P_{sr} is the wetted perimeter of a cross-section of the surface flow. Substituting the right-hand side of this equation for A_{sr} in equation 2-51 gives:

$$\alpha_{k,sr} = \left(\frac{n \cdot P_{sr}^{2/3}}{\sqrt{S_0}}\right)^{0.6} \quad ; \quad \beta_k = 0.6 \qquad (2\text{-}54)$$

At present, LISFLOOD uses values for $\alpha_{k,sr}$ which are based on a static (reference) flow depth, and a flow width that equals the pixel size, Δx. For each time step, all runoff that is generated (R_s) is added as side-flow (q_{sr}). For each flowpath, the routing stops at the first downstream pixel that is part of the channel network. In other words,

the routine only routes the surface runoff *to* the nearest channel; no runoff *through* the channel network is simulated at this stage (runoff- and channel routing are completely separated).

Routing of sub-surface runoff to channel

All water that flows out of the upper- and lower groundwater zone is routed to the nearest downstream channel pixel within one time step. Recalling once more that the groundwater equations are valid for the pixel's permeable fraction only, the contribution of each pixel to the nearest channel is made up of $(1\text{-}f_{dr})\cdot Q_{uz}$ and $(1\text{-}f_{dr})\cdot(Q_{lz}\text{-}D_{loss})$, respectively. Figure 3 illustrates the routing procedure: for each pixel that contains a river channel, its contributing pixels are defined by the drainage network. For every 'river pixel' the groundwater outflow that is generated by its upstream pixels is simply summed. For instance, there are two flow paths that are contributing to the second 'river pixel' from the left in Figure 2.5. Hence, the amount of water that is transported to this pixel equals the sum of the amounts of water produced by these flowpaths, q1 + q2. Note that, as with the surface runoff routing, no water is routed *through* the river network at this stage.

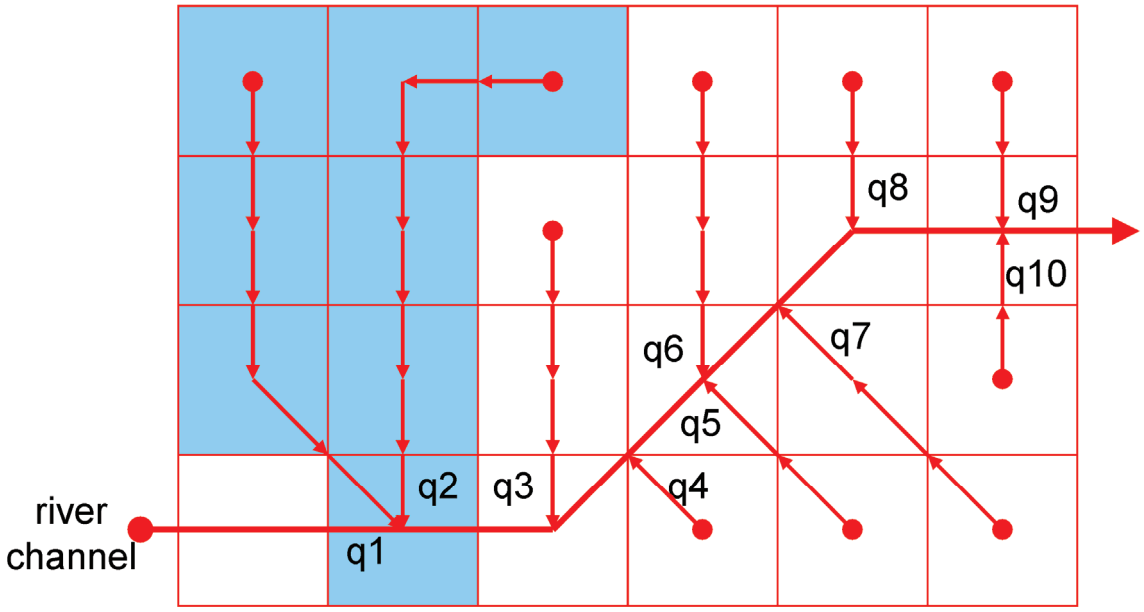


Figure 2.5 *Routing of groundwater to channel network. Groundwater flow is routed to the nearest 'channel' pixel.*

Channel routing

Flow through the channel is simulated using the kinematic wave equations. The basic equations and the numerical solution are identical to those used for the surface runoff routing:

$$\frac{\partial Q_{ch}}{\partial x}+\frac{\partial A_{ch}}{\partial t}=q_{ch} \qquad (2\text{-}55)$$

where Q_{ch} is the channel discharge [$m^3\ s^{-1}$], A_{ch} is the cross-sectional area of the flow [m^2] and q_{ch} is the amount of lateral inflow per unit flow length [$m^2\ s^{-1}$]. The momentum equation then becomes:

$$\rho g A_{ch}(S_0 - S_f) = 0 \qquad (2\text{-}56)$$

where S_0 now equals the gradient of the channel bed, and $S_0 = S_f$. As with the surface runoff, values for parameter $\alpha_{k,ch}$ are estimated using Manning's equation:

$$\alpha_{k,ch} = \left(\frac{n \cdot P_{ch}^{2/3}}{\sqrt{S_0}}\right)^{0.6} \quad ; \quad \beta_k = 0.6 \qquad (2\text{-}57)$$

At present, LISFLOOD uses values for $\alpha_{k,ch}$ which are based on a static (reference) channel flow depth (half bankfull) and measured channel dimensions. The term q_{ch} (sideflow) now represents the runoff that enters the channel per unit channel length:

$$q_{ch} = (\sum Q_{sr} + \sum Q_{uz} + \sum Q_{lz} + Q_{in} + Q_{res}) / L_{ch} \qquad (2\text{-}58)$$

Here, Q_{sr}, Q_{uz} and Q_{lz} denote the contributions of surface runoff, outflow from the upper zone and outflow from the lower zone, respectively. Q_{in} is the inflow from an external inflow hydrograph; by default its value is 0, unless the 'inflow hydrograph' option is activated (see Annex 2). Q_{res} is the water that flows out of a reservoir into the channel; by default its value is 0, unless the 'reservoir' option is activated (see Annex 1). Q_{sr}, Q_{uz}, Q_{lz}, Q_{in} and Q_{res} are all expressed in [m^3] per time step. L_{ch} is the channel length [m], which may exceed the pixel size (Δx) in case of meandering channels. The kinematic wave channel routing can be run using a smaller time-step than the over simulation timestep, Δt, if needed.

Special simulation options

The above model description covers the processes that are simulated in a 'standard' LISFLOOD run. By default, special structures in the river channel such as (natural) lakes and regulated reservoirs are not taken into account. However, LISFLOOD has some optional features to model these structures. The description of these features can be found in a series of Annexes at the end of this manual.

3. Installation of the LISFLOOD model

System requirements

Currently LISFLOOD is available on both Linux and 32-bit Windows systems. Either way, the model requires that a recent version of the PCRaster software is available, or at least PCRaster's 'pcrcalc' application and all associated libraries. LISFLOOD versions October 3 2007 and later require 'pcrcalc' version October 2, 2007, or more recent. Older 'pcrcalc' versions will either not work at all, or they might produce erroneous results. Unless you are using a 'sealed' version of LISFLOOD (i.e. a version in which the source code is made unreadable), you will also need a licensed version of 'pcrcalc'. For details on how to install PCRaster we refer to the PCRaster documentation.

Installation on Windows systems

For Windows users the installation involves two steps:

1. Unzip the contents of 'lisflood_win32.zip' to an empty folder on your PC (e.g. 'lisflood')
2. Open the file 'config.xml' in a text editor. This file contains the full path to all files and applications that are used by LISFLOOD. The items in the file are:
   - *Pcrcalc application* : this is the name of the pcrcalc application, including the full path
   - *LISFLOOD Master Code* (optional). This item is usually omitted, and LISFLOOD assumes that the master code is called 'lisflood.xml', and that it is located in the root of the 'lisflood' directory (i.e. the directory that contains 'lisflood.exe' and all libraries). If –for whatever reason- you want to overrule this behaviour, you can add a 'mastercode' element, e.g.:

   <mastercode>d:\Lisflood\beta\mastercode\lisflood.xml**</mastercode>**

The configuration file should look something like this:

```
<?xml version="1.0" encoding="ISO-8859-1"?>

<!-- Lisflood configuration file, JvdK, 8 July 2004 -->
<!-- !! This file MUST be in the same directory as lisflood.exe -->
<!-- (or lisflood) !!! -->

<lfconfig>

<!-- location of pcrcalc application -->
<pcrcalcapp>C:\pcraster\apps\pcrcalc.exe</pcrcalcapp>


</lfconfig>
```

The lisflood executable is a command-line application which can be called from the command prompt ('DOS' prompt). To make life easier you may include the full path to 'lisflood.exe' in the 'Path' environment variable. In Windows XP you can do this by selecting 'settings' from the 'Start' menu; then go to 'control panel'/'system' and go to the 'advanced' tab. Click on the 'environment variables' button. Finally, locate the

'Path' variable in the 'system variables' window and click on 'Edit' (this requires local Administrator privileges).

Installation on Linux systems

Under Linux LISFLOOD requires that the Python interpreter (version 2.4 or more recent) is installed on the system. Most Linux distributions already have Python pre-installed. If needed you can download Python free of any charge from the following location:

http://www.python.org/

The installation process is largely identical to the Windows procedure: unzip the contents of 'lisflood_llinux.zip' to an empty directory. Check if the file 'lisflood' is executable. If not, make it executable using:

```
chmod 755 lisflood
```

Then update the paths in the configuration file. The configuration file will look something like this:

```
<?xml version="1.0" encoding="ISO-8859-1"?>

<!-- Lisflood configuration file, JvdK, 8 July 2004 -->
<!-- !! This file MUST be in the same directory as lisflood.exe -->
<!-- (or lisflood) !!! -->

<lfconfig>

<!-- location of pcrcalc application -->
<pcrcalcapp>/usr/local/PCRBeta/linux/pcrcalc</pcrcalcapp>


</lfconfig>
```

Running the model

Type 'lisflood' at the command prompt. You should see something like this:

```
LISFLOOD version March 24 2008
Water balance and flood simulation model for large catchments

   (C) Institute for Environment and Sustainability
       Joint Research Centre of the European Commission
       TP261, I-21020 Ispra (Va), Italy

usage (1): lisflood [switches] <InputFile>
usage (2): lisflood --listoptions (show options only)

 InputFile     : LISFLOOD input file (see documentation
                 for description of format)

 switches:
          -s  : keep temporary script after simulation
```

You can run LISFLOOD by typing 'lisflood' followed by a specially-formatted settings file. The layout of this file is described in Chapters 4 and 5. Chapter 3 explains all other input files.

4. Model setup: input files

In the current version of LISFLOOD, all model input is provided as either maps (grid files in PCRaster format) or tables. This chapter describes all the data that are required to run the model. Files that are specific to *optional* LISFLOOD features (e.g. inflow hydrographs, reservoirs) are not listed here; they are described in the documentation for each option.

Input maps

All input maps roughly fall into any of the following six categories:

- maps related to topography
- maps related to soil
- maps related to land use
- maps related to channel geometry
- maps related to the meteorological conditions
- maps related to the development of vegetation over time
- maps that define at which locations output is generated as time series

All maps that are needed to run the model are listed in the following table[3]:

[3] The file names listed in the table are not obligatory. However, it is suggested to stick to the default names suggested in the table. This will make both setting up the model for new catchments as well as upgrading to possible future LISFLOOD versions much easier.

Table 4.1 *LISFLOOD input maps (continued on next page)*

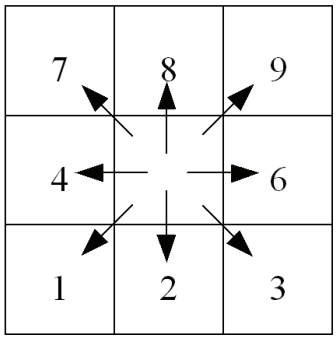
GENERAL		
Map	**Default name**	**Description**
MaskMap	area.map	*Boolean* map that defines model boundaries
TOPOGRAPHY		
Map	**Default name**	**Description**
Ldd	ldd.map	local drain direction map (with value 1-9); this file contains flow directions from each cell to its steepest downslope neighbour. Ldd directions are coded according to the following diagram:  This resembles the numeric key pad of your PC's keyboard, except for the value 5, which defines a cell without local drain direction (pit). The pit cell at the end of the path is the outlet point of a catchment
Grad	gradient.map	Slope gradient [m m^{-1}], i.e. value of 0.5 indicates a 26.5 degree angle (gradient equals tangent of slope in degrees)
ElevationRange	elvrange.map	Elevation range, i.e. difference between maximum and minimum elevation within pixel [m]
LAND USE		
Map	**Default name**	**Description**
LandUse	landuse.map	Map with land use classes (CORINE land cover, CEC 1993)
Forest	forest.map	Forest fraction for each cell. Values range from 0 (no forest at all) to 1 (pixel is 100% forest)
DirectRunoffFraction	directrf.map	Fraction urban area for each cell. Values range from 0 (no urban area at all) to 1 (pixel is 100% urban)
SOIL		
Map	**Default name**	**Description**
Texture1	soiltex1.map	Soil texture class layer 1 (upper layer)
Texture2	soiltex2.map	Soil texture class layer 2 (lower layer)
SoilDepth	soildep.map	Soil depth [cm]: depth to bedrock or groundwater

Table 4.1 *LISFLOOD input maps (continued from previous page)*

CHANNEL GEOMETRY		
Map	**Default name**	**Description**
Channels	chan.map	Map with Boolean 1 for all channel pixels, and Boolean 0 for all other pixels on MaskMap
ChanGrad	changrad.map	Channel gradient [m m^{-1}]
ChanMan	chanman.map	Manning's roughness coefficient for channels
ChanLength	chanleng.map	Channel length [m] (can exceed grid size, to account for meandering rivers)
ChanBottomWidth	chanbw.map	Channel bottom width [m].
ChanSdXdY	chans.map	Channel side slope [m m^{-1}] **Important:** currently defined as horizontal distance divided by vertical distance (dx/dy); this may be confusing because slope is usually defined the other way round (i.e. dy/dx)!!
ChanDepthThreshold	chanbnkf.map	Bankfull channel depth [m]
METEOROLOGICAL VARIABLES		
Map	**Default prefix**	**Description**
PrecipitationMaps	pr	Precipitation rate [mm day^{-1}]
TavgMaps	ta	Average *daily* temperature [°C]
E0Maps	e	Daily potential evaporation rate, free water surface [mm day^{-1}]
ES0Maps	es	Daily potential evaporation rate, bare soil [mm day^{-1}]
ET0Maps	et	Daily potential evapotranspiration rate, reference crop [mm day^{-1}]
DEVELOPMENT OF VEGETATION OVER TIME		
Map	**Default prefix**	**Description**
LAIMaps	lai	Pixel-average Leaf Area Index [m^2 m^{-2}]
DEFINITION OF INPUT/OUTPUT TIMESERIES		
Map	**Default name**	**Description**
Gauges	outlets.map	Nominal map with locations at which discharge timeseries are reported (usually correspond to gauging stations)
Sites	sites.map	Nominal map with locations (individual pixels or areas) at which timeseries of intermediate state and rate variables are reported (soil moisture, infiltration, snow, etcetera)

Map location attributes and distance units

All maps must have *identical* location attributes (number of rows, columns, and so on). LISFLOOD needs to know the size properties of each grid cell (length, area) in order to calculate water *volumes* from meteorological forcing variables that are all defined as water *depths*. By default, LISFLOOD obtains this information from the location attributes of the input maps. This will only work if all maps are in an "equal area" (equiareal) projection, and the map co-ordinates (and cell size) are defined in meters. For datasets that use, for example, a latitude-longitude system, neither of these conditions is met. In such cases you can still run LISFLOOD if you provide two additional maps that contain the length and area of each grid cell:

Table 4.2 *Optional maps that define grid size*

Map	Default name	Description
PixelLengthUser	pixleng.map	Map with pixel length [m]
PixelAreaUser	pixarea.map	Map with pixel area [m^2]

Both maps should be stored in the same directory where all other input maps are. The values on both maps may vary in space. A limitation is that a pixel is always represented as a square, so length and width are considered equal (no rectangles). In order to tell LISFLOOD to ignore the default location attributes and use the maps instead, you need to activate the special option "*gridSizeUserDefined*", which involves adding the following line to the LISFLOOD settings file:

```
<setoption choice="1" name="gridSizeUserDefined" />
```

LISFLOOD settings files and the use of options are explained in detail in Chapter 5 of this document.

Role of "mask" and "channels" maps

The mask map (i.e. "area.map") defines the model domain. In order to avoid unexpected results, it is vital that all maps that are related to topography, land use and soil are defined (i.e. don't contain a missing value) for each pixel that is "true" (has a Boolean 1 value) on the mask map. The same applies for all meteorological input and the Leaf Area Index maps. Similarly, all pixels that are "true" on the channels map must have some valid (non-missing) value on each of the channel parameter maps. Undefined pixels can lead to unexpected behaviour of the model, output that is full of missing values, loss of mass balance and possibly even model crashes.

Naming of meteorological variable maps

The meteorological forcing variables (and Leaf Area Index) are defined in *map stacks*. A *map stack* is simply a series of maps, where each map represents the value of a variable at an individual time step. The name of each map is made up of a total of 11 characters: 8 characters, a dot and a 3-character suffix. Each map name starts with a *prefix*, and ends with the time step number. All character positions in between are filled with zeros ("0"). Take for example a stack of precipitation maps. Table 4.1 shows that the default prefix for precipitation is "pr", which produces the following file names:

pr000000.007 : at time step 7
pr000035.260 : at time step 35260

LISFLOOD can handle two types of stacks. First, there are *regular* stacks, in which a map is defined for each time step. For instance, the following 10-step stack is a regular stack:

t	map name
1	pr000000.001
2	pr000000.002
3	pr000000.003
4	pr000000.004
5	pr000000.005
6	pr000000.006
7	pr000000.007
8	pr000000.008
9	pr000000.009
10	pr000000.010

In addition to regular stacks, it is also possible to define *sparse* stacks. A *sparse* stack is a stack in which maps are not defined for all time steps, for instance:

t	map name
1	pr000000.001
2	-
3	-
4	pr000000.004
5	-
6	-
7	pr000000.007
8	-
9	-
10	-

Here, maps are defined *only* for time steps 1, 4 and 7. In this case, LISFLOOD will use the map values of *pr000000.001* during time steps 1, 2 and 3, those of *pr000000.004* during time steps 4, 5 and 6, and those of *pr000000.007* during time steps 7, 8, 9 and 10. Since both regular and sparse stacks can be combined within one single run, sparse stacks can be very useful to save disk space. For instance, LISFLOOD always needs the *average daily* temperature, even when the model is run on an hourly time step. So, instead of defining 24 identical maps for each hour, you can simply define 1 for the first hour of each day and leave out the rest, for instance:

t	map name
1	ta000000.001
2	-
:	:
:	:
25	ta000000.025
:	:
:	:
49	ta000000.049
:	:

Similarly, potential evapo(transpi)ration is usually calculated on a daily basis. So for hourly model runs it is often convenient to define *E0*, *ES0* and *ET0* in sparse stacks as well. Leaf Area Index (*LAI*) is a variable that changes relatively slowly over time, and as a result it is usually advantageous to define *LAI* in a sparse map stack.

