2.2 Models

2.2.1 A range of models and underlying assumptions

The basic logic of a water balance that follows water in its passage through vegetation, soil, and rivers to either the atmosphere or the ocean is easily captured in quantitative models.

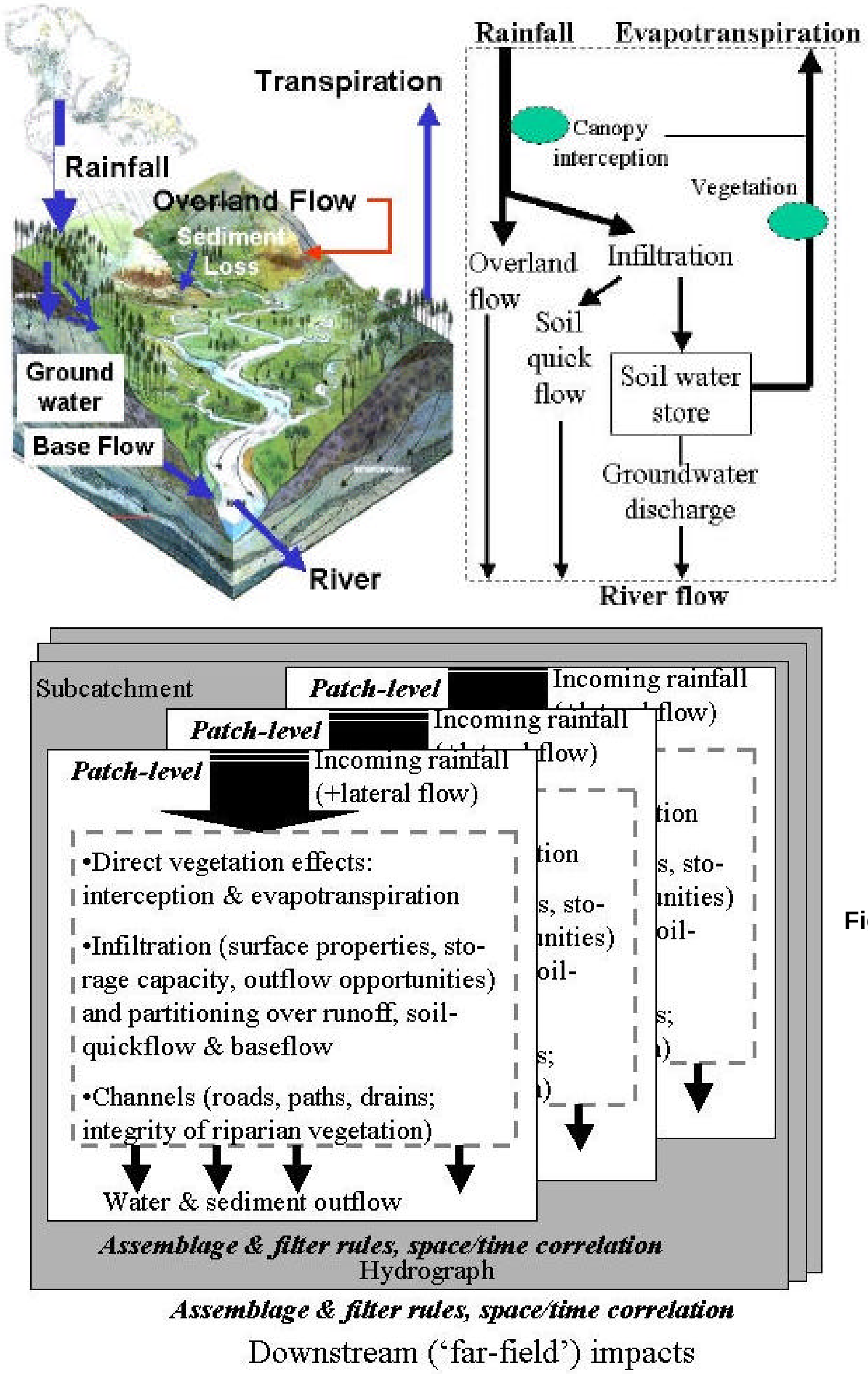


Figure 2.28. Link between patch-level water balance and catchment level hydrological functions; the various models are all based on similar 'water balance logic' but differ in the details of the assemblage and filter rules that are used to predict river flows.

Models, if correctly implemented, allow for an explicit representation of the consequences of a series of assumptions. No model is correct, no model is wrong – but the assumptions may or may not be sufficient and necessary to reconstruct the phenomena that we can observe. As different modelers may have slightly different interpretations of the same set of assumptions, or differ in the assumptions they make, it is generally relevant to compare between different model implementations, even if they refer to broadly the same set of hypotheses. In the context of 'activity 2', we will explore a number of models that were initially developed for different sets of circumstances, temporal and spatial scales. Before we represent results of these models, we thus need to clarify the various assumptions, similarities and differences.