Input tables

In addition to the maps and time series above, a number of model parameters are read through tables that are linked to the classes on the land use and soil (texture) maps. The following table gives a complete overview:

Table 4.3 *LISFLOOD input tables*

LAND USE		
Table	**Default name**	**Description**
TabCropCoef	cropcoef.txt	Crop coefficient for each land use class [-]
TabCropGroupNumber	cropgrpn.txt	Crop group number for each land use class
TabRootDepth	rootdep.txt	Rooting depth for each land use class [cm]
TabN	n.txt	Manning's roughness for each land use class [-]
SOIL TEXTURE		
Table	**Default name**	**Description**
TabThetaSat1	thetas1.txt	Saturated volumetric soil moisture content layer 1 [-]
TabThetaSat2	thetas2.txt	Saturated volumetric soil moisture content layer 2 [-]
TabThetaRes1	thetar1.txt	Residual volumetric soil moisture content layer 1 [-]
TabThetaRes2	thetar2.txt	Residual volumetric soil moisture content layer 2 [-]
TabLambda1	lambda1.txt	Pore size index (λ) layer 1 [-]
TabLambda2	lambda2.txt	Pore size index (λ) layer 2 [-]
TabGenuAlpha1	alpha1.txt	Van Genuchten parameter α layer 1 [-]
TabGenuAlpha2	alpha2.txt	Van Genuchten parameter α layer 2 [-]
TabKSat1	ksat1.txt	Saturated conductivity layer 1 [cm day^{-1}]
TabKSat2	ksat2.txt	Saturated conductivity layer 2 [cm day^{-1}]

Organisation of input data

It is up to the user how the input data are organised. However, it is advised to keep the base maps, meteorological maps and tables separated (i.e. store them in separate directories). For practical reasons the following input structure is suggested:

- all base maps are in one directory (e.g. 'maps')
- all tables are in one directory (e.g. 'tables')
- all meteorological input maps are in one directory (e.g. 'meteo')
- all Leaf Area Index maps are in one directory (e.g. 'lai')
- all output goes to one directory (e.g. 'out')

The following Figure illustrates this:

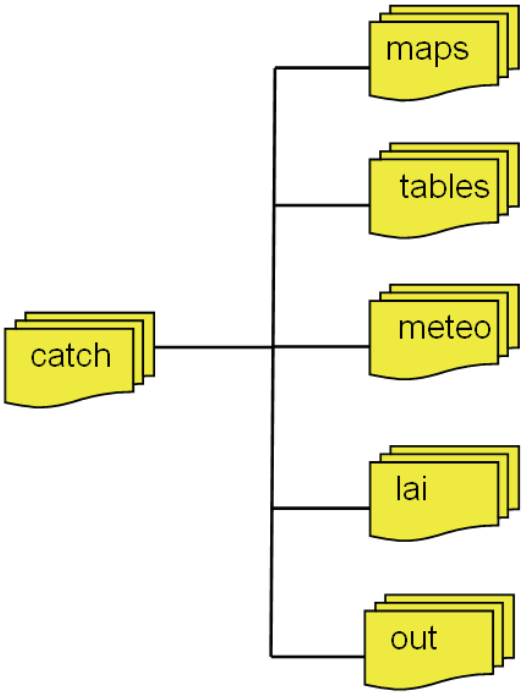


Figure 4.1 *Suggested file structure for LISFLOOD*

Generating input base maps

At the time of writing this document, complete sets of LISFLOOD base maps covering the whole of Europe have been compiled at 1- and 5-km pixel resolution. A number of automated procedures have been written that allow you to generate sub-sets of these for pre-defined areas (using either existing mask maps or co-ordinates of catchment outlets). These procedures (which are specific to the data server setup at the Floods Action, IES, JRC, Ispra) are documented in a separate document on 'LISFLOOD and LISVAP map extraction'. If you are an external user of LISFLOOD, please contact the Floods Action to extract the data for you.

5. LISFLOOD setup: the settings file

In LISFLOOD, all file and parameter specifications are defined in a settings file. The purpose of the settings file is to link variables and parameters in the model to in- and output files (maps, time series, tables) and numerical values. In addition, the settings file can be used to specify several *options*. The settings file has a special (XML) structure. In the next sections the general layout of the settings file is explained. Although the file layout is not particularly complex, a basic understanding of the general principles explained here is essential for doing any successful model runs.

The settings file has an XML ('E**x**tensible **M**arkup **L**anguage') structure. You can edit it using any text editor (e.g. Notepad, Editpad, Emacs, vi). Alternatively, you can also use a dedicated XML editor such as XMLSpy.

Layout of the settings file

A LISFLOOD settings file is made up of 4 elements, each of which has a specific function. The general structure of the file is described using XML-tags. XML stands for 'E**x**tensible **M**arkup **L**anguage', and it is really nothing more than a way to describe data in a file. It works by putting information that goes into a (text) file between tags, and this makes it very easy add structure. For a LISFLOOD settings file, the basic structure looks like this:

<lfsettings>	Start of settings element
<lfuser>	Start of element with user-defined variables
</lfuser>	End of element with user-defined variables
<lfoptions>	Start of element with options
</lfoptions>	End of element with options
<lfbinding>	Start of element with 'binding' variables
</lfbinding>	End of element with 'binding' variables
<prolog>	Start of prolog
</prolog>	End of prolog
<lfsettings>	End of settings element

From this you can see the following things:

- The settings file is made up of the elements 'lfuser', 'lfoptions' and 'lfbinding'; in addition, there is a 'prolog' element (but this will ultimately disappear in future LISFLOOD versions)
- The start of each element is indicated by the element's name wrapped in square brackets, e.g. <element>
- The end of each element is indicated by a forward slash followed by the element's name, all wrapped in square brackets, e.g. </element>

- All elements are part of a ‘root’ element called ‘<lfsettings>’.

In brief, the main function of each element is:

lfuser	: definition of paths to all in- and output files, and main model parameters (calibration + time-related)
lfbinding	: definition of all individual in- and output files, and model parameters
lfoptions	: switches to turn specific components of the model on or off

The following sections explain the function of each element in more detail. This is mainly to illustrate the main concepts and how it all fits together. A detailed description of all the variables that are relevant for setting up and running LISFLOOD is given in Chapter 6.

lfuser and and lfbinding elements

The ‘lfbinding’ element provides a very low-level way to define all model parameter values as well as all in- and output maps, time series and tables. The ‘lfuser’ element is used to define (user-defined) text variables. These text variables can be used to substitute repeatedly used expressions in the binding element. This greatly reduces the amount of work that is needed to prepare the settings file. Each variable is defined as a ‘textvar’ element within ‘lfuser’/’lfbinding’. Each ‘textvar’ element has the attributes ‘name’ and ‘value’. The following example demonstrates the main principle (note that in the examples below the prolog element is left out, but you will never need to edit this anyway) :

```
<?xml version="1.0" encoding="UTF-8"?>
<!DOCTYPE lfsettings SYSTEM "lisflood.dtd">

<lfsettings>

<lfuser>

<textvar name="PathMaps" value="//cllx01/floods2/knijfjo/test/maps">
</textvar>

</lfuser>


<lfoptions>

</lfoptions>


<lfbinding>

<textvar name="LandUse" value="$(PathMaps)/landuse.map">
</textvar>

<textvar name="SoilDepth" value="$(PathMaps)/soildep.map">
</textvar>

</lfbinding>

</lfsettings>
```

In the example two input files (maps) are defined. Both maps are in the same directory. Instead of entering the full file path for every map, we define a variable called *PathMaps* in the ‘lfuser’ element. This variable can then be used in the ‘lfbinding’ element. Note that in the ‘lfbinding’ element you should always wrap user-defined variables in brackets and add a leading dollar sign, e.g. *$(PathMaps)*. Since the names of the in- and output files are usually the same for each model run, the

use of user-defined variables greatly simplifies setting up the model for new catchments. In general, it is a good idea to use user-defined variables for *everything* that needs to be changed on a regular basis (paths to input maps, tables, meteorological data, parameter values). This way you only have to deal with the variables in the 'lfuser' element, without having to worry about anything in 'lfbinding' at all.

Now for a somewhat more realistic example:

```
<?xml version="1.0" encoding="UTF-8"?>
<!DOCTYPE lfsettings SYSTEM "lisflood.dtd">

<lfsettings>

<lfuser>

<comment>
*************************************************************
CALIBRATION PARAMETERS
*************************************************************
</comment>

<textvar name="UpperZoneTimeConstant" value="10">
<comment>
Time constant for water in upper zone [days*mm^GwAlpha]
</comment>
</textvar>

<comment>
*************************************************************
FILE PATHS
*************************************************************
</comment>

<textvar name="PathMeteo" value="//cllx01/floods2/knijfjo/test/meteo">
<comment>
Meteo path
</comment>
</textvar>

<comment>
*************************************************************
PREFIXES OF METEO VARIABLES
*************************************************************
</comment>

<textvar name="PrefixPrecipitation" value="pr">
<comment>
prefix precipitation maps
</comment>
</textvar>

</lfuser>


<lfoptions> </lfoptions>


<lfbinding>

<textvar name="UpperZoneTimeConstant" value="$(UpperZoneTimeConstant)">
<comment>
Time constant for water in upper zone [days*mm^GwAlpha]
</comment>
</textvar>

<textvar name="PrecipitationMaps" value="$(PathMeteo)/$(PrefixPrecipitation)">
<comment>
precipitation [mm/day]
</comment>
</textvar>

</lfbinding>

</lfsettings>
```

From this example, note that *anything* can be defined with 'lfuser' variables, whether it be paths, file prefixes or parameter value. At first sight it might seem odd to define model parameter like *UpperZoneTimeConstant* as a text variable when it is already

defined in the 'lfbinding' element. However, in practice it is much easier to have all the important variables defined in the same element: in total the model needs around 200 variables, parameters and file names. By specifying each of those in the 'lfbinding' element you need to specify each of them separately. Using the 'lfuser' variables this can be reduced to about 50, which greatly simplifies things. You should think of the 'lfbinding' element as a low-level way of describing the model in- and output structure: anything can be changed and any file can be in any given location, but the price to pay for this flexibility is that the definition of the input structure will take a lot of work. By using the 'lfuser' variables in a smart way, custom template settings files can be created for specific model applications (calibration, scenario modelling, operational flood forecasting). Typically, each of these applications requires its own input structure, and you can use the 'lfuser' variables to define this structure. Also, note that the both the *name* and *value* of each variable must be wrapped in (single or double) quotes. Dedicated XML-editors like XmlSpy take care of this automatically, so you won't usually have to worry about this.

NOTES:

1. It is important to remember that the *only* function of the 'lfuser' element is to *define* text variables; you can not *use* any of these text variables within the 'lfuser' element. For example, the following 'lfuser' element is *wrong* and *will not work*:

```
<lfuser>

<textvar name="PathInit"
value="//cllx01/floods2/knijfjo/test/init">
<comment>
Path to initial conditions maps
</comment>
</textvar>

<textvar name="LZInit" value="$(PathInit)/lzInit.map)">
<comment>
Initial lower zone storage
** USE OF USER VARIABLE WITHIN LFUSER
** IS NOT ALLOWED, SO THIS EXAMPLE WILL NOT WORK!!
</comment>
</textvar>

</lfuser>
```

2. It *is* possible to define *everything* directly in the 'lfbinding' element without using any text variables at all! In that case the 'lfuser' element can remain empty, even though it *has* to be present (i.e. <lfuser> </lfuser>). In general this is not recommended.
3. Within the *lfuser* and *lfbinding* elements, model variables are organised into *groups*. This is just to make navigation in an xml editor easier.

Variables in the lfbinding element

The variables that are defined in the 'lfbinding' element fall in either of the following categories:

1. Single map

Example:

```
<textvar name="LandUse" value="$(PathMaps)/landuse.map">
<comment>
Land Use Classes
</comment>
</textvar>
```

2. Table

Example:

```
<textvar name="TabKSat1" value="$(PathTables)/ksat1.txt">
<comment>
Saturated conductivity [cm/day]
</comment>
</textvar>
```

3. Stack of maps

Example:

```
<textvar name="PrecipitationMaps"
value="$(PathMeteo)/$(PrefixPrecipitation)">
<comment>
precipitation [mm/day]
</comment>
</textvar>
```

Note:

Taking -as an example- a prefix that equals "*pr*", the name of each map in the stack starts with "*pr*", and ends with the number of the time step. The name of each map is made up of a total of 11 characters: 8 characters, a dot and a 3-character suffix. For instance:

```
pr000000.007        : at time step 7
pr000035.260        : at time step 35260
```

To avoid unexpected behaviour, do **not** use numbers in the prefix! For example:

```
<textvar name="PrecipitationMaps"
value="$(PathMeteo)/pr10 ">
<comment>
precipitation [mm/day]
</comment>
</textvar>
```

For the first time step this yields the following file name:

```
pr100000.001
```

But this is actually interpreted as time step 100,000,001!

4. Time series file

Example:

```
<textvar name="DisTS" value="$(PathOut)/dis.tss">
<comment>
Reported discharge [cu m/s]
</comment>
</textvar>
```

5. **Single parameter value**

Example:

```
<textvar name="UpperZoneTimeConstant"
value="$(UpperZoneTimeConstant)">
<comment>
Time constant for water in upper zone [days]
</comment>
</textvar>
```

Variables in the lfuser element

As said before the variables in the 'lfuser' elements are all text variables, and they are used simply to substitute text in the 'lfbinding' element. In practice it is sometimes convenient to use the same name for a text variable that is defined in the 'lfuser' element and a 'lfbinding' variable. For example:

```
<lfuser>

<textvar name="UpperZoneTimeConstant" value="10">
<comment>
Time constant for water in upper zone [days]
</comment>
</textvar>

</lfuser>


<lfbinding>

<textvar name="UpperZoneTimeConstant" value="$(UpperZoneTimeConstant)">
<comment>
Time constant for water in upper zone [days]
</comment>
</textvar>

</lfbinding>
```

In this case 'UpperZoneTimeConstant' in the 'lfuser' element (just a text variable) is something different from 'UpperZoneTimeConstant' in the 'lfbinding' element!

lfoption element

The 'lfoption' element effectively allows you to switch certain parts of the model on or off. Within LISFLOOD, there are two categories of options:

1. Options to activate the reporting of additional output maps and time series (e.g. soil moisture maps)
2. Options that activate special LISFLOOD features, such as inflow hydrographs and the simulation of reservoirs

Viewing available options

You can view all options by running LISFLOOD with the *--listoptions* flag. For each option, the following information is listed:

```
OptionName Choices DefaultValue
```

'OptionName' -as you might have guessed already- simply is the name of the option. 'Choices' indicates the possible values of the option, and 'DefaultValue' describes the default behaviour. For instance, if you look at the reservoir option:

```
simulateReservoirs choices=(1,0) default=0
```

you see that the value of this option is either 0 (off) or 1 (on), and that the default value is 0 (off, i.e. do not simulate any reservoirs).

The information on the reporting options is a little bit different (and slightly confusing). Looking at the option for reporting discharge maps:

```
repDischargeMaps choices=(1) noDefault
```

By default, discharge maps are not reported, so you would expect something like "default=0". However, due to the way options are defined internally in the model, in this case we have no default value, which means it is switched off.[4] Report options that are switched *on* by default look like this:

```
repStateMaps choices=(1) default=1
```

To minimise the confusion, you should:

1. Ignore the "Choices" item
2. Interpret "noDefault" as "default=0"

This is all a bit confusing, and the displaying of option information may well change in future LISFLOOD versions.

Defining options

Within the 'lfoptions' element of the settings file, each option is defined using a 'setoption' element, which has the attributes 'name' and 'choice' (i.e. the actual value). For example:

```
<lfoptions>
<setoption choice="1" name="inflow" />
</lfoptions>
```

[4] The reason why *–listoptions* produces "default=0" for the reservoirs option, is that –internally within the model- the reservoir option consists of two blocks of code: one block is the actual reservoir code, and another one is some dummy code that is activated if the reservoirs option is switched off (the dummy code is needed because some internal model variables that are associated with reservoirs need to be defined, even if no reservoirs are simulated). Both blocks are associated with "*simulateReservoirs=1*" and "*simulateReservoirs=0*", respectively, where the "*simulateReservoirs=0*" block is marked as the default choice. In case of the "*repDischargeMaps*" option, there *is* no block of code that is associated with "*repDischargeMaps=0*", hence formally there is no default value.

You are not obliged to use any options: if you leave the ‘lfoptions’ element empty, LISFLOOD will simply run using the default values (i.e. run model without optional modules; only report most basic output files). However, the ‘lfoptions’ element itself (i.e. <lfoptions> </lfoptions>) *has* to be present, even if empty!

6. Preparing the settings file

This chapter describes how to prepare your own settings file. Instead of writing the settings file completely from scratch, we suggest to use the settings template that is provided with LISFLOOD as a starting point. In order to use the template, you should make sure the following requirements are met:

- All input maps and tables are named according to default file names (see Chapter 4)
- All base maps are in one directory
- All tables are in one directory
- All meteo input is in one directory
- All Leaf Area Index input is in one directory
- An (empty) directory where all model data can be written exists

If this is all true, the settings file can be prepared very quickly by editing the items in the 'lfuser' element. The following is a detailed description of the different sections of the 'lfuser' element. The present LISFLOOD version contains 24 process-related parameters (not taking into account the parameters that are defined through the base maps and lookup tables). These are all defined in the 'lfuser' element, and default values are given for each of them. Even though *any* of these parameters can be treated as calibration constants, doing so for *all* of them would lead to serious over-parameterisation problems. In the description of these parameters we will therefore provide some suggestions as to which parameters should be used for calibration, and which one are better left untouched.

Time-related constants

The 'lfuser' section starts with a number of constants that are related to the simulation period and the time interval used. These are all defined as single values.

```
<comment>
************************************************************
TIME-RELATED CONSTANTS
************************************************************
</comment>

<textvar name="DtSec" value="86400">
<comment>
timestep [seconds]
</comment>
</textvar>

<textvar name="DtSecChannel" value="86400">
<comment>
Sub time step used for kinematic wave channel routing [seconds]
Within the model,the smallest out of DtSecChannel and DtSec is used
</comment>
</textvar>

<textvar name="StepStart" value="1">
<comment>
Number of first time step in simulation
</comment>
</textvar>

<textvar name="StepEnd" value="10">
<comment>
Number of last time step in simulation
</comment>
</textvar>

<textvar name="ReportSteps" value="endtime">
<comment>
Time steps at which to write model state maps (i.e. only
those maps that would be needed to define initial conditions
for succeeding model run)
</comment>
</textvar>
```

DtSec is the simulation time interval in seconds. It has a value of 86400 for a daily time interval, 3600 for an hourly interval, etcetera

DtSecChannel is the simulation time interval used by the kinematic wave channel routing (in seconds). Using a value that is smaller than *DtSec* may result in a better simulation of the overall shape the calculated hydrograph (at the expense of requiring more computing time)

StepStart is the number of the first time step in your simulation. It is normally set to 1. Other (larger) values can be used if you want to run LISFLOOD for only a part of the time period for which you have meteo and LAI maps.

StepEnd is the number of the last time step in your simulation.

ReportSteps defines the time step number(s) at which the model state (i.e. all maps that you would need to define the initial conditions of a succeeding model run) is written. You can define this parameter as a (comma separated) list of time steps. For example:

```
<textvar name="ReportSteps" value="10,20,40">
```

will result in state maps being written at time steps 10, 20 and 40. For the *last* time step of a model run you can use the special ‘endtime’ keyword, e.g.:

```
<textvar name="ReportSteps" value="endtime">
```

Alternatively, in some cases you may need the state maps at regular intervals. In that case you can use the following syntax:

```
<textvar name="ReportSteps" value="start+increment..end">
```

For instance, in the following example state maps are written every 5th time step, starting at time step 10, until the last time step:

```
<textvar name="ReportSteps" value="10+5..endtime">
```

Parameters related to evapo(transpi)ration and interception

The following parameters are all related to the simulation of evapo(transpi)ration and rainfall interception. Although they can all be defined as either a single value or as a map, we recommend using the single values that are included in the template. We do not recommend using any of these parameters as calibration constants.

```
<comment>
************************************************************
PARAMETERS RELATED TO EVAPO(TRANSPI)RATION AND INTERCEPTION
************************************************************
</comment>

<textvar name="CalEvaporation" value="1">
<comment>
Multiplier applied to potential evapo(transpi)ration rates
</comment>
</textvar>

<textvar name="LeafDrainageTimeConstant" value="1">
<comment>
Time constant for water in interception store [days]
</comment>
</textvar>

<textvar name="kdf" value="0.72">
<comment>
Average extinction coefficient for the diffuse radiation flux
varies with crop from 0.4 to 1.1 (Goudriaan (1977))
</comment>
</textvar>

<textvar name="AvWaterRateThreshold" value="5">
<comment>
Critical amount of available water (expressed in [mm/day]!), above which 'Days Since
Last Rain' parameter is set to 1
</comment>
</textvar>
```

CalEvaporation is a multiplier that is applied to the potential evapo(transpi)ration input (*ET0*, *EW0* and *ES0*) [-]

LeafDrainageTimeConstant (T_{int} in Eq 2-11) is the time constant for the interception store [days]

kdf is the average extinction for the diffuse radiation flux (Goudriaan, 1977). it is used to calculate the extinction coefficient for global radiation, κ_{gb} ,which is used in Equations 2-9, 2-14 and 2-19 [-]

AvWaterRateThreshold defines a critical amount of water that is used as a threshold for resetting the variable D_{slr} in Eq 2-20. Because the equation was

originally developed for daily timesteps only, the threshold is currently defined (somewhat confusingly) as an equivalent *intensity* in [mm day^{-1}]

Parameters related to snow and frost

The following parameters are all related to the simulation of snow accumulation, snowmelt and frost. All these parameters can be defined as either single values or maps. We recommend to start out by leaving them all at their default values. If prior data suggest major under- or overcatch problems in the observed snowfall, *SnowFactor* can be adjusted accordingly. *SnowMeltCoef* may be used as a calibration constant, but since snow observations are typically associated with large uncertainty bands, the calibration may effectively just be compensating for these input errors.

```
<comment>
************************************************************
SNOW AND FROST RELATED PARAMETERS
************************************************************
</comment>

<textvar name="SnowFactor" value="1">
<comment>
Multiplier applied to precipitation that falls as snow
</comment>
</textvar>

<textvar name="SnowMeltCoef" value="4.5">
<comment>
Snowmelt coefficient [mm/deg C /day]
See also Martinec et al., 1998.
</comment>
</textvar>

<textvar name="TempMelt" value="0.0">
<comment>
Average temperature at which snow melts
</comment>
</textvar>

<textvar name="TempSnow" value="1.0">
<comment>
Average temperature below which precipitation is snow
</comment>
</textvar>

<textvar name="TemperatureLapseRate" value="0.0065">
<comment>
Temperature lapse rate with altitude [deg C / m]
</comment>
</textvar>

<textvar name="Afrost" value="0.97">
<comment>
Daily decay coefficient, (Handbook of Hydrology, p. 7.28)
</comment>
</textvar>

<textvar name="Kfrost" value="0.57">
<comment>
Snow depth reduction coefficient, [cm-1], (HH, p. 7.28)
</comment>
</textvar>

<textvar name="SnowWaterEquivalent" value="0.45">
<comment>
Snow water equivalent, (based on snow density of 450 kg/m3) (e.g. Tarboton and Luce,
1996)
</comment>
</textvar>

<textvar name="FrostIndexThreshold" value="56">
<comment>
Degree Days Frost Threshold (stops infiltration, percolation and capillary rise)
Molnau and Bissel found a value 56-85 for NW USA.
</comment>
</textvar>
```

SnowFactor is a multiplier that is applied to the rate of precipitation in case the precipitation falls as snow. Since snow is commonly underestimated in meteorological observation data, setting this multiplier to some value greater than 1 can counteract for this [-]

SnowMeltCoef (C_m in Eq 2-3) is the degree-day factor that controls the rate of snowmelt [mm °C^{-1} day^{-1}]

TempMelt (T_m in Eq 2-3) is the average temperature above which snow starts to melt [°C]

TempSnow is the average temperature below which precipitation is assumed to be snow [°C]

TemperatureLapseRate (*L* in Figure 2.2) is the temperature lapse rate that is used to estimate average temperature at the centroid of each pixel's elevation zones [°C m^{-1}]

Afrost (*A* in Eq 2-4) is the frost index decay coefficient [day^{-1}]. It has a value in the range 0-1.

Kfrost (*K* in Eq 2-4) is a snow depth reduction coefficient [cm^{-1}]

SnowWaterEquivalent (we_s in Eq 2-4) is the equivalent water depth of a given snow cover, expressed as a fraction [-]

FrostIndexThreshold is the critical value of the frost index (Eq 2-5) above which the soil is considered frozen [°C day^{-1}]

Infiltration parameters

The following two parameters control the simulation of infiltration and preferential flow. Both are empirical parameters that are treated as calibration constants, and both can be defined as single values or maps.

```
<comment>
************************************************************
INFILTRATION PARAMETERS
************************************************************
</comment>

<textvar name="b_Xinanjiang" value="0.1">
<comment>
Power in Xinanjiang distribution function
</comment>
</textvar>

<textvar name="PowerPrefFlow" value="3">
<comment>
Power that controls increase of proportion of preferential
flow with increased soil moisture storage
</comment>
</textvar>
```

b_Xinanjiang (*b* in Eq 2-23) is the power in the infiltration equation [-]

PowerPrefFlow (c_{pref} in Eq 2-25) is the power in the preferential flow equation [-]

Groundwater parameters

The following parameters control the simulation shallow and deeper groundwater. *GwLossFraction* should be kept at 0 unless prior information clearly indicates that groundwater is lost beyond the catchment boundaries (or to deep groundwater systems). The other parameters are treated as calibration constants. All these parameters can be defined as single values or maps.

```
<comment>
************************************************************
GROUNDWATER RELATED PARAMETERS
************************************************************
</comment>

<textvar name="UpperZoneTimeConstant" value="10">
<comment>
Time constant for water in upper zone [days]
</comment>
</textvar>

<textvar name="LowerZoneTimeConstant" value="1000">
<comment>
Time constant for water in lower zone [days]
This is the average time a water 'particle' remains in the reservoir
if we had a stationary system (average inflow=average outflow)
</comment>
</textvar>

<textvar name="GwPercValue" value="0.5">
<comment>
Maximum rate of percolation going from the Upper to the Lower
response box [mm/day]
</comment>
</textvar>

<textvar name="GwLossFraction" value="0">
<comment>
Maximum loss rate out of Lower response box, expressed as a fraction of
lower zone outflow. Fraction [-], range 0-1
A value of 0 (closed lower boundary) is recommended as a starting value
</comment>
</textvar>
```

UpperZoneTimeConstant (T_{uz} in Eq 2-42) is the time constant for the upper groundwater zone [days]

LowerZoneTimeConstant (T_{lz} in Eq 2-43) is the time constant for the lower groundwater zone [days]

GwPercValue (GW_{perc} in Eq 2-44) is the maximum rate of percolation going from the upper to the lower groundwater zone [mm day^{-1}]

GwLossFraction (f_{loss} in Eq 2-45) is the rate of flow out of the lower groundwater zone, expressed as a fraction [-] of the total outflow. Hence, the value of *GwLossFraction* is always between 0 and 1

Routing parameters

These parameters are all related to the routing of water in the channels as well as the routing of surface runoff. The multiplier *CalChanMan* can be used to fine-tune the timing of the channel routing, and it may be defined as either a single value or a map. All other parameters should be kept at their default values.

```
<comment>
************************************************************
ROUTING PARAMETERS
************************************************************
</comment>

<textvar name="CalChanMan" value="1">
<comment>
Multiplier applied to Channel Manning's n
</comment>
</textvar>

<textvar name="beta" value="0.6">
<comment>
kinematic wave parameter: 0.6 is for broad sheet flow
</comment>
</textvar>

<textvar name="OFDepRef" value="5">
<comment>
Reference depth of overland flow [mm], used to compute
overland flow Alpha for kin. wave
</comment>
</textvar>

<textvar name="GradMin" value="0.001">
<comment>
Minimum slope gradient (for kin. wave: slope cannot be 0)
</comment>
</textvar>

<textvar name="ChanGradMin" value="0.0001">
<comment>
Minimum channel gradient (for kin. wave: slope cannot be 0)
</comment>
</textvar>
```

CalChanMan is a multiplier that is applied to the Manning's roughness maps of the channel system [-]

beta is routing coefficient β_k in Equations 2-51, 2-52, 2-54 and 2-57 [-]

OFDepRef is a reference flow depth from which the flow velocity of the surface runoff is calculated [mm]

GradMin is a lower limit for the slope gradient used in the calculation of the surface runoff flow velocity [m m^{-1}]

ChanGradMin is a lower limit for the channel gradient used in the calculation of the channel flow velocity [m m^{-1}]

Parameters related to numerics

This category only contains one parameter at the moment, which can only be a single value. We strongly recommend keeping this parameter at its default value.

```
<comment>
************************************************************
PARAMETERS RELATED TO NUMERICS
************************************************************
</comment>

<textvar name="CourantCrit" value="0.4">
<comment>
Minimum value for Courant condition in soil moisture routine
</comment>
</textvar>
```

CourantCrit (C_{crit} in Eq 2-36) is the critical Courant number which controls the numerical accuracy of the simulated soil moisture fluxes [-]. Any value between 0 and 1 can be used, but using values that are too high can lead to unrealistic "jumps" in the simulated soil moisture, whereas very low values result in reduced computational performance (because many iterations will be necessary to obtain the required accuracy). Values above 1 should never be used, as they will result in a loss of mass balance. In most cases the default value of 0.4 results in sufficiently realistic simulations using just a few iterations.

File paths

Here you can specify where all the input files are located, and where output should be written. Note that you can use both forward and backward slashes on both Windows and Linux-based systems without any problem (when LISFLOOD reads the settings file it automatically formats these paths according to the conventions used by the operating system used). The default settings template contains relative paths, which in most cases allows you to run the model directly without changing these settings (assuming that you execute LISFLOOD from the root directory of your catchment).

```
<comment>
************************************************************
FILE PATHS
************************************************************
</comment>

<textvar name="PathOut" value="./out">
<comment>
Output path
</comment>
</textvar>

<textvar name="PathMaps" value="./maps">
<comment>
Maps path
</comment>
</textvar>

<textvar name="PathTables" value="./tables">
<comment>
Tables path
</comment>
</textvar>

<textvar name="PathMeteo" value="./meteo">
<comment>
Meteo path
</comment>
</textvar>

<textvar name="PathLAI" value="./lai">
<comment>
Leaf Area Index maps path
</comment>
</textvar>
```

PathOut is the directory where all output files are written. It must be an existing directory (if not you will get an error message)

PathMaps is the directory where all input base maps are located

PathTables is the directory where all input tables are located

PathMeteo is the directory where all maps with meteorological input are located (rain, evapo(transpi)ration, temperature)

PathLAI is the directory where you Leaf Area Index maps are located

Prefixes of meteo and vegetation related variables

Here you can define the prefix that is used for each meteorological variable (and LAI).

```
<comment>
************************************************************
PREFIXES OF METEO AND VEGETATION RELATED VARIABLES
************************************************************
</comment>

<textvar name="PrefixPrecipitation" value="pr">
<comment>
prefix precipitation maps
</comment>
</textvar>

<textvar name="PrefixTavg" value="ta">
<comment>
prefix average temperature maps
</comment>
</textvar>

<textvar name="PrefixE0" value="e">
<comment>
prefix E0 maps
</comment>
</textvar>

<textvar name="PrefixES0" value="es">
<comment>
prefix ES0 maps
</comment>
</textvar>

<textvar name="PrefixET0" value="et">
<comment>
prefix ET0 maps
</comment>
</textvar>

<textvar name="PrefixLAI" value="lai">
<comment>
prefix LAI maps
</comment>
</textvar>
```

Each variable is read as a stack of maps. The name of each map starts with prefix, and ends with the number of the time step. All characters in between are filled with zeroes. The name of each map is made up of a total of 11 characters: 8 characters, a dot and a 3-character suffix. For instance, using a prefix ‘pr’ we get:

```
pr000000.007      : at time step 7
pr000035.260      : at time step 35260
```

To avoid unexpected behaviour, **never** use numbers in the prefix! For example:

```
PrefixRain=pr10
```

For the first time step this yields the following file name:

```
pr100000.001
```

But this is actually interpreted as time step 100,000,001! **Therefore, do not use numbers in the prefix!**

The corresponding part of the settings file is pretty self-explanatory:

PrefixPrecipitation is the prefix of the precipitation maps

PrefixTavg is the prefix of the daily average temperature maps

PrefixE0 is the prefix of the potential open-water evaporation maps

PrefixES0 is the prefix of the potential bare-soil evaporation maps

PrefixET0 is the prefix of the potential (reference) evapotranspiration maps

PrefixLAI is the prefix of the Leaf Area Index maps

Initial conditions

As with the calibration parameters you can use both maps and single values to define the catchment conditions at the start of a simulation. Note that a couple of variables can be initialized internally in the model (explained below). Also, be aware that the initial conditions define the state of the model at *t=(StepStart -1)*. As long as *StepStart* equals 1 this corresponds to *t=0*, but for larger values of *StepStart* this is (obviously) not the case!

```
<group>

<comment>
************************************************************
INITIAL CONDITIONS
(maps or single values)
************************************************************
</comment>

<textvar name="WaterDepthInitValue" value="0">
<comment>
initial overland flow water depth [mm]
</comment>
</textvar>

<textvar name="SnowCoverAInitValue" value="0">
<comment>
initial snow depth in snow zone A [mm]
</comment>
</textvar>

<textvar name="SnowCoverBInitValue" value="0">
<comment>
initial snow depth in snow zone B [mm]
</comment>
</textvar>

<textvar name="SnowCoverCInitValue" value="0">
<comment>
initial snow depth in snow zone C [mm]
</comment>
</textvar>

<textvar name="FrostIndexInitValue" value="0">
<comment>
initial Frost Index value
</comment>
</textvar>
```

```
<textvar name="CumIntInitValue" value="0">
<comment>
cumulative interception [mm]
</comment>
</textvar>

<textvar name="UZInitValue" value="0">
<comment>
water in upper store [mm]
</comment>
</textvar>

<textvar name="DSLRInitValue" value="1">
<comment>
days since last rainfall
</comment>
</textvar>

</group>

<group>

<comment>
************************************************************
The following variables can also be initialized in the model
internally. if you want this to happen set them to bogus value
of -9999
************************************************************
</comment>

<textvar name="LZInitValue" value="-9999">
<comment>
water in lower store [mm]
-9999: use steady-state storage
</comment>
</textvar>

<textvar name="TotalCrossSectionAreaInitValue" value="-9999">
<comment>
initial cross-sectional area of flow in channel[m2]
-9999: use half bankfull
</comment>
</textvar>

<textvar name="ThetaInit1Value" value="-9999">
<comment>
initial soil moisture content layer 1
-9999: use field capacity values
</comment>
</textvar>

<textvar name="ThetaInit2Value" value="-9999">
<comment>
initial soil moisture content layer 2
-9999: use field capacity values
</comment>
</textvar>

<textvar name="LZAvInflowEstimate" value="1000">
<comment>
Estimated average inflow [mm/day] into lower groundwater zone
Used to calculated steady-state initial lower zone storage
Use very high value (e.g. 1000) if you don't have any estimate
(in that case steady-state storage bazed on GwPercValue, although
this may give some initialisation problems)
This parameter ONLY affects the simulation results if
LZInitValue is set to -9999 !!
Initialisation speedup parameter, not a calibration parameter!
</comment>
</textvar>
</group>
```

WaterDepthInitValue is the initial amount of water on the soil surface [mm]

SnowCoverInitAValue is the initial snow cover on the soil surface in elevation zone *A* [mm]

SnowCoverInitBValue is the initial snow cover on the soil surface in elevation zone *B* [mm]

SnowCoverInitCValue is the initial snow cover on the soil surface in elevation zone *C* [mm]

FrostIndexInitValue (*F* in Eq 2-5) is the initial value of the frost index [°C day^{-1}]

CumIntInitValue is the initial interception storage [mm]

UZInitValue is the initial storage in the upper groundwater zone [mm]

DSLRInitValue (D_{slr} in Eq 2-20) is the initial number of days since the last rainfall event [days]

LZInitValue is the initial storage in the lower groundwater zone [mm]. In order to avoid initialization problems it is possible to let the model calculate a 'steady state' storage that will usually minimize any initialization problems. This feature is described in detail in Chapter 7 of this User Manual. To activate it, simply set *LZInitValue* to *-9999*.

TotalCrossSectionAreaInitValue is the initial cross-sectional area [m^2] of the water in the river channels (a substitute for initial discharge, which is directly dependent on this). A value of *-9999* sets the initial amount of water in the channel to half bankfull.

ThetaInit1Value is the initial moisture content [mm^3 mm^{-3}] of the upper soil layer. A value of *-9999* will set the initial soil moisture content to field capacity.

ThetaInit2Value is the initial moisture content [mm^3 mm^{-3}] of the lower soil layer. A value of *-9999* will set the initial soil moisture content to field capacity

LZAvInflowEstimate is an estimate of the average rate [mm day^{-1}] at which water flows into the lower groundwater zone. This can be used to speed up the initialisation of the lower zone. LISFLOOD's 'repLZAvInflowMap' option produces a map that can be used for optimized values of *LZAvInflowEstimate* at each pixel. For more details about this feature please have a look at Chapter 7 of this User Manual.

Running the model

To run the model, start up a command prompt (Windows) or a console window (Linux) and type 'lisflood' followed by the name of the settings file, e.g.:

```
lisflood settings.xml
```

If everything goes well you should see something like this:

```
  LISFLOOD version October 3 2007
  Water balance and flood simulation model for large catchments

     (C) Institute for Environment and Sustainability
         Joint Research Centre of the European Commission
         TP261, I-21020 Ispra (Va), Italy

Created:  X:\test\txlGsbMlbr.tmp
pcrcalc version: Oct 3 2007 (win32)

Executing timestep 1
```

Using options

As explained in Chapter 5, the 'lfoptions' element gives you additional control over what LISFLOOD is doing. Using options it is possible to switch certain parts of the model on or off. This way you can tell the model exactly which output files are reported and which ones aren't. Also, they can be used to activate a number of additional model features, such as the simulation of reservoirs and inflow hydrographs.

The table below lists all currently implemented options and their corresponding defaults. All currently implemented options are switches (1= on, 0=off). You can set as many options as you want (or none at all). Table 6.1 lists all currently implemented options[5]. Note that each option generally requires additional items in the settings file. For instance, using the inflow hydrograph option requires an input map and time series, which have to be specified in the settings file. If you want to report discharge maps at each time step, you will first have to specify under which name they will be written. The template settings file that is provided with LISFLOOD always contains file definitions for all optional output maps and time series. The use of the *output* options is described in detail in Chapter 8.

[5] Actually, the –listoptions switch will show you a couple of options that are not listed in Table 6.1. These are either debugging options (which are irrelevant to the model user) or experimental features that may not be completely finalised (and thus remain undocumented here until they are)

Table 6.1 *LISFLOOD options (continued on next page)*

SIMULATION OPTIONS		
Option	**Description**	**Default**
gridSizeUserDefined	Get grid size attributes (length, area) from user-defined maps (instead of using map location attributes directly)	0
simulateReservoirs	Simulate retention and hydropower reservoirs (kin. wave only)	0
simulateLakes	Simulate unregulated lakes (kin. wave only)	0
simulatePolders	Simulate flood protection polders (dyn. wave only)	0
inflow	Use inflow hydrographs	0
dynamicWave	Perform dynamic wave channel routing	0
simulateWaterLevels	Simulate water levels in channel	0
OUTPUT, TIME SERIES		
Option	**Description**	**Default**
repDischargeTs	Report timeseries of discharge at gauge locations	1
repWaterLevelTs	Report timeseries of water level at gauge locations[6]	0
repStateSites	Report timeseries of all intermediate state variables at 'sites'	0
repRateSites	Report timeseries of all intermediate rate variables at 'sites'	0
repMeteoUpsGauges	Report timeseries of meteorological input, averaged over contributing area of each gauging station	0
repStateUpsGauges	Report timeseries of model state variables, averaged over contributing area of each gauging station	0
repRateUpsGauges	Report timeseries of model rate variables, averaged over contributing area of each gauging station	0
OUTPUT, MASS BALANCE		
Option	**Description**	**Default**
repMBTs	Report timeseries of absolute cumulative mass balance error	1
repMBMMTs	Report timeseries of cumulative mass balance error expressed as mm water slice	1

[6] This option can only be used in combination with the 'simulateWaterLevels' option!