All models will be used for a comparison of 'natural vegetation (baseline) versus current land use pattern', with current climate. A specific effort will be made to derive location-specific scenarios of plausible land use change, that will be evaluated for its bearing on hydrological functions (see section 2.3).

Although most models follow a water balance logic (compare Table 1.4), there are substantial differences in model complexity based on the number of feedbacks that are included in the interaction between vegetation, soil and rainfall (Fig. 2.29)

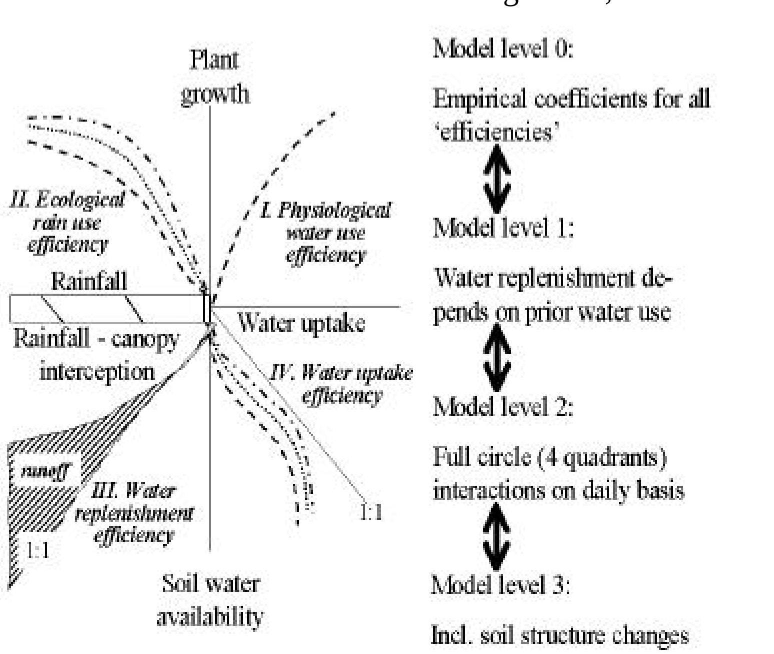


Figure 2.29. Four-quadrant representation (compare Van Noordwijk et al., 2004) of the relations involved in water use efficiency, and 4 model 'levels' depending on the use of interactions between quadrants rather than fixed coefficients; the different lines relate to plants with different uptake efficiency and/or transpirational demand

The simplest models ('null-models') work on the basis of 'run-off coefficients' and 'water uptake and water utilization efficiency' and can thus relate total rainfall to both total water yield in rivers and plant production. Models at level 1 acknowledge that infiltration depends on prior water use. Models at level 2 include two-way interactions between all quadrants. Models at level 3, in addition, consider changes in soil structure and infiltration properties over longer time scales. The more complex the model, the larger the number of parameters and the easier it is to 'fit' the model to any empirical data set, without gain in confidence for extrapolation to new situations. Yet, a number of the feedbacks are based on solid empirical evidence and their inclusion can enhance the range of model applicability.

Empirical run-off coefficients

The relationship between daily rainfall events and surface runoff (Fig. 2.30) is often approached by linear regression to derive a 'typical runoff fraction ' (suggesting a line through the origin) or a linear function with an intercept on the X-axis (all rainfall below X_0 mm day^{-1} can infiltrate, above that only a fraction); in more complete data sets we normally see a tendency for an increase in slope of the amount of run-off per unit rainfall. Theoretically we expect the marginal increase in runoff per unit additional rainfall to approach 1 once the full is fully saturated.