Table 6.1 *LISFLOOD options (continued from previous page)*

OUTPUT, MAPS, DISCHARGE		
Option	**Description**	**Default**
repDischargeMaps	Report maps of discharge (for each time step)	0
repWaterLevelMaps[7]	Report maps of water level in channel (for each time step)	0
OUTPUT, MAPS, STATE VARIABLES (all, at selected time steps)		
Option	**Description**	**Default**
repStateMaps	Report maps of model state variables (as defined by "ReportSteps" variable)	1
repEndMaps[8]	Report maps of model state variables (at last time step)	0
OUTPUT, MAPS, STATE VARIABLES		
Option	**Description**	**Default**
repDSLRMaps	Report maps of days since last rain (for each time step)	0
repFrostIndexMaps	Report maps of frost index (for each time step)	0
repWaterDepthMaps	Report maps of depth of water layer on soil surface (for each time step)	0
repSnowCoverMaps	Report maps of snow cover (for each time step)	0
repCumInterceptionMaps	Report maps of interception storage (for each time step)	0
repTheta1Maps	Report maps of soil moisture layer 1(for each time step)	0
repTheta2Maps	Report maps of soil moisture layer 2 (for each time step)	0
repUZMaps	Report maps of upper zone storage (for each time step)	0
repLZMaps	Report maps of lower zone storage (for each time step)	0
repChanCrossSection Maps	Report maps of channel cross-sectional area (for each time step)	0
OUTPUT, MAPS, METEOROLOGICAL FORCING VARIABLES		
Option	**Description**	**Default**
repPrecipitationMaps	Report maps of precipitation (for each time step)	0
repTavgMaps	Report maps of average temperature (for each time step)	0
repETRefMaps	Report maps of potential reference evapotranspiration (for each time step)	0
repESRefMaps	Report maps of potential soil evaporation (for each time step)	0
repEWRefMaps	Report maps of potential open water evaporation (for each time step)	0

[7] This option can only be used in combination with the 'simulateWaterLevels' option!

[8] Deprecated; this feature may not be supported in forthcoming LISFLOOD releases. Use *repStateMaps* instead, which gives you the same maps with the added possibility to report them for any required time step(s).

Table 6.1 *LISFLOOD options (continued from previous page)*

OUTPUT, MAPS, RATE VARIABLES		
Option	**Description**	**Default**
repRainMaps	Report maps of rain (excluding snow!) (for each time step)	0
repSnowMaps	Report maps of snow (for each time step)	0
repSnowMeltMaps	Report maps of snowmelt (for each time step)	0
repInterceptionMaps	Report maps of interception (for each time step)	0
repLeafDrainageMaps	Report maps of leaf drainage (for each time step)	0
repTaMaps	Report maps of actual transpiration (for each time step)	0
repESActMaps	Report maps of actual soil evaporation (for each time step)	0
repEWIntMaps	Report maps of actual evaporation of intercepted water (for each time step)	0
repInfiltrationMaps	Report maps of infiltration (for each time step)	0
repPrefFlowMaps	Report maps of preferential flow (for each time step)	0
repPercolationMaps	Report maps of percolation from upper to lower soil layer (for each time step)	0
repSeepSubToGWMaps	Report maps of seepage from lower soil layer to ground water (for each time step)	0
repGwPercUZLZMaps	Report maps of percolation from upper to lower ground water zone (for each time step)	0
repGwLossMaps	Report maps of loss from lower ground water zone (for each time step)	0
repSurfaceRunoffMaps	Report maps of surface runoff (for each time step)	0
repUZOutflowMaps	Report maps of upper zone outflow (for each time step)	0
repLZOutflowMaps	Report maps of lower zone outflow (for each time step)	0
repTotalRunoffMaps	Report maps of total runoff (surface + upper + lower zone) (for each time step)	0
OUTPUT, MAPS (MISCELLANEOUS)		
Option	**Description**	**Default**
repLZAvInflowMap	Report computed average inflow rate into lower zone (map, at last time step)	0
repLZAvInflowSites	Report computed average inflow rate into lower zone (time series, at points defined on sites map)	0
repLZAvInflowUpsGauges	Report computed average inflow rate into lower zone (time series, averaged over upstream area of each gauge location)	0

7. Initialisation of LISFLOOD

Introduction

Just as any other hydrological model, LISFLOOD needs to have some estimate of the initial state (i.e. amount of water stored) of its internal state variables. Two situations can occur:

1. The initial state of all state variables is known (for example, the “end maps” of a daily water balance run are used to define the initial conditions of an hourly flood-event run)
2. The initial state of all state variables is unknown

The second situation is the most common one, and this chapter presents an in-depth look at the initialisation of LISFLOOD. First the effect of the model’s initial state on the results of a simulation is demonstrated using a simple example. Then, LISFLOOD’s various initialisation options are discussed. Most of this chspter focuses on the initialisation of the lower groundwater zone, as this is the model storage component that is the most difficult to in initialise.

An example

To better understand the impact of the initial model state on simulation results, let’s start with a simple example. Figure 7.1 shows 3 LISFLOOD simulations of soil moisture for the upper soil layer. In the first simulation, it was assumed that the soil is initially completely saturated. In the second one, the soil was assumed to be completely dry (i.e. at residual moisture content). Finally, a third simulation was done where the initial soil moisture content was assumed to be in between these two extremes.

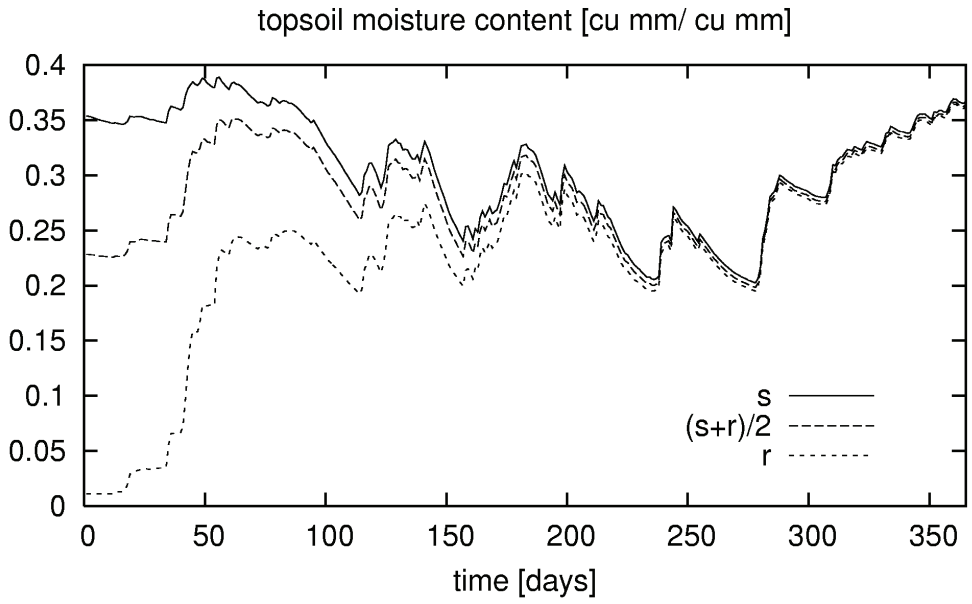


Figure 7.1 *Simulation of soil moisture in upper soil layer for a soil that is initially at saturation (s), at residual moisture content (r) and in between ([s+r]/2)*

What is clear from the Figure is that the initial amount of moisture in the soil only has a marked effect on the start of each simulation; after a couple of months the three curves converge. In other words, the "memory" of the upper soil layer only goes back a couple of months (or, more precisely, for time lags of more than about 8 months the autocorrelation in time is negligible).

In theory, this behaviour provides a convenient and simple way to initialise a model such as LISFLOOD. Suppose we want to do a simulation of the year 1995. We obviously don't know the state of the soil at the beginning of that year. However, we can get around this by starting the simulation a bit earlier than 1995, say one year. In that case we use the year 1994 as a *warm-up* period, assuming that by the start of 1995 the influence of the initial conditions (i.e. 1-1-1994) is negligible. The very same technique can be applied to initialise LISFLOOD's other state variables, such as the amounts of water in the lower soil layer, the upper groundwater zone, the lower groundwater zone, and in the channel.

Setting up a LISFLOOD run with warm-up period

When setting up a model run that includes a warm-up period, most of the internal state variables can be simply set to 0 at the start of the run. This applies to the initial amount of water on the soil surface (*WaterDepthInitValue*), snow cover (*SnowCoverInitValue*), frost index (*FrostIndexInitValue*), interception storage (*CumIntInitValue*), and storage in the upper groundwater zone (*UZInitValue*). The initial value of the 'days since last rainfall event' (*DSLRInitValue*) is typically set to 1.

For the remaining state variables, initialisation is somewhat less straightforward. The amount of water in the channel (defined by *TotalCrossSectionAreaInitValue*) is highly spatially variable (and limited by the channel geometry). The amount of water that can be stored in the upper and lower soil layers (*ThetaInit1Value*, *ThetaInit2Value*) is limited by the soil's porosity. The lower groundwater zone poses special problems because of its overall slow response (discussed in a separate section below). Because of this, LISFLOOD provides the possibility to initialise these variables internally, and these special initialisation methods can be activated by setting the initial values of each of these variables to a special 'bogus' value of *-9999*. Table 7.1 summarises these special initialisation methods:

Table 7.1 *LISFLOOD special initialisation methods**

Variable	**Description**	**Initialisation method**
ThetaInit1Value	initial soil moisture content upper soil layer (V/V)	set to soil moisture content at field capacity
ThetaInit2Value	initial soil moisture content lower soil layer (V/V)	set to soil moisture content at field capacity
LZInitValue	initial water in lower groundwater zone (mm)	set to steady-state storage
TotalCrossSectionAreaInitValue	initial cross-sectional area of water in channels	set to half of bankfull depth

**) These special initialisation methods are activated by setting the value of each respective variable to a 'bogus' value of "-9999"*

Note that the "-9999" 'bogus' value can *only* be used with the variables in Table 7.1; for all other variables they will produce nonsense results! The initialisation of the lower groundwater zone will be discussed in the next sections.

Initialisation of the lower groundwater zone

Even though the use of a sufficiently long warm-up period usually results in a correct initialisation, a complicating factor is that the time needed to initialise any storage component of the model is dependent on the average residence time of the water in it. For example, the moisture content of the upper soil layer tends to respond almost instantly to LISFLOOD's meteorological forcing variables (precipitation, evapo(transpi)ration). As a result, relatively short warm-up periods are sufficient to initialise this storage component. At the other extreme, the response of the lower groundwater zone is generally very slow (especially for large values of T_{lz}). Consequently, to avoid unrealistic trends in the simulations, very long warm-up periods may be needed. Figure 7.2 shows a typical example for an 8-year simulation, in which a decreasing trend in the lower groundwater zone is visible throughout the whole simulation period. Because the amount of water in the lower zone is directly proportional to the baseflow in the channel, this will obviously lead to an unrealistic long-term simulation of baseflow. Assuming the long-term climatic input is more or less constant, the baseflow (and thus the storage in the lower zone) should be free of any long-term trends (although some seasonal variation is normal). In order to avoid the need for excessive warm-up periods, LISFLOOD is capable of calculating a 'steady-state' storage amount for the lower groundwater zone. This *steady state* storage is very effective for reducing the lower zone's warm-up time. In the next sections the concept of *steady state* is first explained, and it is shown how it can be used to speed up the initialisation of a LISFLOOD run.

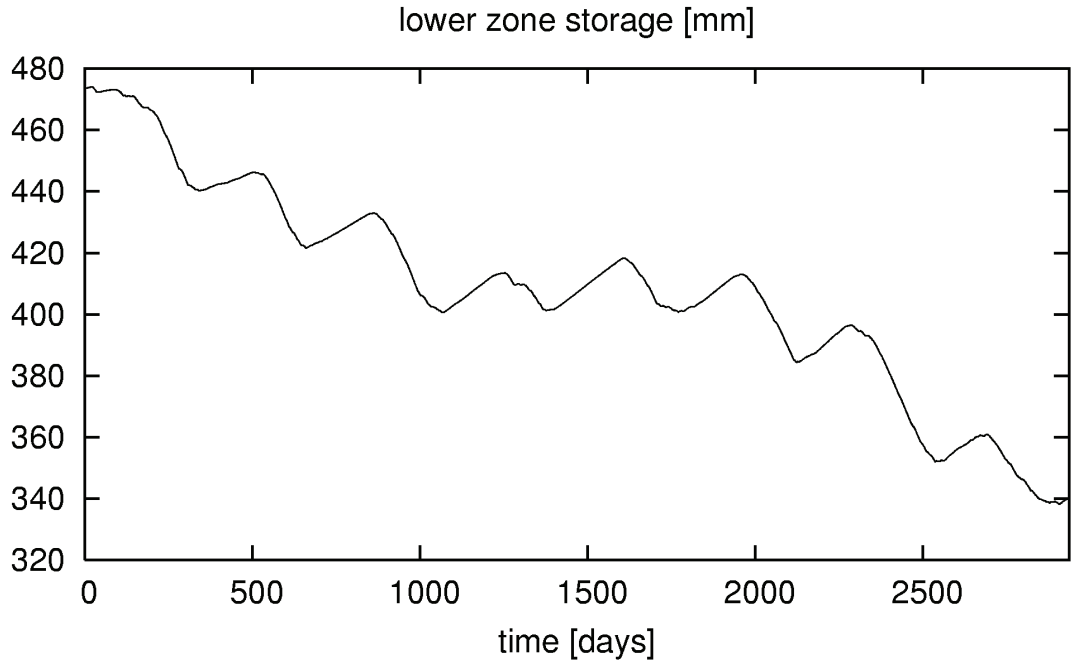


Figure 7.2 *8-year simulation of lower zone storage. Note how the influence of the initial storage persists throughout the simulation period.*

Lower groundwater zone: steady state storage

The response of the lower groundwater zone is defined by two simple equations. First, we have the inflow into the lower zone, which occurs at the following rate [mm day^{-1}]:

$$D_{uz,lz} = \min(GW_{perc}, UZ / \Delta t) \quad (7\text{-}1)$$

Here, GW_{perc} [mm day^{-1}] is a user-defined value (calibration constant), and *UZ* is the amount of water available in the upper groundwater zone [mm]. The rate of flow out of the lower zone [mm day^{-1}] equals:

$$Q_{lz} = \frac{1}{\mathrm{T}_{\mathrm{lz}}} \cdot LZ \quad (7\text{-}2)$$

where T_{lz} is a reservoir constant [days], and *LZ* is the amount of water that is stored in the lower zone [mm].

Now, let's do a simple numerical experiment: assuming that $D_{uz,lz}$ is a constant value, we can take some arbitrary initial value for *LZ* and then simulate (e.g. in a spreadsheet) the development over *LZ* over time. Figure 7.3 shows the results of 2 such experiments. In the upper Figure, we start with a very high initial storage (1500 mm). The inflow rate is fairly small (0.2 mm/day), and T_{lz} is quite small as well (which means a relatively short residence time of the water in the lower zone). What is interesting here is that, over time, the storage evolves asymptotically towards a constant state. In the lower Figure, we start with a much smaller initial storage (50 mm), but the inflow rate is much higher here (1.5 mm/day) and so is T_{lz} (1000 days). Here we see an upward trend, again towards a constant value. However, in this case the constant 'end' value is not reached within the simulation period, which is mainly because T_{lz} is set to a value for which the response is very slow.

At this point it should be clear that what you see in these graphs is exactly the same behaviour that is also apparent in the 'real' LISFLOOD simulation in Figure 7.2. Being able to know the 'end' storages in Figure 7.3 in advance would be very helpful, because it would eliminate any trends. As it happens, this can be done very easily from the model equations. A storage that is constant over time means that the in- and outflow terms balance each other out. This is known as a *steady state* situation, and the constant 'end' storage is in fact the *steady state storage*. The rate of change of the lower zone's storage at any moment is given by the continuity equation:

$$\frac{dLZ}{dt} = I(t) - O(t) \quad (7\text{-}3)$$

where *I* is the (time dependent) inflow (i.e. groundwater recharge) and *O* is the outflow rate. For a situation where the storage remains constant, we can write:

$$\frac{dLZ}{dt} = 0 \quad \Leftrightarrow \quad I(t) - O(t) = 0 \quad (7\text{-}4)$$

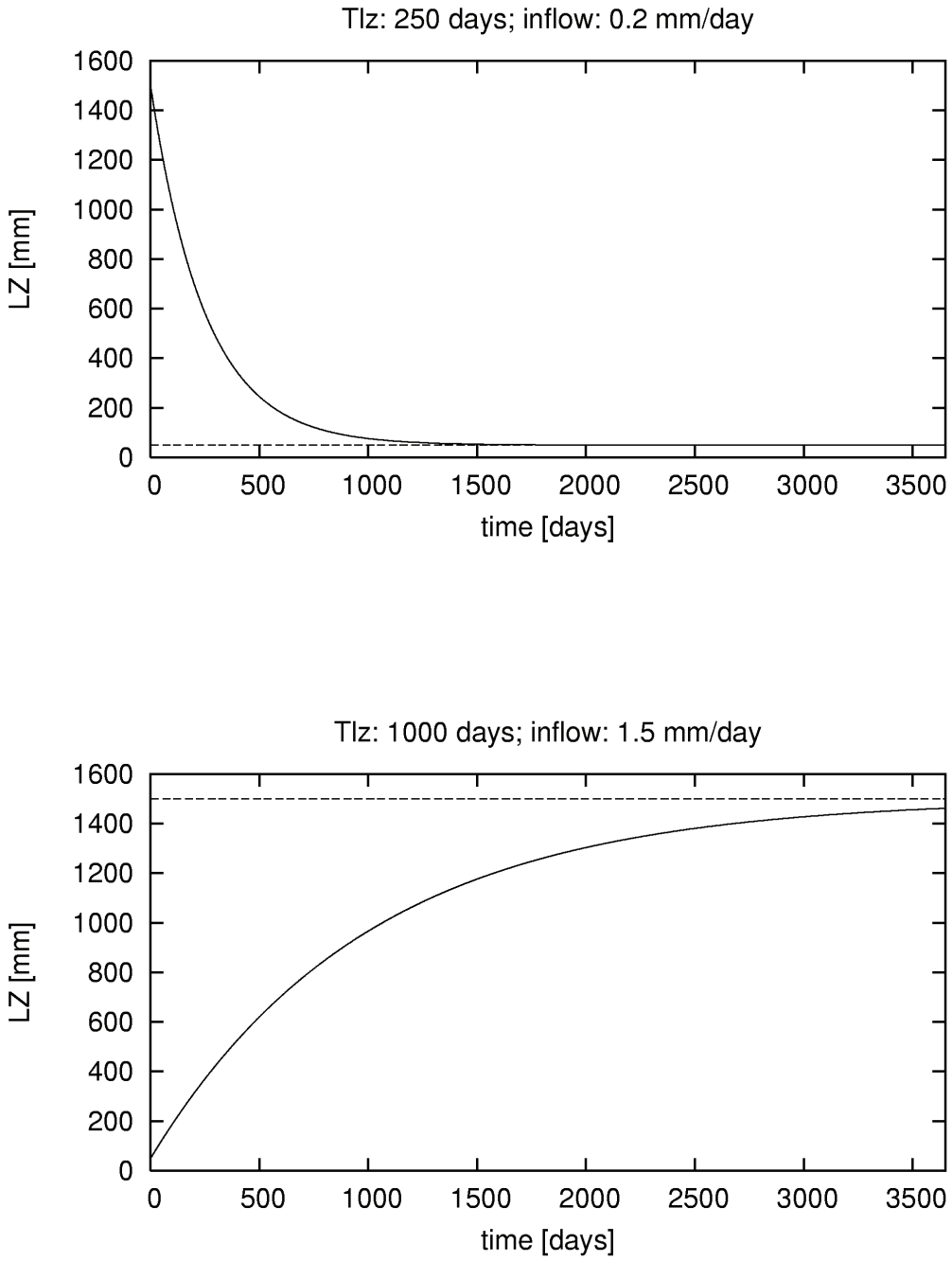


Figure 7.3 *Two 10-year simulations of lower zone storage with constant inflow. Upper Figure: high initial storage, storage approaches steady-state storage (dashed) after about 1500 days. Lower Figure: low initial storage, storage doesn't reach steady-state within 10 years.*

This equation can be re-written as:

$$I(t) - \frac{1}{\mathrm{T_{lz}}} \cdot LZ = 0 \qquad (7\text{-}5)$$

Solving this for *LZ* gives the steady state storage:

$$LZ_{ss} = \mathrm{T}_{\mathrm{lz}} \cdot I(t) \qquad (7\text{-}6)$$

We can check this for our numerical examples:

T_{lz}	I	LZ_{ss}
250	0.2	50
1000	1.5	1500

which corresponds exactly to the results of Figure 7.3.