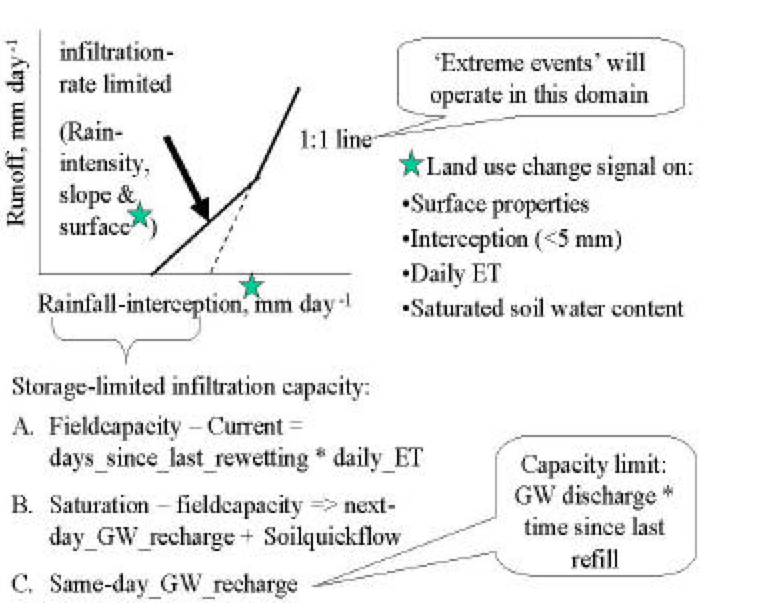


Figure 2.30. Schematic representation of the empirical relationship between surface runoff and rainfall and the aspects of the graph that can potentially be influenced by land use change

While the textbooks distinguish 'infiltration limited' (or Hortonian) overland flow from saturation overland flow (or SOF), in mechanistic models at least four controls on infiltration of rain into soils can be distinguished (Fig. 2.31).

Of these four controls, the following three can be influenced by land cover:

- 2. the rate of water use between rainfall events (relative to the potential evapotranspiration dominated by the energy balance), which determines the '***antecedent soil water deficit***' (at the time of the next rainfall event) below field capacity that can be recharged through rainfall; the faster water is used, the more will be able to infiltrate during the next rainfall event,
- 3. the fraction of water that can actually infiltrate given the rate at which it arrives, the potential infiltration and the time available:

- o 3A. the rate at which rainfall arrives at the soil surface, modified by canopy interception and leaf drip (this is only of importance for short periods of intense rainfall)
- o 3B. ***infiltration potential of the soil surface*** and its change in soils sensitive to slaking (i.e. fine soil particles can regroup from micro-aggregates to form a 'sealed' surface; in some soils algae may further contribute to a 'hydrophobic' character of the surface,
- o 3C. the ***time available for infiltration*** will depend on the slope and opportunities for temporary surface water storage related to micro-relief, which can be modified by land users
- o 3D. the possible rate of outflow from the soil profile, either vertically into subsoil and groundwater or laterally, during the infiltration event

- 4. the difference between field capacity and saturated soil water content (over the whole profile depth) may lead to infiltration at the time of rainfall and either seepage into groundwater or subsurface lateral flow ('soil quick flow') during the next 24 hours.

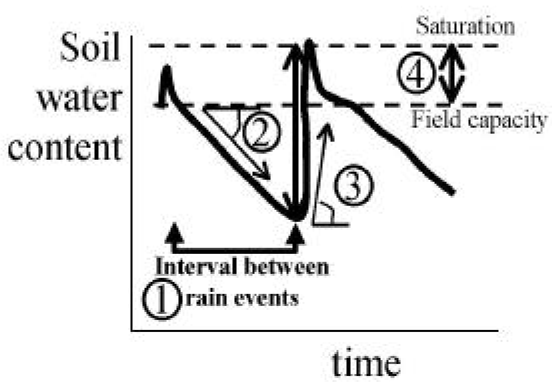


Fig. 2.31. Schematic time course of soil water content and soil physical understanding of the determinants of the infiltration process: (1) time interval between rainfall events, (2) rate of soil water depletion between rainfall events, creating soil storage space, (3) potential rate of infiltration into the soil, in relation to the intensity of rainfall and (slope-dependent) opportunities for temporary water storage at the soil surface, and (4) difference between 'field capacity' (= soil water content 24 hours after a heavy fall of rain, when the rate of water seepage to deeper layers tends to reach a small value) and 'saturated' soil water content, when all soil pores are water-filled

Land use change can affect all these controls, through difference in water use of vegetation relative to potential evapotranspiration (even though differences are likely to be bigger during a 'dry season' due to differences in deciduousness),

- 3A) providing a protective cover that slows down (and evens out) the rate at which water reaches the soil surface
- 3B) providing continuous protection of the mineral soil via a litter layer that also stimulate soil biota that increase soil porosity, or expose the soil to sun and rain with opportunity for slaking and sealing,
- 3C) providing more or less temporary water storage opportunities at the soil surface, and thus increasing or decreasing the time available for infiltration,
- increasing or decreasing macroporosity of the soil, and thus the propensity for 'soil quick flow' rather than overland flow.

Nearly all models, even those applied at a global or river-basin scale used in 'activity 1' (Vörösmarty *et al.*, 2000), include the first and second control listed above in their predictions of the impact land-use change will have on river behaviour (and thus operate on 'level 1' of the classification in Fig. 2.33). The effects of land use on the third and fourth controls listed above are only included in the 'level 2 & 3' models such as DHSVM (http://www.hydro.washington.edu/Lettenmaier/Models/DHSVM/index.htm; Wigmosta *et al.*, 1994) and WaNuLCAS (van Noordwijk and Lusiana, 1999), which were developed for high-resolution applications.

All models predict a 'hydrograph' (daily (or monthly) rate of flow at specific points in the network), and from this the annual water yield and the dry season river flow can be inferred. Maximum and minimum discharge per month or year can always be derived; the operational definitions used for base flow and peak flow vary.

In deciding on an appropriate process description for a model of the water balance choices for spatial and temporal scale need to be linked. Models that describe soil physical details of the infiltration process may need to consider a time scale of seconds, as there are rapid changes in hydraulic conductivity during infiltration into dry soils, and consider spatial units of 1 cm^3 or less as basic entity; integrating them over more than one or a few m^2 may put limits to the speed of model execution. Yet, models at this temporal and spatial scale can be used to test the validity of coarser ('bucket overflow') descriptors that can be used in models at daily scale and integrated over substantially larger areas. The main relations in the 'family' of models developed and/or used by ICRAF is shown in Fig. 2.32. The models and technical descriptions are available on the ICRAF.org/SEA website (for WEPP see http://topsoil.nserl.purdue.edu/nserlweb/weppmain/wepp.html); we will only highlight some of the key features relative to the scope of our current effort.

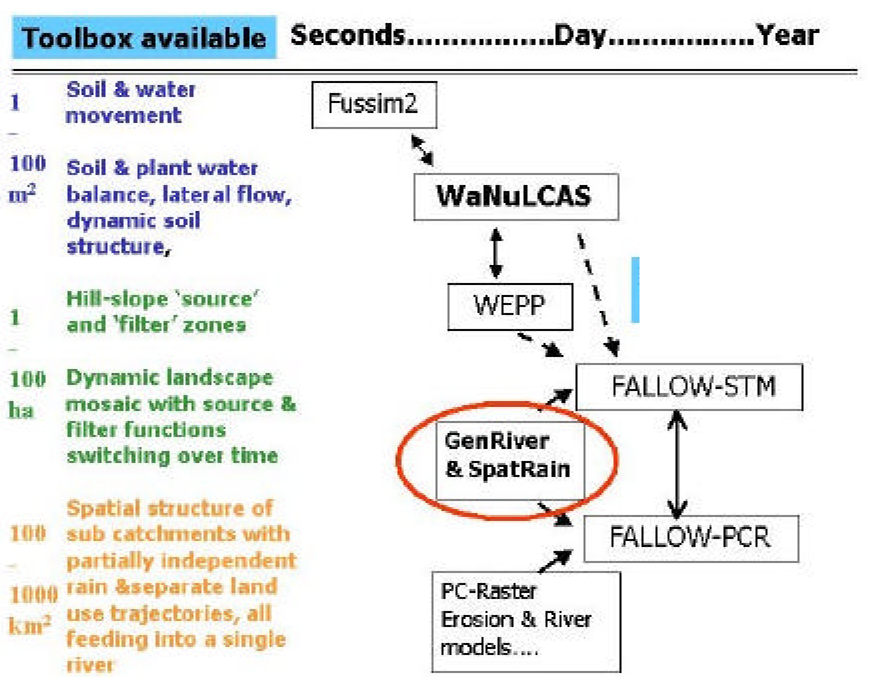


Figure 2.32. Spatial and temporal scale of a number of models of the water balance that can be used to explore relationships between land cover/land use and the water balance, influencing river discharge at landscape scale

2.2.2 Hydrologic Null-model

In Fig. 1.4, three steps can be distinguished in a typical land cover change scenario: A) initial forest conversion, B) subsequent degradation of the land until C) a rehabilitation phase is reached. At a very basic level we can explore what these three stages mean for the total water yield, the base flow of rivers and the amount of peak flow (quick flow), across a wide range of annual rainfall amounts.

To do that we make the following assumptions:

Total water use by vegetation is higher for natural forest (due to greater canopy interception, greater aerodynamic roughness of the canopy, a more perennial nature of green canopy and a deeper root systems allowing for dry period exploitation of subsoil water reserves) than for the agricultural crops that follow it; the difference is typically 300 mm $year^{-1}$ (Zhang et al., 2003; Best et al., 2003)

A simple run-off fraction determines the part of the rainfall that reaches the river as ‘quick flow’ generating ‘peak flow’; the remaining part of the rainfall infiltrates into the soil and, after subtraction of total water use by the vegetation, generates the ‘slow flow’ that determines the ‘base flow’ of the river; the runoff fraction of forest depends on the slope, soil depth, soil texture and the typical intensity of rainfall (with a range of 0.1 – 0.3 as reasonable estimates for the humid tropics).