Steady-state storage in practice

An actual LISFLOOD simulation differs from the previous example in 2 ways. First, in any real simulation the inflow into the lower zone is not constant, but varies in time. This is not really a problem, since LZ_{ss} can be computed from the *average* recharge. However, this is something we do not know until the end of the simulation! Also, the inflow into the lower zone is controlled by the availability of water in the upper zone, which, in turn, depends on the supply of water from the soil. Hence, it is influenced by any calibration parameters that control behaviour of soil- and subsoil (e.g. T_{uz}, GW_{perc}, b, and so on). This means that –when calibrating the model- the average recharge will be different for every parameter set. Note, however, that it will *always* be smaller than the value of GW_{perc}, which is used as an upper limit in the model. There are now 2 different ways to proceed. Note that both procedures include a sufficiently long warm-up period! In general, using a warm-up period of 1 year is good enough.

Procedure 1: prior estimate of average recharge

This is the most straightforward way to initialise the lower zone, and also the riskiest one:

1. Select LISFLOOD parameter set (in calibration)
2. Set *ThetaInit1Value*,*ThetaInit2Value*,*LZInitValue* and *TotalCrossSectionAreaInitValue* to *-9999*
3. Make an estimate of the average recharge (i.e. the average flow of water from the upper to the lower groundwater zone, expressed in [mm day^{-1}]). Then set initialisation parameter *LZAvInflowEstimate* to this value. Remember that the *actual* recharge can never exceed the value of model parameter GW_{perc}, and LISFLOOD will always base its steady-state storage estimate on the smallest value out of *LZAvInflowEstimate* and GW_{perc}.[9]
4. Run the model

What happens now is that LISFLOOD computes the initial state of *LZ*, assuming that the average recharge can be approximated by *LZAvInflowEstimate*. In general, initialising LISFLOOD like this is quite risky, and the simulated development of the lower zone will often still show (strong) long-term trends.

[9] If you want to base your steady-state storage estimate on the assumption of an average recharge that equals the value of GW_{perc}, you can do this by simply setting *LZAvInflowEstimate* to any ridiculously large value (e.g. 1000).

Procedure 2: use pre-run to calculate average recharge

Here, we first do a "pre-run" that is used to calculate the average inflow into the lower zone. This average inflow can be reported as a map, which is then used in the actual run. This involves the following steps:

1. Set *ThetaInit1Value*,*ThetaInit2Value*,*LZInitValue* and *TotalCrossSectionAreaInitValue* to *-9999*
2. Activate the "repLZAvInflowMap" option by adding the following line to the 'lfoptions' element in the settings file:

```
<setoption name="repLZAvInflowMap" choice="1"></setoption>
```

3. Run the model
4. Find the map 'lzavin.map' in the output directory and copy it to another location
5. Go back to the LISFLOOD settings file, and enter the name of 'lzavin.map' (including full path) for initialisation parameter *LZAvInflowEstimate*. For example:

```
<textvar name="LZAvInflowEstimate" value="D:\meuse\lzavin.map">
```

6. Switch off the "repLZAvInflowMap" option (optional, leaving it on will not do any harm, but it makes LISFLOOD run somewhat slower)
7. Run the model again using the modified settings file

In this case, the initial state of *LZ* is computed for the correct average inflow, and the simulated storage in the lower zone throughout the simulation will not show any systematic (long-term) trends. The obvious price to pay for this is that the pre-run doubles the computational load. However, as long as the simulation period for the actual run and the pre-run are identical, the procedure gives a 100% guarantee that the development of the lower zone storage will be free of any systematic bias. Since the computed recharge values are dependent on the model parameterisation used, in a calibration setting the whole procedure must be repeated for each parameter set!

Checking the lower zone initialisation

The presence of any initialisation problems of the lower zone can be checked by adding the following line to the 'lfoptions' element of the settings file:

```
<setoption name=" repStateUpsGauges" choice="1"></setoption>
```

This tells the model to write the values of all state variables (averages, upstream of contributing area to each gauge) to time series files. The default name of the lower zone time series is 'lzUps.tss'. Figure 7.4 shows an example of an 8-year simulation that was done both without (dashed line) and with a pre-run. The simulation without the pre-run shows a steady decreasing trend throughout the 8-year period, whereas the simulation for which the pre-run was used doesn't show this long-term trend (although in this specific case a modest increasing trend is visible throughout the first 6 years of the simulation, but this is related to trends in the meteorological input).

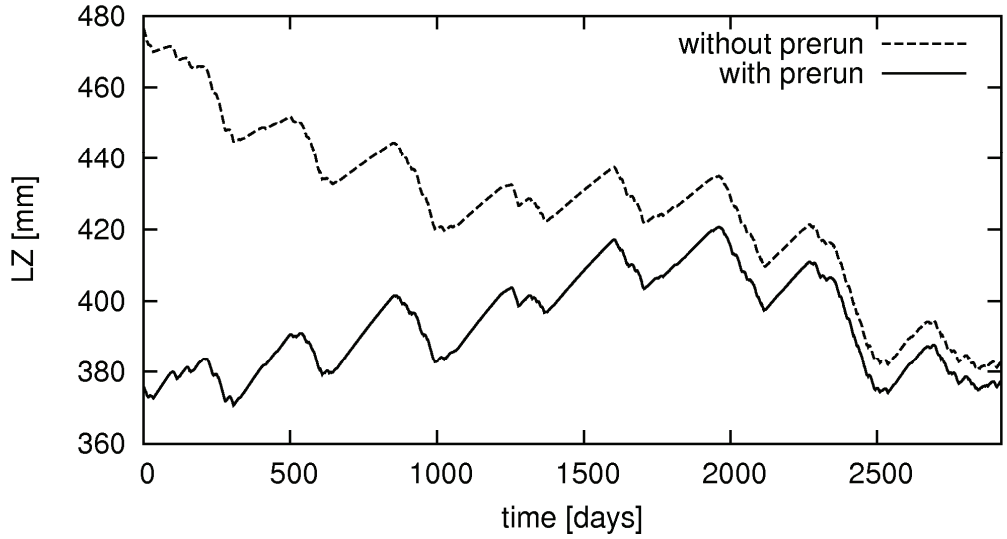


Figure 7.4 *Initialisation of lower groundwater zone with and without using a pre-run. Note the strong decreasing trend in the simulation without pre-run.*

Using the 'end' maps of a previous run as initial conditions

At the end of each model run, LISFLOOD writes maps of all internal state variables at the last time step. You can use these maps as the initial conditions for a succeeding simulation. This is particularly useful if you are simulating individual flood events on a small time interval (e.g. hourly). For instance, to estimate the initial conditions just before the flood you can do a 'pre-run' on a *daily* time interval for the year before the flood. You can then use the 'end maps' as the initial conditions for the hourly simulation.

In any case, you should be aware that values of some internal state variables of the model (especially lower zone storage) are very much dependent on the parameterisation used. Hence, suppose we have 'end maps' that were created using some parameterisation of the model (let's say parameter set *A*), then these maps should *not* be used as initial conditions for a model run with another parameterisation (parameter set *B*). If you decide to do this anyway, you are likely to encounter serious initialisation problems (but these may not be immediately visible in the output!). If you do this while calibrating the model (i.e. parameter set *B* is the calibration set), this will render the calibration exercise pretty much useless (since the output is the result of a mix of different parameter sets). However, for *SnowCoverInitAValue*, *SnowCoverInitBValue*, *SnowCoverInitCValue*, *FrostIndexInitValue* and *DSLRInitValue* it is perfectly safe to use the 'end maps', since the values of these maps do not depend on any calibration parameters (that is, only if you do not calibrate on any of the snow or frost-related parameters!). If you need to calibrate for individual events (i.e.hourly), you should apply *each* parameterisation on *both* the (daily) pre-run and the 'event' run! This may seem awkward, but there is no way of getting around this (except from avoiding event-based calibration at all, which may be a good idea anyway).

Summary of LISFLOOD initialisation procedure

From the foregoing it is clear that the initialisation of LISFLOOD can be done in a number of ways. Figure 7.5 gives an overview. As already stated in the introduction section, any LISFLOOD simulation will fall into either of the following two categories:

1. The initial state of all state variables is known and defined by the end state of a previous run. In this case you can use the 'end' maps of the previous run's state variables as the initial conditions of you current run. Note that this requires that both simulations are run using exactly the same parameter set! Mixing parameter sets here will introduce unwanted artefacts into your simulation results.
2. The initial state of all state variables is unknown. In this case you should run the model with a sufficient warm-up period (one year will usually do), using the available special initialisation methods to initialise soil moisture, lower zone storage and the amount of water in the channel. In addition, you should first do a "pre-run" to calculate the average recharge into the lower zone. The average recharge map that is generated from the pre-run can subsequently be used as the average lower zone inflow estimate (*LZAvInflowEstimate*) in the actual simulation, which will avoid any initialisation problems of the lower groundwater zone.

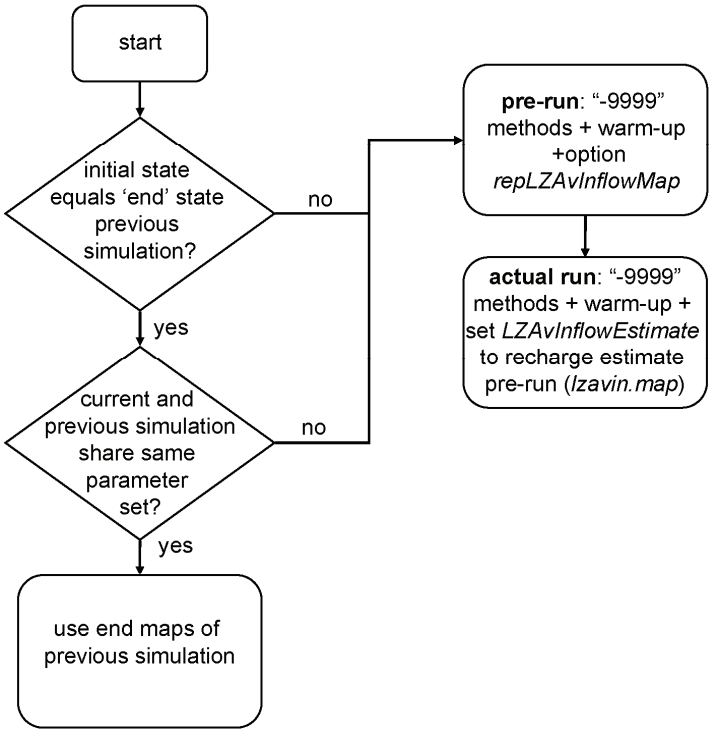


Figure 7.5 *LISFLOOD initialisation flowchart*

8. Output generated by LISFLOOD

Default LISFLOOD output

LISFLOOD can generate a wide variety of output. Output is generated as either maps (PCRaster format, which can be visualised with PCRaster's 'display' application) or time series (can be visualised with PCRaster's 'timeplot' application or any other plotting software that can read or import ASCII files). Reporting of output files can be switched on and off using options in the LISFLOOD settings file. Also, a number of output files are specific to other optional modules, such as the simulation of reservoirs. The following table lists all the output time series that are reported by default (note that the file names can always be changed by the user, although this is not recommended):

Table 8.1 *LISFLOOD default output time series*

RATE VARIABLES AT GAUGES		
Description	**Units**	**File name**
channel discharge	m^3/s	dis.tss
NUMERICAL CHECKS		
Description	**Units**	**File name**
cumulative mass balance error	m^3	mbError.tss
cumulative mass balance error, expressed as mm water slice (average over catchment)	mm	mbErrorMm.tss
number of sub-steps needed for gravity-based soil moisture routine	-	steps.tss

In addition to these time series, by default LISFLOOD reports maps of all state variables at the last timestep of a simulation. These maps can be used to define the initial conditions of a succeeding simulation. For instance, you can do a 1-year simulation on a daily time step, and use the 'end maps' of this simulation to simulate a flood event using an hourly time step. Table 8.2 lists all these maps. Note that some state variables are valid for the whole pixel, whereas others are only valid for a sub-domain of each pixel. This is indicated in the last column of the table.

Table 8.2 *LISFLOOD default state variable output maps. These maps can be used to define the initial conditions of another simulation*

DEFAULT OUTPUT MAPS LISFLOOD (option *repStateMaps*)			
Description	**Units**	**File name[10]**	**Domain**
waterdepth at last time step	mm	wdepth00.xxx	whole pixel
channel cross-sectional area at last time step	m^2	chcross0.xxx	channel
days since last rain variable at last time step	days	dslr0000.xxx	whole pixel
snow cover zone *A* at last time step	mm	scova000.xxx	snow zone A (1/3rd pixel)
snow cover zone *B* at last time step	mm	scovb000.xxx	snow zone B (1/3rd pixel)
snow cover zone *C* at last time step	mm	scovc000.xxx	snow zone C (1/3rd pixel)
frost index at last time step	degree-days	frost000.xxx	whole pixel
cumulative interception at last time step	mm	cumint00.xxx	whole pixel
soil moisture upper layer at last time step	mm^3/mm^3	thtop000.xxx	permeable fraction pixel
soil moisture lower layer at last time step	mm^3/mm^3	thsub000.xxx	permeable fraction pixel
water in lower zone at last time step	mm	lz000000.xxx	permeable fraction pixel
water in upper zone at last time step	mm	uz000000.xxx	permeable fraction pixel

Additional output

Apart from the default output, the model can –optionally- generate some additional time series and maps. Roughly this additional output falls in either of the following categories:

1. Time series with values of model state variables at user-defined locations (sites); reporting of these time series can be activated using the option *repStateSites=1.* Note that 'sites' can be either individual pixels or larger areas (e.g. catchments, administrative areas, and so on). In case of larger areas the model reports the average value for each respective area.
2. Time series with values of model rate variables at user-defined locations (sites); reporting of these time series can be activated using the option *repRateSites=1*
3. Time series with values of meteorological input variables, averaged over the area upstream of each gauge location; reporting of these time series can be activated using the option *repMeteoUpsGauges=1*
4. Time series with values of model state variables, averaged over area upstream of each gauge location; reporting of these time series can be activated using the option *repStateUpsGauges=1*
5. Time series with values of model rate variables, averaged over area upstream of each gauge location; reporting of these time series can be activated using the option *repRateUpsGauges=1*
6. Maps of discharge at each time step; reporting of these maps can be activated using the option *repDischargeMaps=1*
7. Maps with values of driving meteorological values at each time step
8. Maps with values of model rate variables at each time step
9. Maps or time series that are specific to other options (e.g. simulation of reservoirs).

[10] xxx represents the number of the last time step; e.g. or a 730-step simulation the end map of 'waterdepth' will be 'wdepth00.730', and so on.

In addition, some additional maps and time series may be reported for debugging purposes. In general these are not of any interest to the LISFLOOD user, so they remain undocumented here.

Note that the options *repStateUpsGauges*, *repRateUpsGauges* and *repDischargeMaps* tend to slow down the execution of the model quite dramatically. For applications of the model where performance is critical (e.g. automated calibration runs), we advise to keep them switched off, if possible. The additional time series are listed in the Table 8.3. Note again the domains for which variables are valid: all *rate variables* are reported as pixel-average values. Soil moisture and groundwater storage are reported for the permeable fraction of each pixel only. The reported snow cover is the average of the snow depths in snow zones A, B and C.

Table 8.3 *LISFLOOD optional output time series*

TIME SERIES, VALUES AT SITES			
STATE VARIABLES (option *repStateSites*)			
Description	**Units**	**Settings variable**	**Default name**
depth of water on soil surface	mm	WaterDepthTS	wDepth.tss
depth of snow cover on soil surface (pixel-average)	mm	SnowCoverTS	snowCover.tss
depth of interception storage	mm	CumInterceptionTS	cumInt.tss
soil moisture content upper layer (*)	mm^3 / mm^3	Theta1TS	thTop.tss
soil moisture content lower layer (*)	mm^3 / mm^3	Theta2TS	thSub.tss
storage in upper groundwater zone (*)	mm	UZTS	uz.tss
storage in lower groundwater zone (*)	mm	LZTS	lz.tss
number of days since last rain	days	DSLRTS	dslr.tss
frost index	degree C -days	FrostIndexTS	frost.tss
RATE VARIABLES (option *repRateSites*)			
Description	**Units**	**Settings variable**	**Default name**
rain (excluding snow)	mm / time step	RainTS	rain.tss
snow	mm / time step	SnowTS	snow.tss
snow melt	mm / time step	SnowmeltTS	snowMelt.tss
actual evaporation	mm / time step	ESActTS	esAct.tss
actual transpiration	mm / time step	TaTS	tAct.tss
rainfall interception	mm / time step	InterceptionTS	interception.tss
evaporation of intercepted water	mm / time step	EWIntTS	ewIntAct.tss
leaf drainage	mm / time step	LeafDrainageTS	leafDrainage.tss
infiltration	mm / time step	InfiltrationTS	infiltration.tss
preferential (bypass) flow	mm / time step	PrefFlowTS	prefFlow.tss
percolation upper to lower soil layer	mm / time step	PercolationTS	dTopToSub.tss
percolation lower soil layer to subsoil	mm / time step	SeepSubToGWTS	dSubToUz.tss
surface runoff	mm / time step	SurfaceRunoffTS	surfaceRunoff.tss
outflow from upper zone	mm / time step	UZOutflowTS	qUz.tss
outflow from lower zone	mm / time step	LZOutflowTS	qLz.tss
total runoff	mm / time step	TotalRunoffTS	totalRunoff.tss
percolation from upper to lower zone	mm / time step	GwPercUZLZTS	percUZLZ.tss
loss from lower zone	mm / time step	GwLossTS	loss.tss
(*): Valid only for permeable fraction of pixel, (1- f_{dr}). All other variables are pixel-averages			

Table 8.3 *LISFLOOD optional output time series (continued)*

TIME SERIES, AVERAGE UPSTREAM OF GAUGES

METEOROLOGICAL INPUT VARIABLES (option *repMeteoUpsGauges*)

Description	Units	Settings variable	Default name
precipitation	mm/time step	PrecipitationAvUpsTS	precipUps.tss
potential reference evapotranspiration	mm/time step	ETRefAvUpsTS	etUps.tss
potential evaporation from soil	mm/time step	ESRefAvUpsTS	esUps.tss
potential open water evaporation	mm/time step	EWRefAvUpsTS	ewUps.tss
average daily temperature	°C	TavgAvUpsTS	tAvgUps.tss