Depending on the land use practice after forest conversion, the runoff fraction will tend to increase above its value for the natural forest, causing a shift from base flow towards peak flow; the increase may reach a 0.2 - 0.4 for open –field agriculture in the absence of any soil conservation practices.

Reforestation as part of ‘rehabilitation’ will rapidly return the total water use to the level of the preceding natural forest (or more than that for fast-growing trees), but will only gradually induce changes in the soil that reduce the run-off fraction.

In a ‘hydrological null-model’ we can directly derive from 3 equations:

$$\Sigma Stormflow = Runoff\_fraction * \Sigma Rainfall \qquad (1)$$

$$VegWatUse = \min(\Sigma(E_{pot} * ReductionFactor), (1 - Runoff\_fraction) * \Sigma Rainfall) \qquad (2)$$

$$\Sigma Baseflow = \Sigma Rainfall - \Sigma Stormflow - VegWaterUse \qquad (3)$$

where

- ΣQuickflow = summation over one year (or more if inter-annual changes in water storage are deemed to be important) of river flow based on surface runoff during storm events
- Runoff_fraction = fraction of rainfall that does not infiltrate into the soil but becomes surface runoff
- ΣRainfall = summation over one year (or more if inter-annual changes in water storage are deemed to be important) of rainfall
- ΣVegWatUse = total water use by vegetation and soil
- E_{pot} = the energy-limited potential rate

- ReductionFactor = potential evapotranspiration of the land cover relative to the energy-limited potential rate, linked to (seasonal) leaf area index
- ΣBaseflow = summation over one year (or more if inter-annual changes in water storage are deemed to be important) of river flow that is based on infiltration during storm events

These equations combine to a simple expression for our first indicator of watershed functions (total water yield per unit rainfall) (if we assume that the daily ReductionFactors are not linked to daily E_{pot} values):

TotWatYield/ΣRainfall = (ΣQuickflow+ΣBaseflow)/ΣRainfall = 1–VegWatUse/ΣRainfall = 1 - min((Epot/ΣRainfall)*ΣReductionFactor, (1- Runoff_fraction) (4)

where

- TotWatYield is total water yield of a river catchment, per unit catchment area.

From equation (4) we can see that in relatively dry areas (E_{pot} /ΣRainfall >> 1) total water yield per unit rainfall directly depends on the runoff fraction, as is evident from traditional 'water harvesting practices' that enhance run-off in catchment areas (as there is a negligible 'base flow' and all water infiltrating will be used by vegetation). In very wet areas (E_{pot} /ΣRainfall << 1) total water yield may be influenced by vegetation via the reduction factors.

This model can be easily implemented in a simple spreadsheet and applied across a full range of rainfall regimes. In the results section we describe model calculations for the three stages (A, B and C) of a land use trajectory.

2.2.3 FALLOW

FALLOW (van Noordwijk, 2002; Suyamto *et al.*, 2003) is a spatially explicit landscape-dynamics model, which considers households of farmers as the changing agents and comprises the following main annual dynamic processes (Fig. 2.33):

- plot-level soil fertility dynamics in crop and fallow phases affecting agricultural crop production and plot-level productivity of other land uses (e.g. ntfp, agroforestry, monoculture plantation, etc.);
- food consumption and storing by agents, that may involve exchange of other resources through trading (i.e. food and any other yields), with options along the spectrum from 'full dependence on local food production' to 'fully market-integrated' economy, affecting landscape level household economy;
- agents' learning on expected profitability of various land use options, affecting the decisions on increase or decrease of the area cropped, adopted land use systems and labor allocation;
- plot-level implementation of strategic decisions by agents through resource availability identification, covering labor and preferred sites availability; and
- ecosystem succession and growth.

FALLOW also provides impact assessment toolboxes on how the resultant mosaic of land cover will affect watershed functions (annual water yield, base flow, net sediment loss), biodiversity indicators and carbon stocks.

Initially developed as a Stella model, FALLOW has now been re-implemented in the spatially explicit modelling environment of PCRaster, making it possible to apply the model to larger landscapes with real spatial data sets. FALLOW can be used for impact assessment and scenario studies, assisting the negotiation process between stakeholders in a changing landscape by visualizing possible/likely consequences of factors such as changes in prices, population density and human migration, availability of new technology, spatial zoning of land use, pest and disease pressure or climate.

Staying essentially at a yearly time step, the FALLOW model differs from the hydrological null-model in that it:

- integrates over a mosaic of patches that each have their own runoff fraction (linked to slope, soil conditions and land cover history) and current water use depending on the vegetation,
- considers spatially explicit changes in land cover in a mosaic context, that impact of soil physically quality and thus infiltration and runoff,
- includes human agents decisions on land use driven by overall targets and a spatially-explicit rule set for implementation,
- includes rules for surface erosion and deposition in filter zones,
- allows for estimation of a number of biodiversity indicators, and thus for studying trade-offs between land use intensity, watershed functions and biodiversity.

For the Mae Chaem situation, we began with parameterization of the FALLOW model for a subsistence-oriented shifting cultivation system that is experiencing a steady reduction in the length of its fallow period, during which soil recovery is associated with regenerating forest vegetation.

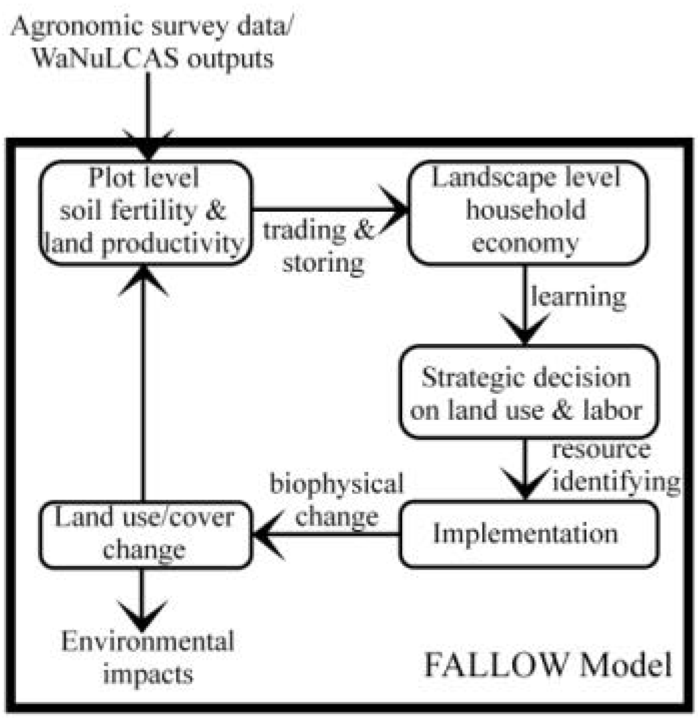


Figure 2.33. Core module of FALLOW and the use of the WaNuLCAS model (see below) for parameterizing crop yields and plot level impacts on the water balance of different crop-fallow mosaics

FALLOW includes a simple annual water balance at patch level, with an allocation of incoming rain over evapotranspiration, overland flow and infiltration, that depends on a soil physical quality that changes in a positive or negative direction depending on current land cover type and its assumed supply of food for soil biota. In interaction with soil physical quality, water infiltration is also determined by slope at plot level (Figure 2.34). Surplus from this first filtering step determines the overland flow. Under saturated soil conditions, infiltrated water will flow out as subsurface quick flow and together with the overland flow produce storm flow. Water that reaches the groundwater storage is released as base flow. Overland flow multiplied with a user-defined average sediment concentration per land cover class determines gross erosion. FALLOW also assigns a potential filter function to each plot (depending on contact cover by litter) and derives a net erosion loss that leads to the sediment load of rivers. The most critical phase of land use/cover change is found within the pioneer phase, due to relatively low filter efficiency. Filter effects only can be exerted along the pathway of overland flow, giving a specific relevance to 'riparian filter zones'.