STATE VARIABLES (option *repStateUpsGauges*)

Description	Units	Settings variable	Default name
depth of water on soil surface	mm	WaterDepthAvUpsTS	wdepthUps.tss
depth of snow cover on	mm	SnowCoverAvUpsTS	snowCoverUps.tss
depth of interception storage	mm	CumInterceptionAvUpsTS	cumInterceptionUps.tss
soil moisture upper layer (*)	mm^3 / mm^3	Theta1AvUpsTS	thTopUps.tss
soil moisture lower layer (*)	mm^3 / mm^3	Theta2AvUpsTS	thSubUps.tss
groundwater upper zone (*)	mm	UZAvUpsTS	uzUps.tss
groundwater lower zone (*)	mm	LZAvUpsTS	lzUps.tss
number of days since last rain	days	DSLRAvUpsTS	dslrUps.tss
frost index	°C $days^{-1}$	FrostIndexAvUpsTS	frostUps.tss

RATE VARIABLES (option *repRateUpsGauges*)

Description	Units	Settings variable	Default name
rain (excluding snow)	mm / time step	RainAvUpsTS	rainUps.tss
snow	mm / time step	SnowAvUpsTS	snowUps.tss
snow melt	mm / time step	SnowmeltAvUpsTS	snowMeltUps.tss
actual evaporation	mm / time step	ESActAvUpsTS	esActUps.tss
actual transpiration	mm / time step	TaAvUpsTS	tActUps.tss
rainfall interception	mm / time step	InterceptionAvUpsTS	interceptionUps.tss
evaporation of intercepted water	mm / time step	EWIntAvUpsTS	ewIntActUps.tss
leaf drainage	mm / time step	LeafDrainageAvUpsTS	leafDrainageUps.tss
infiltration	mm / time step	InfiltrationAvUpsTS	infiltrationUps.tss
preferential (bypass) flow	mm / time step	PrefFlowAvUpsTS	prefFlowUps.tss
percolation upper to lower soil layer	mm / time step	PercolationAvUpsTS	dTopToSubUps.tss
percolation lower soil layer to subsoil	mm / time step	SeepSubToGWAvUpsTS	dSubToUzUps.tss
surface runoff	mm / time step	SurfaceRunoffAvUpsTS	surfaceRunoffUps.tss
outflow from upper zone	mm / time step	UZOutflowAvUpsTS	qUzUps.tss
outflow from lower zone	mm / time step	LZOutflowAvUpsTS	qLzUps.tss
total runoff	mm / time step	TotalRunoffAvUpsTS	totalRunoffUps.tss
percolation upper to lower zone	mm / time step	GwPercUZLZAvUpsTS	percUZLZUps.tss
loss from lower zone	mm / time step	GwLossTS	lossUps.tss

(*): Valid only for permeable fraction of pixel, (1- f_{dr}). All other variables are pixel-averages

Table 8.3 *LISFLOOD optional output time series (continued)*

WATER LEVEL IN CHANNEL (option *repWaterLevelTs*)			
Description	**Units**	**Settings variable**	**Default name**
water level in channel	m (above channel bottom)	WaterLevelTS	waterLevel.tss

By default, the names of the reported discharge maps start with the prefix '*dis*' and end with the time step number (the naming conventions are identical to the ones used for the input maps with meteorological variables, which is explained in Chapter 4). Table 8.4 summarises all options to report additional output maps. The previous remarks related to the domains foe which the state variable values are valid also apply to the maps listed in Table 8.4.

Table 8.4 *LISFLOOD optional series of output maps (all units identical to the ones listed in Table 8.3)*

DISCHARGE			
Description	**Option**	**Settings variable**	**Prefix**
discharge	repDischargeMaps	DischargeMaps	dis
water level	repWaterLevelMaps	WaterLevelMaps	wl
METEOROLOGICAL INPUT VARIABLES			
Description	**Option**	**Settings variable**	**Prefix**
precipitation	repPrecipitationMaps	PrecipitationMaps	pr
potential reference evapotranspiration	repETRefMaps	ETRefMaps	et
potential evaporation from soil	repESRefMaps	ESRefMaps	es
potential open water evaporation	repEWRefMaps	EWRefMaps	ew
average daily temperature	repTavgMaps	TavgMaps	tav
STATE VARIABLES			
Description	**Option**	**Settings variable**	**Prefix**
depth of water on soil surface	repWaterDepthMaps	WaterDepthMaps	wdep
depth of snow cover on soil surface	repSnowCoverMaps	SnowCoverMaps	scov
depth of interception storage	repCumInterceptionMaps	CumInterceptionMaps	cumint
soil moisture content upper layer (*)	repTheta1Maps	Theta1Maps	thtop
soil moisture content lower layer (*)	repTheta2Maps	Theta2Maps	thsub
storage in upper groundwater zone (*)	repUZMaps	UZMaps	uz
storage in lower groundwater zone (*)	repLZMaps	LZMaps	lz
number of days since last rain	repDSLRMaps	DSLRMaps	dslr
frost index	repFrostIndexMaps	FrostIndexMaps	frost
RATE VARIABLES			
Description	**Option**	**Settings variable**	**Prefix**
rain (excluding snow)	repRainMaps	RainMaps	rain
snow	repSnowMaps	SnowMaps	snow
snow melt	repSnowMeltMaps	SnowMeltMaps	smelt
actual evaporation	repESActMaps	ESActMaps	esact
actual transpiration	repTaMaps	TaMaps	tact
rainfall interception	repInterceptionMaps	InterceptionMaps	int
evaporation of intercepted water	repEWIntMaps	EWIntMaps	ewint
leaf drainage	repLeafDrainageMaps	LeafDrainageMaps	ldra
infiltration	repInfiltrationMaps	InfiltrationMaps	inf
preferential (bypass) flow	repPrefFlowMaps	PrefFlowMaps	pflow
percolation upper to lower soil layer	repPercolationMaps	PercolationMaps	to2su
percolation lower soil layer to subsoil	repSeepSubToGWMaps	SeepSubToGWMaps	su2gw
surface runoff	repSurfaceRunoffMaps	SurfaceRunoffMaps	srun
outflow from upper zone	repUZOutflowMaps	UZOutflowMaps	quz
outflow from lower zone	repLZOutflowMaps	LZOutflowMaps	qlz
total runoff	repTotalRunoffMaps	TotalRunoffMaps	trun
percolation upper to lower zone	repGwPercUZLZMaps	GwPercUZLZMaps	uz2lz
loss from lower zone	rep GwLossMaps	GwLossMaps	loss

(*): Valid only for permeable fraction of pixel, (1- f_{dr}). All other variables are pixel-averages

Finally, some additional output options exist that don't fit in any of the above categories. They are listed in Table 8.5:

Table 8.5 *LISFLOOD miscellaneous optional output*

OUTPUT RELATED TO LOWER ZONE INITIALISATION			
Description	**Option**	**Settings variable**	**Default name**
average inflow into lower zone [mm day^{-1}]	repLZAvInflowMap	LZAvInflowMap	lzavin.map
average inflow into lower zone [mm day^{-1}]	repLZAvInflowSites	LZAvInflowTS	lzAvIn.tss
average inflow into lower zone [mm day^{-1}]	repLZAvInflowUpsGauges	LZAvInflowAvUpsTS	lzAvInUps.tss

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Annex 1: Simulation of reservoirs

Introduction

This annex describes the LISFLOOD reservoirs routine, and how it is used. The simulation of reservoirs is *optional*, and it can be activated by adding the following line to the 'lfoptions' element:

```
<setoption name="simulateReservoirs" choice="1" />
```

Reservoirs can be simulated on channel pixels where kinematic wave routing is used. The routine does *not* work for channel stretches where the dynamic wave is used!

Description of the reservoir routine

Reservoirs are simulated as points in the channel network. The inflow into each reservoir equals the channel flow upstream of the reservoir. The outflow behaviour is described by a number of parameters. First, each reservoir has a total storage capacity S [m^3]. The relative filling of a reservoir, F, is a fraction between 0 and 1. There are three 'special' filling levels. First, each reservoir has a 'dead storage' fraction, since reservoirs never empty completely. The corresponding filling fraction is the 'conservative storage limit', L_c. For safety reasons a reservoir is never filled to the full storage capacity. The 'flood storage limit' (L_f) represents this maximum allowed storage fraction. The buffering capacity of a reservoir is the storage available between the 'flood storage limit' and the 'normal storage limit' (L_n). Three additional parameters define the way the outflow of a reservoir is regulated. For e.g. ecological reasons each reservoir has a 'minimum outflow' (O_{min}, [$m^3\ s^{-1}$]). For high discharge situations, the 'non-damaging outflow' (O_{nd}, [$m^3\ s^{-1}$]) is the maximum possible outflow that will not cause problems downstream. The 'normal outflow' (O_{norm}, [$m^3\ s^{-1}$]) is valid once the reservoir reaches its 'normal storage' filling level.

Depending on the relative filling of the reservoir, outflow (O_{res}, [$m^3\ s^{-1}$]) is calculated as:

$$O_{res} = \min(O_{\min}, \frac{1}{\Delta t} F \cdot S) \qquad F \le 2L_c$$

$$O_{res} = O_{\min} + (O_{norm} - O_{\min}) \frac{(F - 2L_c)}{(L_n - 2L_c)} \qquad L_n \ge F > 2L_c$$

$$O_{res} = O_{norm} + \frac{(F - L_n)}{(L_f - L_n)} \cdot \max\{(I_{res} - O_{norm}), (O_{nd} - O_{norm})\} \qquad L_f \ge F > L_n$$

$$O_{res} = \max(\frac{(F - L_f)}{\Delta t} S, O_{nd}) \qquad F > L_f$$

with:

S	: Reservoir storage capacity [m^3]
F	: Reservoir fill (fraction, 1 at total storage capacity) [-]
L_c	: Conservative storage limit [-]
L_n	: Normal storage limit [-]
L_f	: Flood storage limit [-]
O_{min}	: Minimum outflow [$m^3\ s^{-1}$]

O_{norm} : Normal outflow [m^3 s^{-1}]
O_{nd} : Non-damaging outflow [m^3 s^{-1}]
I_{res} : Reservoir inflow [m^3 s^{-1}]
In order to prevent numerical problems, the reservoir outflow is calculated using a user-defined time interval (or Δt, if it is smaller than this value).

Preparation of input data

For the simulation of reservoirs a number of addition input files are necessary. First, the locations of the reservoirs are defined on a (nominal) map called '*res.map*'. It is important that all reservoirs are located on a channel pixel (you can verify this by displaying the reservoirs map on top of the channel map). Also, since each reservoir receives its inflow from its upstream neighbouring channel pixel, you may want to check if each reservoir has any upstream channel pixels at all (if not, the reservoir will gradually empty during a model run!). The management of the reservoirs is described by 7 tables. The following table lists all required input:

Table A1.1 *Input requirements reservoir routine*

Maps	**Default name**	**Description**	**Units**	**Remarks**
ReservoirSites	res.map	reservoir locations	-	nominal
Tables	**Default name**	**Description**	**Units**	**Remarks**
TabTotStorage	rtstor.txt	reservoir storage capacity	m^3	
TabConservativeStorageLimit	rclim.txt	conservative storage limit	-	fraction of storage capacity
TabNormalStorageLimit	rnlim.txt	normal storage limit	-	
TabFloodStorageLimit	rflim.txt	flood storage limit	-	
TabMinOutflowQ	rminq.txt	minimum outflow	m^3/s	
TabNormalOutflowQ	rnormq.txt	normal outflow	m^3/s	
TabNonDamagingOutflowQ	rndq.txt	non-damaging outflow	m^3/s	

When you create the map with the reservoir sites, pay special attention to the following: if a reservoir is on the most downstream cell (i.e. the outflow point, see Figure A1.1), the reservoir routine may produce erroneous output. In particular, the mass balance errors cannot be calculated correctly in that case. The same applies if you simulate only a sub-catchment of a larger map (by selecting the subcatchment in the mask map). This situation can usually be avoided by extending the mask map by one cell in downstream direction.

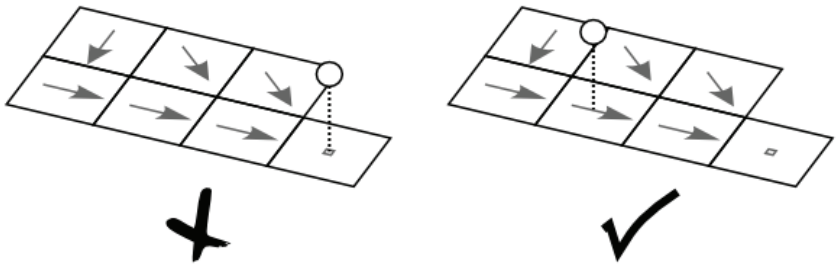

Figure A1.1 *Placement of the reservoirs: reservoirs on the outflow point (left) result in erroneous behavior of the reservoir routine.*

Preparation of settings file

All in- and output files need to be defined in the settings file. If you are using a default LISFLOOD settings template, all file definitions are already defined in the 'lfbinding' element. Just make sure that the map with the reservoir locations is in the "maps" directory, and all tables in the 'tables" directory. If this is the case, you only have to specify the time-step used for the reservoir calculations and the initial reservoir filling level (expressed as a fraction of the storage capacity). Both are defined in the 'lfuser' element of the settings file. For the reservoir time step (*DtSecReservoirs*) it is recommended to start with a value of 14400 (4 hours), and try smaller values if the simulated reservoir outflow shows large oscillations. *ReservoirInitialFillValue* can be either a map or a value (between 0 and 1). So we add this to the 'lfuser' element (if it is not there already):

```
<group>

<comment>
************************************************************
RESERVOIR OPTION
************************************************************
</comment>

<textvar name="DtSecReservoirs" value="14400">
<comment>
Sub time step used for reservoir simulation [s]. Within the model,
the smallest out of DtSecReservoirs and DtSec is used.
</comment>
</textvar>

<textvar name="ReservoirInitialFillValue" value="-9999">
<comment>
Initial reservoir fill fraction
-9999 sets initial fill to normal storage limit
if you're not using the reservoir option, enter some bogus value
</comment>
</textvar>

</group>
```

The value -9999 tells the model to set the initial reservoir fill to the normal storage limit. Note that this value is completely arbitrary. However, if no other information is available this may be a reasonable starting point.

Finally, you have to tell LISFLOOD that you want to simulate reservoirs! To do this, add the following statement to the 'lfoptions' element:

```
<setoption name="simulateReservoirs" choice="1" />
```

Now you are ready to run the model. If you want to compare the model results both with and without the inclusion of reservoirs, you can switch off the simulation of reservoirs either by:

1. Removing the 'simulateReservoirs' statement from the 'lfoptions element, or
2. changing it into `<setoption name="simulateReservoirs" choice="0" />`

Both have exactly the same effect. You don't need to change anything in either 'lfuser' or 'lfbinding'; all file definitions here are simply ignored during the execution of the model.

Reservoir output files

The reservoir routine produces 3 additional time series and one map, as listed in the following table:

Table A1.2 *Output of reservoir routine*

Maps	**Default name**	**Description**	**Units**	**Remarks**
ReservoirFillState	rsfilxxx.xxx	reservoir fill at last time step[11]	-	
Time series	**Default name**	**Description**	**Units**	**Remarks**
ReservoirInflowTS	qresin.tss	inflow into reservoirs	m^3/s	
ReservoirOutflowTS	qresout.tss	outflow out of reservoirs	m^3/s	
ReservoirFillTS	resfill.tss	reservoir fill	-	

Note that you can use the map with the reservoir fill at the last time step to define the initial conditions of a succeeding simulation, e.g.:

```
<textvar name="ReservoirInitialFillValue" value="/mycatchment/rsfil000.730">
```

[11] xxx represents the number of the last time step; e.g. for a 730-step simulation the name will be ‘rsfil000.730’, and so on.

Annex 2: Inflow hydrograph option

Introduction

This annex describes the LISFLOOD inflow hydrograph routine, and how it is used. Inflow hydrographs are *optional*, and can be activated by adding the following line to the 'lfoptions' element:

```
<setoption name="inflow" choice="1" />
```

Description of the inflow hydrograph routine

When using the inflow hydrograph option, time series of discharge [m^3/s] are added at some user-defined location(s) on the channel network. The inflow is added as side-flow in the channel routing equations (this works for both kinematic and dynamic wave). *Negative* inflows (i.e. outflows) are also possible, but large outflow rates may sometimes result in numerical problems in the routing equations. If you use a negative inflow rate, we advise to carefully inspect the model output for any signs of numerical problems (i.e. strange oscillations in simulated discharge, generation of missing values). Also check the mass balance time series after your simulation (numerical problems often result in unusually large mass balance errors).

Using inflow hydrographs

The table below lists the input requirements for the inflow hydrograph option. All you need is a map that defines where you want to add the inflow, and a time series with the corresponding inflow rates.

Table A2.1 *Input requirements inflow hydrograph routine*

Maps	**Default name**	**Description**	**Units**	**Remarks**
InflowPoints	-	locations for inflow hydrographs	-	nominal
Time series	**Default name**	**Description**	**Units**	**Remarks**
QInTS	-	inflow hydrograph(s)	m^3/s	

Using the inflow hydrograph option involves four steps:

1. **Create a (nominal) PCRaster map with unique identifiers that point to the location(s) where you want to insert the inflow hydrograph(s)**

2. **Save the inflow hydrograph(s) in PCRaster time series format; inflow hydrographs need to be given in [m^3 s^{-1}]**

IMPORTANT: PCRaster assumes that the first data series in the time series file (i.e. the second column, since the first column contains the time step number) corresponds to unique identifier 1 on the *InflowPoints* map; the second series to unique identifier 2, and so on. So, even if your *InflowPoints* map only contains (as an example) identifiers 3 and 4, you *still need to include the columns for identifiers 1 and 2*!! The best thing to do in such a case is to fill any unused columns with zeroes (0). Also, your inflow hydrograph time series should always start at *t=1*, even if you set *StepStart* to some higher value. For more info on time series files please have a look at the PCRaster documentation.

3. Make sure that the names of the map and time series are defined in the settings file

In the 'lfuser' element (replace the file paths/names by the ones you want to use):

```
<group>

<comment>
************************************************************
INFLOW HYDROGRAPH (OPTIONAL)
************************************************************
</comment>

<textvar name="InflowPoints"
value="/floods2/yourhomedir/yourcatchment/maps/inlets.map">
<comment>
OPTIONAL: nominal map with locations of (measured)
inflow hydrographs [cu m / s]
</comment>
</textvar>

<textvar name="QInTS"
value="/floods2/yourhomedir/yourcatchment/inflow/inflow.tss">
<comment>
OPTIONAL: observed or simulated input hydrographs as
time series [cu m / s]
Note that identifiers in time series correspond to
InflowPoints map (also optional)
</comment>
</textvar>

</group>
```

4. Activate the inflow hydrograph option
Add the following line to the 'lfoptions' element:

```
<setoption name="inflow" choice="1" />
```

Now you are ready to run the model with the inflow hydrograph.

Substituting subcatchments with measured inflow hydrographs

One of the most common uses of the inflow hydrograph option is this: suppose we have a catchment where we only want to simulate the downstream part. If measured time series of discharge are available for the upstream catchment(s), we can use

these to represent the inflow into the more downstream part. Figure A2.1 shows an example, where we have measured discharge of subcatchment *A* (just before it enters the main river). In this case it is important to pay special attention to two issues.

Exclude subcatchments from MaskMap

First, make sure that subcatchment *A* is *excluded* (i.e. have boolean(0) or missing value) on LISFLOOD's *MaskMap* (which defines which pixels are included in the calculations and which are not). If you include it, LISFLOOD will first *simulate* discharge coming out of subcatchment *A*, and then *add* the (measured) inflow on top of it! Of course this doesn't make any sense, so always be careful which areas are included in your simulation and which are not.

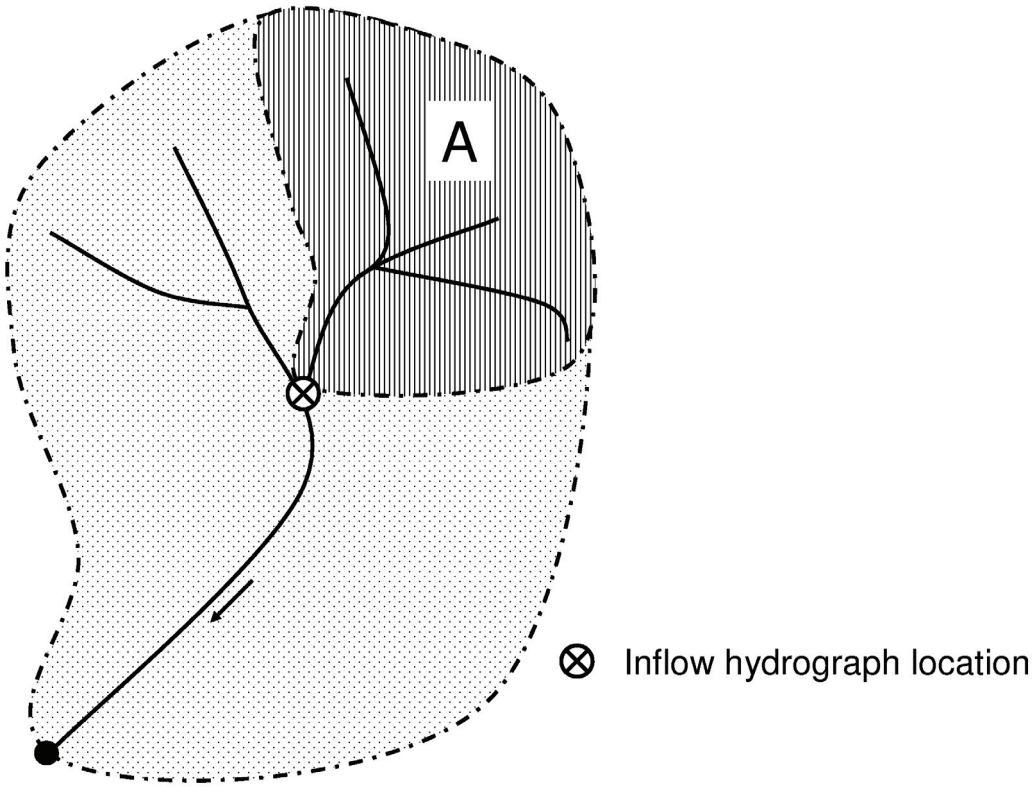

Figure A2.1 *Using the inflow hydrograph using measured discharge of subcatchment A. MaskMap must have boolean(0) (or missing value) for subcatchment A, see text for explanation.*

Make sure your inflow points are where you need them

If you already have all gauge locations on a PCRaster map, these mostly cannot be used directly as inflow hydrograph locations. The reason is simple: suppose –in our previous example– we know the outflow point of subcatchment *A*. This point is the most downstream point within that subcatchment. However, the flow out of subcatchment *A* is actually added to the main river one cell downstream! Also, if we exclude subcatchment *A* from our simulation (as explained in the foregoing), this means we also exclude the outflow point of that subcatchment. Because of this, *inflow* points into the main river are usually located one pixel downstream of the

outflow points of the corresponding subcatchment. If you already have a (nominal) map of of your subcatchments, a PCRaster script exists that automatically calculates the corresponding out- and inflow points.

Annex 3: Dynamic wave option

Introduction

This annex describes the LISFLOOD dynamic wave routine, and how it is used. The current implementation of the dynamic wave function in PCRaster is not a complete dynamic wave formulation according to the summary of the Saint Venant equations as discussed in Chow (1988). The implementation currently consists of the friction force term, the gravity force term and the pressure force term and should therefore be correctly characterised as a diffusion wave formulation. The equations are solved as an explicit, finite forward difference scheme. A straightforward iteration using an Euler solution scheme is used to solve these equations. Dynamic wave routing is *optional*, and can be activated by adding the following line to the 'lfoptions' element:

```
<setoption name="dynamicWave" choice="1" />
```

Time step selection

The current dynamic wave implementation requires that all equations are solved using a time step that is much smaller (order of magnitude: seconds-minutes) than the typical overall time step used by LISFLOOD (order of magnitude: hours-day). More specifically, during one (sub) time step no water should be allowed to travel more than 1 cell downstream, i.e.:

$$\Delta' t_{dyn} \leq \frac{\Delta x}{V + c_d}$$

where $\Delta' t_{dyn}$ is the sub-step for the dynamic wave [seconds], Δx is the length of one channel element (pixel) [m], V is the flow velocity [m s^{-1}] and c_d is dynamic wave celerity [m s^{-1}]. The dynamic wave celerity can be calculated as (Chow, 1988):

$$c_d = \sqrt{gy}$$

where g is the acceleration by gravity [m s^{-2}] and y is the depth of flow [m]. For a cross-section of a regular geometric shape, y can be calculated from the channel dimensions. Since the current dynamic wave routine uses irregularly shaped cross-section data, we simply assume than y equals the water level above the channel bed. The flow velocity is simply:

$$V = Q_{ch} / A$$

where Q_{ch} is the discharge in the channel [m^3 s^{-1}], and A the cross-sectional area [m^2].

The Courant number for the dynamic wave, C_{dyn}, can now be computed as:

$$C_{dyn} = \frac{(V + c_d)\Delta t}{\Delta x}$$

where Δt is the overall model time step [s]. The number of sub-steps is then given by:

$$SubSteps = \max(1, roundup(\frac{C_{dyn}}{C_{dyn,crit}}))$$

where $C_{dyn,crit}$ is the critical Courant number. The maximum value of the critical Courant number is 1; in practice it is safer to use a somewhat smaller value (although if you make it too small the model becomes excessively slow). It is recommended to stick to the default value (0.4) that is used the settings file template.

Input data

A number of addition input files are necessary to use the dynamic wave option. First, the channel stretches for which the dynamic wave is to be used are defined on a Boolean map. Next, a cross-section identifier map is needed that links the (dynamic wave) channel pixels to the cross-section table (see further on). A channel bottom level map describes the bottom level of the channel (relative to sea level). Finally, a cross-section table describes the relationship between water height (*H*), channel cross-sectional area (*A*) and wetted perimeter (*P*) for a succession of *H* levels.

The following table lists all required input:

Table A3.1 *Input requirements dynamic wave routine*

Maps	**Default name**	**Description**	**Units**	**Remarks**
ChannelsDynamic	chandyn.map	dynamic wave channels (1,0)	-	Boolean
ChanCrossSections	chanxsect.map	channel cross section IDs	-	nominal
ChanBottomLevel	chblevel.map	channel bottom level	[m]	
Tables	**Default name**	**Description**	**Units**	**Remarks**
TabCrossSections	chanxsect.txt	cross section parameter table (H,A,P)	H:[m] A:[m^2] P:[m]	

Layout of the cross-section parameter table

The cross-section parameter table is a text file that contains –for each cross-section- a sequence of water levels (*H*) with their corresponding cross-sectional area (*A*) and wetted perimeter (*P*). The format of each line is as follows:

ID H A P

As an example:

```
167     0               0                       0
167     1.507           103.044                 114.183
167     3.015           362.28                  302.652
167     4.522           902.288                 448.206
167     6.03            1709.097                600.382
167     6.217           1821.849                609.433
167     6.591           2049.726                615.835
167     6.778           2164.351                618.012
167     6.965           2279.355                620.14
167     7.152           2395.037                626.183
167     7.526           2629.098                631.759
167     7.713           2746.569                634.07
167     7.9             2864.589                636.93
167     307.9           192201.4874             5225.165294
```

Note here that the first *H*-level is always 0, for which *A* and *P* are (of course) 0 as well. For the last line for each cross-section it is recommended to use some very (i.e. unrealistically) high *H*-level. The reason for doing this is that the dynamic wave routine will crash if during a simulation a water level (or cross-sectional area) is simulated which is beyond the range of the table. This can occur due to a number of reasons (e.g. if the measured cross-section is incomplete, or during calibration of the model). To estimate the corresponding values of *A* and *P* one could for example calculate *dA/dH* and *dP/dH* over the last two 'real' (i.e. measured) *H*-levels, and extrapolate the results to a very high *H*-level.

The number of H/A/P combinations that are used for each cross section is user-defined. LISFLOOD automatically interpolates in between the table values.

Using the dynamic wave

The 'lfuser' element contains two parameters that can be set by the user: *CourantDynamicCrit* (which should always be smaller than 1) and a parameter called *DynWaveConstantHeadBoundary*, which defines the boundary condition at the most downstream cell. All remaining dynamic-wave related input is defined in the 'lfbinding' element, and doesn't require any changes from the user (provided that all default names are used, all maps are in the standard 'maps' directory and the profile table is in the 'tables' directory). In 'lfuser' this will look like this:

```
<group>

<comment>
************************************************************
DYNAMIC WAVE OPTION
************************************************************
</comment>

<textvar name="CourantDynamicCrit" value="0.5">
<comment>
Critical Courant number for dynamic wave
value between 0-1 (smaller values result in greater numerical accuracy,
but also increase computational time)
</comment>
</textvar>

<textvar name="DynWaveConstantHeadBoundary" value="0">
<comment>
Constant head [m] at most downstream pixel (relative to altitude
at most downstream pixel)
</comment>
</textvar>

</group>
```

Annex 4: Polder option

Introduction

This annex describes the LISFLOOD polder routine, and how it is used. The simulation of polders is *optional*, and it can be activated by adding the following line to the 'lfoptions' element:

```
<setoption name="simulatePolders" choice="1" />
```

Polders can be simulated on channel pixels where dynamic wave routing is used. The routine does *not* work for channel stretches where the kinematic wave is used!

Description of the polder routine

Polders are simulated as points in the channel network. The polder routine is adapted from Förster et. al (2004), and based on the weir equation of Poleni (Bollrich & Preißler, 1992). The flow rates from the channel to the polder area and vice versa are calculated by balancing out the water levels in the channel and in the polder, as shown in Figure A4.1.

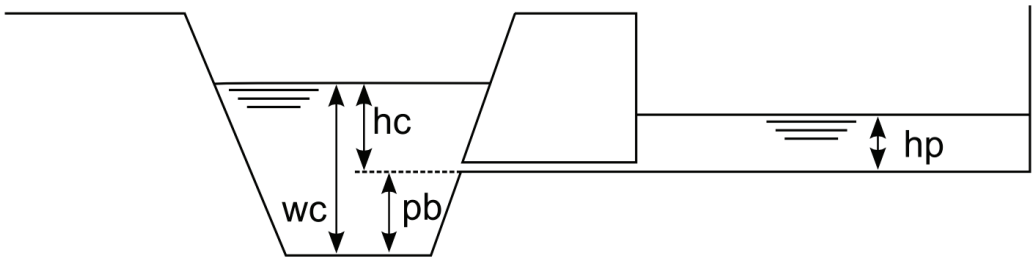

Figure A4.1 *Schematic overview of the simulation of polders.* pb *is the polder bottom level (above the channel bottom);* w_c *is the water level in the channel;* h_c *and* h_p *are the water levels above the polder in- / outflow, respectively*

From the Figure, it is easy to see that there can be three situations:

1. $\boldsymbol{h_c > h_p}$: water flows out of the channel, into the polder. The flow rate, $q_{c,p}$, is calculated using:

$$q_{c,p} = \mu c b \sqrt{2g} h_c^{3/2};$$
$$c = \sqrt{1 - \left[\frac{h_p}{h_c}\right]^{16}} \qquad \text{(A4.1)}$$

where b is the outflow width [m], g is the acceleration due to gravity (9.81 m s^{-2}) and μ is a weir constant which has a value of 0.49. Furthermore $q_{c,p}$ is in [m^3 s^{-1}].

2. $\boldsymbol{h_c < h_p}$: water flows out of the polder back into the channel. The flow rate, $q_{p,c}$, is now calculated using:

$$q_{p,c} = \mu c b \sqrt{2g} h_p^{3/2};$$
$$c = \sqrt{1 - \left[\frac{h_c}{h_p}\right]^{16}} \qquad \text{(A4.2)}$$

3. $\boldsymbol{h_c = h_p}$: no water flowing into either direction (note here that the minimum value of h_c is zero). In this case both $q_{c,p}$ and $q_{p,c}$ are zero.

Regulated and unregulated polders

The above equations are valid for *unregulated* polders. It is also possible to simulated *regulated* polders, which is illustrated in Figure A4.2. Regulated polders are opened at a user-defined time (typically during the rising limb of a flood peak). The polder closes automatically once it is full. Subsequently, the polder is opened again to release the stored water back into the channel, which also occurs at a user-defined time. The opening- and release times for each polder are defined in two lookup tables (see Table 4.1). In order to simulate the polders in *unregulated* mode these times should both be set to a bogus value of -9999. *Only* if *both* opening- and release time are set to some other value, LISFLOOD will simulate a polder in regulated mode. Since LISFLOOD only supports *one* single regulated open-close-release cycle per simulation, you should use regulated mode *only* for single flood events. For continuous simulations (e.g. long-tem waterbalance runs) you should only run the polders in unregulated mode.

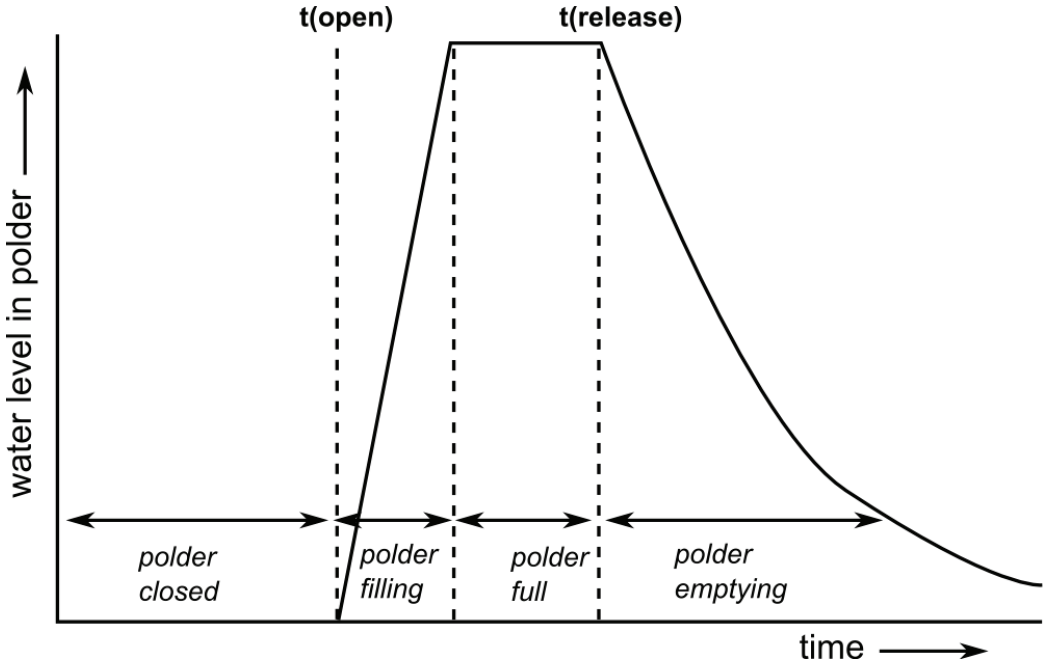

Figure A4.2 *Simulation of a regulated polder. Polder is closed (inactive) until user-defined opening time, after which it fills up to its capacity (flow rate according to Eq A4.1). Water stays in polder until user-defined release time, after which water is released back to the channel (flow rate according to Eq A4.2).*

Preparation of input data

The locations of the reservoirs are defined on a (nominal) map called '*polders.map*'. Any polders that are *not* on a channel pixel are ignored by LISFLOOD, so you may want to check the polder locations before running the model (you can do this by displaying the reservoirs map on top of the channel map). The current implementation of the polder routine may result in numerical instabilities for kinematic wave pixels, so for the moment it is recommended to define polders *only* on channels where the dynamic wave is used. Furthermore, the properties of each polder are described using a number of tables. All required input is listed in the following table:

Table A4.1 *Input requirements polder routine*

Maps	**Default name**	**Description**	**Units**	**Remarks**
PolderSites	polders.map	polder locations	-	nominal
Tables	**Default name**	**Description**	**Units**	**Remarks**
TabPolderArea	poldarea.txt	polder area	m^2	
TabPolderOFWidth	poldofw.txt	polder in- and outflow width	m	
TabPolderTotalCapacity	poldcap.txt	polder storage capacity	m^3	
TabPolderBottomLevel	poldblevel.txt	Bottom level of polder, measured from channel bottom level (see also Figure A4.1)	m	
TabPolderOpeningTime	poldtopen.txt	Time at which polder is opened	time step	
TabPolderReleaseTime	poldtrelease.txt	Time at which water stored in polder is released again	time step	

Note that the polder opening- and release times are both defined a *time step* numbers (*not* days or hours!!). For *unregulated* polders, set both parameters to a bogus value of -9999, i.e.:

```
10     -9999
15     -9999
16     -9999
17     -9999
```

Preparation of settings file

All in- and output files need to be defined in the settings file. If you are using a default LISFLOOD settings template, all file definitions are already defined in the 'lfbinding' element. Just make sure that the map with the polder locations is in the "maps" directory, and all tables in the 'tables" directory. If this is the case, you only have to specify the initial reservoir water level in the polders. *PolderInitialLevelValue* is defined in the 'lfuser' element of the settings file, and it can be either a map or a value. The value of the weir constant μ is also defined here, although you should not change its default value. So we add this to the 'lfuser' element (if it is not there already):

```
<group>

<comment>
************************************************************
POLDER OPTION
************************************************************
</comment>

<textvar name="mu" value="0.49">
<comment>
Weir constant [-] (Do not change!)
</comment>
</textvar>

<textvar name="PolderInitialLevelValue" value="0">
<comment>
Initial water level in polder [m]
</comment>
</textvar>

</group>
```

To switch on the polder routine, add the following line to the 'lfoptions' element:

```
<setoption name="simulatePolders" choice="1" />
```

Now you are ready to run the model. If you want to compare the model results both with and without the inclusion of polders, you can switch off the simulation of polders either by:

3. Removing the 'simulatePolders' statement from the 'lfoptions element, or
4. changing it into `<setoption name="simulatePolders" choice="0" />`

Both have exactly the same effect. You don't need to change anything in either 'lfuser' or 'lfbinding'; all file definitions here are simply ignored during the execution of the model.

Polder output files

The polder routine produces 2 additional time series and one map (or stack of maps, depending on the value of LISFLOOD variable *ReportSteps*), as listed in the following table:

Table A4.2 *Output of polder routine*

Maps	**Default name**	**Description**	**Units**	**Remarks**
PolderLevelState	hpolxxxx.xxx	water level in polder at last time step[12]	m	
Time series	**Default name**	**Description**	**Units**	**Remarks**
PolderLevelTS	hPolder.tss	water level in polder (at polder locations)	m	
PolderFluxTS	qPolder.tss	Flux into and out of polder (positive for flow from channel to polder, negative for flow from polder to channel)	m^3/s	

Note that you can use the map with the polder level at the last time step to define the initial conditions of a succeeding simulation, e.g.:

```
<textvar name="PolderInitialLevelValue" value="/mycatchment/hpol0000.730">
```

Limitations

For the moment, polders can be simulated on channel pixels where dynamic wave routing is used. For channels where the kinematic wave is used, the routine will not work and may lead to numerical instabilities or even model crashes. This limitation may be resolved in future model versions.

[12] xxx represents the number of the last time step; e.g. for a 730-step simulation the name will be ‘hpol0000.730’, and so on.