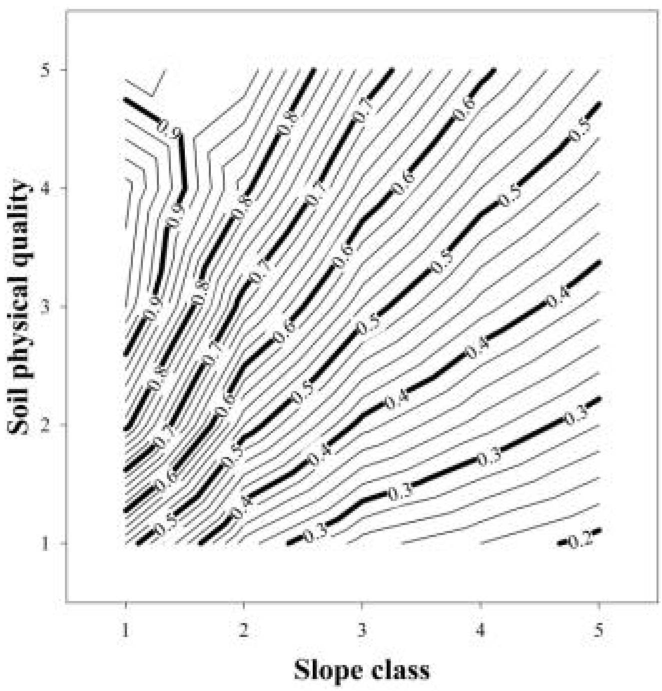


Figure 2.34. Infiltration fraction (contour) of a plot depending on slope and soil physical quality; slope is classified according to USLE **(1:** slope < 1%, **2:** 1%d slope < 3%, **3:** 3%d slope <5%, **4:** 5%d slope < 20%, **5:** slope > 20%); where soil physical quality represents its aggregate stability.

On the basis of the Digital Elevation Model (DEM) and rainfall, we developed an application for the meso-scale catchment of a coffee producing area in Sumberjaya, Lampung, Sumatra, predicting impacts on watershed functions of various ways of spatially allocating 'forest reserves' and land use/cover changes as farmers' response to coffee price shocks.

For a 25% forest cover, a comparison was made based on five allocation rules:

- Random,
- Ridge tops,
- Steepest slopes,
- Riparian zones,
- Zones far from the village.

The zones (Fig. 2.35) were delineated according to distance to river with a threshold of 100 m nearby the river (riparian forests), steepness with threshold of 20% (sloping forests), elevation with threshold of 1000 m a.s.l. (ridge top forests), a uniformly random choice (random forests) and ‘remote forests’ at a distance to settlements of more than 1 km. We focused on the prediction of net sediment loss from the landscape to the river.