Annex 5: Simulation of lakes

Introduction

This annex describes the LISFLOOD lake routine, and how it is used. The simulation of lakes is *optional*, and it can be activated by adding the following line to the 'lfoptions' element:

```
<setoption name="simulateLakes" choice="1" />
```

Lakes can be simulated on channel pixels where kinematic wave routing is used. The routine does *not* work for channel stretches where the dynamic wave is used!

Description of the lake routine

Lakes are simulated as points in the channel network. Figure A5.1 shows all computed in- and outgoing fluxes. Lake inflow equals the channel flow upstream of the lake location. The flow out of the lake is computed using the following rating curve (e.g. Maidment, 1992):

$$O_{lake} = A(H - H_0)^B$$

O_{lake}	: Lake outflow rate [$m^3\ s^{-1}$]
H	: Water level in lake [m]
H_0	: Water level at which lake outflow is zero [m]
A, B	: Constants [-]

.

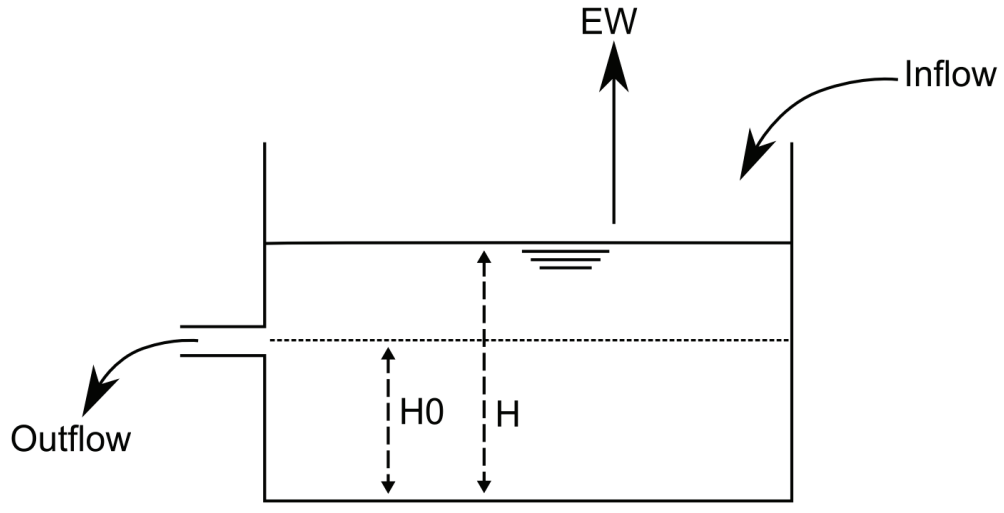

Figure A5.1 *Schematic overview of the simulation of lakes.* H_0 *is the water level at which the outflow is zero;* H *is the water level in the lake and* EW *is the evaporation from the lake*

Both H and H_0 can be defined relative to an arbitrary reference level. Since the outflow is a function of the *difference* between both levels, the actual value of this reference level doesn't matter if $H > H_0$. However, it is advised to define both H and H_0 relative to the *average bottom level* of the lake. This will result in more realistic simulations during severe drought spells, when the water level drops below H_0 (in which case lake outflow ceases). The value of constant A can be approximated by the width of the lake outlet in meters, and B is within the range 1.5-2 (reference?). Lake evaporation occurs at the potential evaporation rate of an open water surface.

Initialisation of the lake routine

Because lakes (especially large ones) tend to produce a relatively slow response over time, it is important to make sure that the initial lake level is set to a more or less sensible value. Just as is the case with the initialisation of the lower groundwater zone, LISFLOOD has a special option that will compute a steady-state lake level and use this as the initial value. The steady-state level is computed from the water balance of the lake. If V_l is the total lake volume [m3], the rate of change of V_l at any moment is given by the continuity equation:

$$\frac{dV_l}{dt} = I(t) - O(t)$$

where I and O are the in- and outflow rates, respectively. For a steady-state situation the storage remains constant, so:

$$\frac{dV_l}{dt} = 0 \quad \Leftrightarrow \quad I(t) - O(t) = 0$$

Substituting all in- and outflow terms gives:

$$I_l - EW_l - A(H - H_0)^B = 0$$

where I_l is the inflow into the lake and EW_l the lake evaporation (both expressed in $m^3\ s^{-1}$). Re-arranging gives the steady-state lake level:

$$H_{ss} = H_0 + \left(\frac{I_l - EW_l}{A} \right)^{1/B}$$

LISFLOOD calculates the steady-state lake level based on a user-defined average net inflow ($=I_l - EW_l$). The average net inflow can be estimated using measured discharge and evaporation records. If measured discharge is available just *downstream* of the lake (i.e. the *outflow*), the (long-term) average outflow can be used as the net inflow estimate (since, for a steady state situation, inflow equals outflow). If only inflow is available, all average inflows should be summed, and the average lake evaporation should be subtracted from this figure. Table A5.1 gives a worked example. Be aware that the calculation can be less straightforward for very large lakes with multiple inlets (which are not well represented by the current point approach anyway).

Table A5.1: Calculation of average net lake inflow

Lake characteristics
lake area: $215 \cdot 10^6$ m^2
mean annual discharge downstream of lake: 293 m^3 s^{-1}
mean annual discharge upstream of lake: 300 m^3 s^{-1}
mean annual evaporation: 1100 mm yr^{-1}

Calculation of average net inflow

METHOD 1: USING AVERAGE OUTFLOW

assuming lake is in quasi steady-state:

average net inflow = average net outflow = 293 m^3 s^{-1}

METHOD 2: USING AVERAGE INFLOW AND EVAPORATION

Only use this method if no outflow data are available

1. **Express lake evaporation in m^3 s^{-1}:**

   1100 mm yr^{-1} / 1000 = 1.1 m yr^{-1}
   1.1 m yr^{-1} x $215 \cdot 10^6$ m^2 = $2.37 \cdot 10^8$ m^3 yr^{-1}
   $2.37 \cdot 10^8$ m^3 yr^{-1} / (365 days x 86400 seconds) = 7.5 m^3 s^{-1}

2. **Compute net inflow:**

   net inflow = 300 m^3 s^{-1} – 7.5 m^3 s^{-1} = 292.5 m^3 s^{-1}

Preparation of input data

The lake locations defined on a (nominal) map called '*lakes.map*'. It is important that all reservoirs are located on a channel pixel (you can verify this by displaying the reservoirs map on top of the channel map). Also, since each lake receives its inflow from its upstream neighbouring channel pixel, you may want to check if each lake has any upstream channel pixels at all (if not, the lake will just gradually empty during a model run!). The lake characteristics are described by 4 tables. Table 5.2 lists all required input.

When you create the map with the lake locations, pay special attention to the following: if a lake is located on the most downstream cell (i.e. the outflow point, see Figure A5.2), the lake routine may produce erroneous output. In particular, the mass balance errors cannot be calculated correctly in that case. The same applies if you simulate only a sub-catchment of a larger map (by selecting the subcatchment in the mask map). This situation can usually be avoided by extending the mask map by one cell in downstream direction.

Table A5.2 *Input requirements lake routine*

Maps	**Default name**	**Description**	**Units**	**Remarks**
LakeSites	lakes.map	lake locations	-	nominal
Tables	**Default name**	**Description**	**Units**	**Remarks**
TabLakeArea	lakearea.txt	lake surface area	m^2	
TabLakeH0	lakeh0.txt	water level at which lake outflow is zero	m	relative to average lake bottom level
TabLakeA	lakea.txt	lake parameter A	-	≈ outlet width in meters
TabLakeB	lakeb.txt	lake parameter B	-	1.5-2

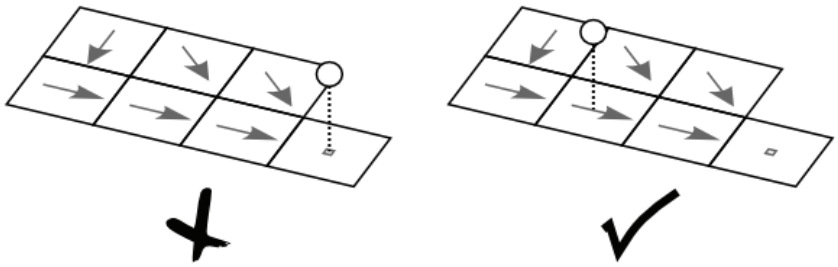

Figure A5.2 *Placement of the lakes: lakes on the outflow point (left) result in erroneous behavior of the lake routine.*

Preparation of settings file

All in- and output files need to be defined in the settings file. If you are using a default LISFLOOD settings template, all file definitions are already defined in the 'lfbinding' element. Just make sure that the map with the lake locations is in the "maps" directory, and all tables in the 'tables" directory. If this is the case, you only have to specify the initial lake level and –if you are using the steady-state option- the mean net lake inflow (make this a map if you're simulating multiple lakes simultaneously). Both can be set in the 'lfuser' element. *LakeInitialLevelValue* can be either a map or a single value. Setting *LakeInitialLevelValue* to *-9999* will cause LISFLOOD to calculate the steady-state level. So we add this to the 'lfuser' element (if it is not there already):

```
<group>

<comment>
************************************************************
LAKE OPTION
************************************************************
</comment>

<textvar name="LakeInitialLevelValue" value="-9999">
<comment>
Initial lake level [m]
-9999 sets initial value to steady-state level
</comment>
</textvar>

<textvar name="LakeAvNetInflowEstimate" value="292.5">
<comment>
Estimate of average net inflow into lake (=inflow - evaporation) [cu m / s]
Used to calculated steady-state lake level in case LakeInitialLevelValue
is set to -9999
</comment>
</textvar>

</group>
```

Finally, you have to tell LISFLOOD that you want to simulate lakes! To do this, add the following statement to the 'lfoptions' element:

```
<setoption name="simulateLakes" choice="1" />
```

Now you are ready to run the model. If you want to compare the model results both with and without the inclusion of lakes, you can switch off the simulation of lakes either by:

5. Removing the 'simulateLakes' statement from the 'lfoptions element, or
6. changing it into `<setoption name="simulateLakes" choice="0" />`

Both have exactly the same effect. You don't need to change anything in either 'lfuser' or 'lfbinding'; all file definitions here are simply ignored during the execution of the model.

Lake output files

The lake routine produces 4 additional time series and one map (or stack), as listed in the following table:

Table A5.3 *Output of lake routine*

Maps	Default name	Description	Units	Remarks
LakeLevelState	lakhxxxx.xxx	lake level at last time step[13]	m	
Time series	**Default name**	**Description**	**Units**	**Remarks**
LakeInflowTS	qLakeIn.tss	inflow into lakes	m^3/s	
LakeOutflowTS	qLakeOut.tss	flow out of lakes	m^3/s	
LakeEWTS	EWLake.tss	lake evaporation	mm	
LakeLevelTS	hLake.tss	lake level	m	

Note that you can use the map with the lake level at the last time step to define the initial conditions of a succeeding simulation, e.g.:

```
<textvar name="LakeInitialLevelValue" value="/mycatchment/lakh0000.730">
```

[13] xxx represents the number of the last time step; e.g. for a 730-step simulation the name will be 'lakh0000.730', and so on.

Annex 6: Simulation and reporting of water levels

Introduction

Within LISFLOOD it is possible to simulate and report water levels in the channel. The simulation of water levels is *optional*, and it can be activated by adding the following line to the 'lfoptions' element:

```
<setoption name="simulateWaterLevels" choice="1" />
```

If the option is switched on, water levels are calculated for channel pixels where either kinematic or dynamic wave routing is used. Using this option does *not* influence the actual model results in any way, and it is included only to allow the model user to report water levels. The actual *reporting* of the simulated water levels (as time series or maps) can be activated using two separate options.

Calculation of water levels

For channel stretches that are simulated using the dynamic wave, the water level in the channel is simply the difference between the channel head and the channel bottom level. For kinematic wave stretches, only approximate water levels can be estimated from the cross-sectional (wetted) channel area, A_{ch} for each time step. Since the channel cross-section is described as a trapezoid, water levels follow directly from A_{ch} , channel bottom width, side slope and bankfull level. If A_{ch} exceeds the bankfull cross-sectional area (A_{bf}), the surplus is distributed evenly over the (rectangular) floodplain, and the depth of water on the floodplain is added to the (bankfull) channel depth. Figure A6.1 below further illustrates the cross-section geometry. All water levels are relative to channel bottom level (z_{bot} in the Figure).

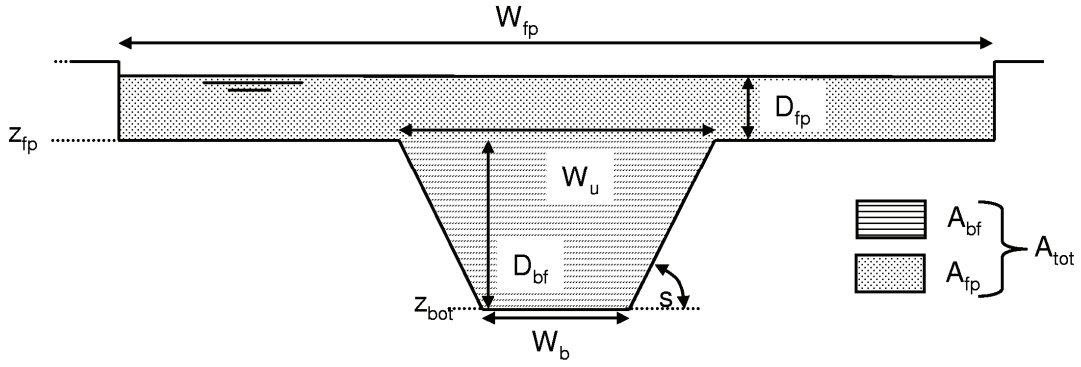

Figure A6.1 *Geometry of channel cross-section in kinematic wave routing.* W_b*: channel bottom width;* W_u*: channel upper width;* z_{bot}*: channel bottom level;* z_{fp}*: floodplain bottom level;* s*: channel side slope;* W_{fp}*: floodplain width;* A_{bf}*: channel cross-sectional area at bankfull;* A_{fp}*: floodplain cross-sectional area;* D_{bf}*: bankfull channel depth,* D_{fp}*: depth of water on the floodplain*

In order to calculate water levels, LISFLOOD needs a map with the with of the floodplain in [m], which is defined by 'lfbinding' variable *FloodPlainWidth* (the default name of this map is chanfpln.map).

Reporting of water levels

Water levels can be reported as time series (at the gauge locations that are also used for reporting discharge), or as maps.

To generate a time series, add the following line to the 'lfoptions' element of your settings file:

```
<setoption name="repWaterLevelTs" choice="1" />
```

For maps, use the following line instead:

```
<setoption name="repWaterLevelMaps" choice="1" />
```

In either case, the reporting options should be used *in addition* to the 'simulateWaterLevels' option. If you do not include the 'simulateWaterLevels' option, there will be nothing to report and LISFLOOD will exit with an error message.

Preparation of settings file

The naming of the reported water level time series and maps is defined in the settings file. If you are using a default LISFLOOD settings template, all file definitions are already defined in the 'lfbinding' element.

Time series:

```
<textvar name="WaterLevelTS" value="$(PathOut)/waterLevel.tss">
<comment>
Reported water level [m]
</comment>
</textvar>
```

Map stack:

```
<textvar name="WaterLevelMaps" value="$(PathOut)/wl">
<comment>
Reported water level [m]
</comment>
</textvar>
```

Annex 7: Simulation and reporting of soil moisture as pF values

Introduction

LISFLOOD offers the possibility to calculate pF values from the moisture content of both soil layers. The calculation of pF values is *optional*, and it can be activated by adding the following line to the 'lfoptions' element:

```
<setoption name="simulatePF" choice="1" />
```

Using this option does *not* influence the actual model results in any way, and it is included only to allow the model user to report pF time series or maps. The actual *reporting* of the computed pF values (as time series or maps) can be activated using separate options (which are discussed further on).

Calculation of pF

A soil's pF is calculated as the logarithm of the capillary suction head, *h*:

$$pF = \log_{10}(h)$$

with *h* in [cm] (positive upwards). Values of pF are typically within the range 1.0 (very wet) to 5.0 (very dry). The relationship between soil moisture status and capillary suction head is described by the Van Genuchten equation (here again re-written in terms of mm water slice, instead of volume fractions):

$$h = \frac{1}{\alpha}\left[\left(\frac{w_s - w_r}{w - w_r}\right)^{1/m} - 1\right]^{1/n}$$

where *h* is the suction head [cm], and *w*, w_r and w_s are the actual, residual and maximum amounts of moisture in the soil respectively (all in [mm]). Parameter α is related to soil texture. Parameters *m* and *n* are calculated from the pore-size index, λ (which is related to soil texture as well):

$$m = \frac{\lambda}{\lambda + 1}$$

$$n = \lambda + 1$$

If the soil contains no moisture at all (*w*=0), *h* is set to a fixed (arbitrary) value of $1 \cdot 10^7$ cm.

Reporting of pF

pF can be reported as time series (at the locations defined on the “sites” map or as average values upstream each gauge location), or as maps. To generate time series at the “sites”, add the following line to the ‘lfoptions’ element of your settings file:

```
<setoption name="repPFTs" choice="1" />
```

For maps, use the following lines instead (for the upper and lower soil layer, respectively):

```
<setoption name="repPF1Maps" choice="1" />
<setoption name="repPF2Maps" choice="1" />
```

In either case, the reporting options should be used *in addition* to the ‘simulatePF’ option. If you do not include the ‘simulatePF’ option, there will be nothing to report and LISFLOOD will exit with an error message.

Preparation of settings file

The naming of the reported time series and maps is defined in the settings file. Tables A7.1 and A7.2 list the settings variables default output names. If you are using a default LISFLOOD settings template, all file definitions are already defined in the ‘lfbinding’ element.

Time series:

```
<comment>
PF TIMESERIES, VALUES AT SITES
</comment>

<textvar name="PF1TS" value="$(PathOut)/pFTop.tss">
<comment>
Reported pF upper soil layer [-]
</comment>
</textvar>

<textvar name="PF2TS" value="$(PathOut)/pFSub.tss">
<comment>
Reported pF lower soil layer [-]
</comment>
</textvar>

<comment>
PF TIMESERIES, AVERAGE VALUES UPSTREAM OF GAUGES
</comment>

<textvar name="PF1AvUpsTS" value="$(PathOut)/pFTopUps.tss">
<comment>
Reported pF upper soil layer [-]
</comment>
</textvar>

<textvar name="PF2AvUpsTS" value="$(PathOut)/pFSubUps.tss">
<comment>
Reported pF lower soil layer [-]
</comment>
</textvar>
```

Map stacks:

```
<comment>
PF MAPS
</comment>

<textvar name="PF1Maps" value="$(PathOut)/pftop">
<comment>
Reported pF upper soil layer [-]
</comment>
</textvar>

<textvar name="PF2Maps" value="$(PathOut)/pfsub">
<comment>
Reported pF lower soil layer [-]
</comment>
</textvar>
```

Table A7.1 *pF map output*

Description	Option name	Settings variable	Default prefix
pF upper layer	repPF1Maps	PF1Maps	pftop
pF lower layer	repPF2Maps	PF2Maps	pfsub

Table A7.2 *pF timeseries output*

pF at sites (option *repPFSites*)		
Description	**Settings variable**	**Default name**
pF upper layer	PF1TS	pFTop.tss
pF lower layer	PF2TS	pFSub.tss

pF, average upstream of gauges (option *repPFUpsGauges*)		
Description	**Settings variable**	**Default name**
pF upper layer	PF1AvUpsTS	pFTopUps.tss
pF lower layer	PF2AvUpsTS	pFSubUps.tss

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Abstract

The revised LISFLOOD User Manual documents the LISFLOOD water balance and flood simulation model. The first part of this document gives a detailed description of the characteristics of the LISFLOOD model, focusing on process descriptions and the governing equations. The second part covers all practical LISFLOOD issues, such as installing the model, setting up the necessary input data and running it.

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