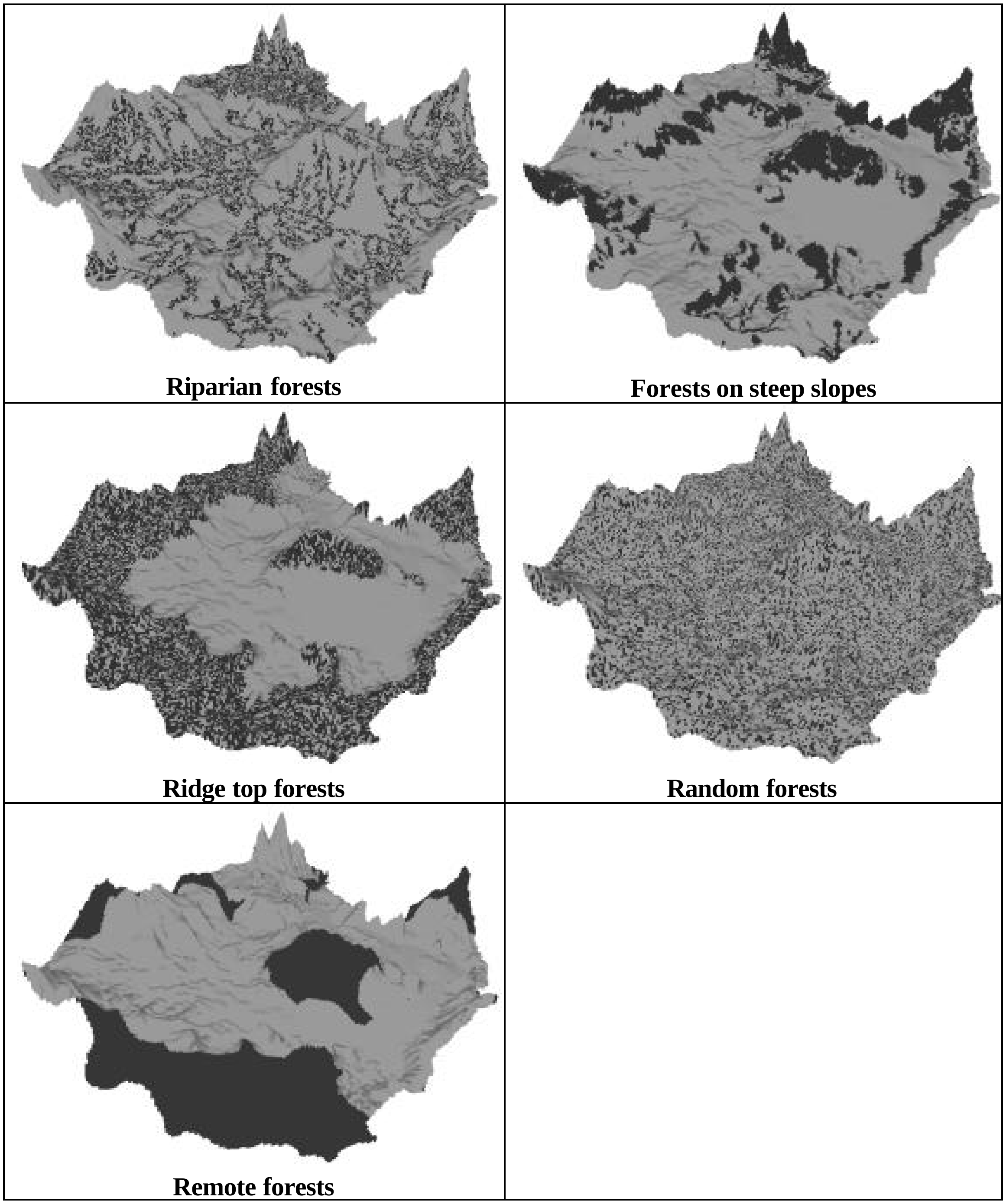
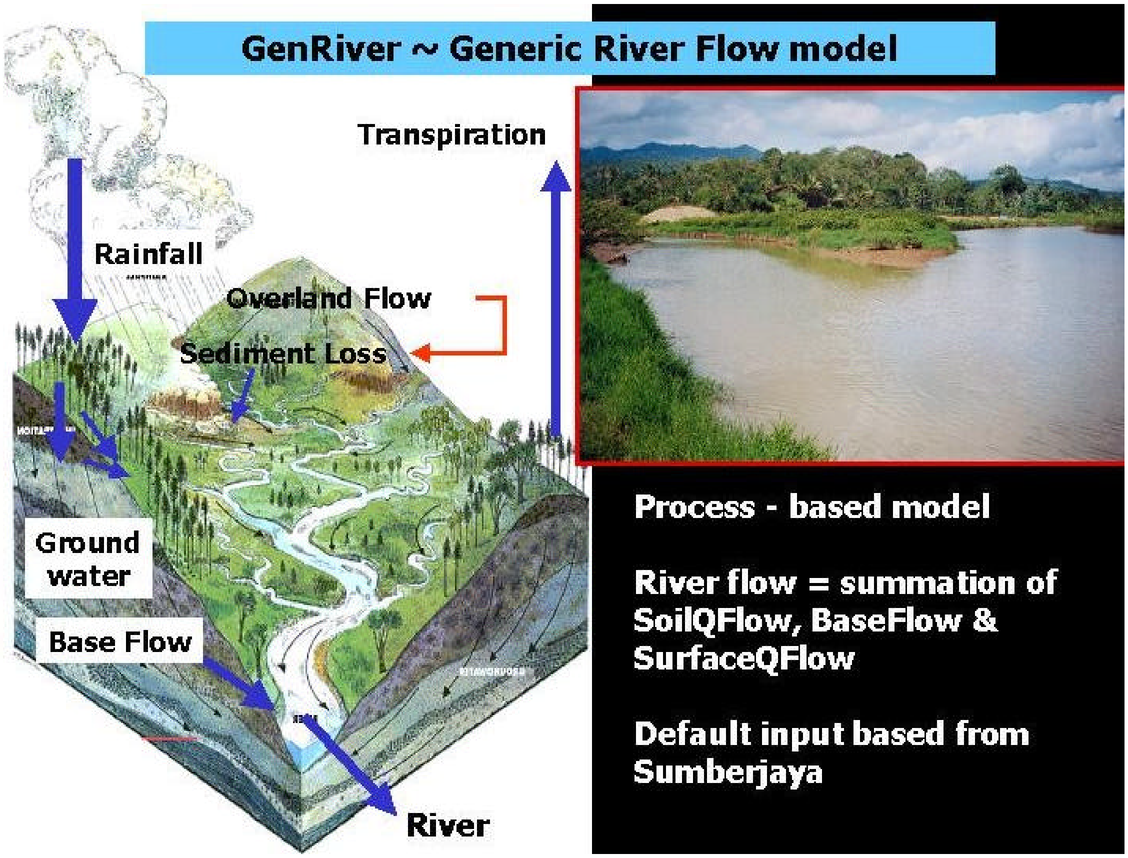


Figure 2.35. Five spatially explicit ways of allocating 25% forest cover over the Sumber Jaya (Way Besai) catchment (with rules that effectively protect forest from conversion, while allowing collection of forest products) for use with the FALLOW model.

2.2.4 GenRiver



The GenRivermodel was designed to bridge between 'parsimonious' (few parameter) models that are essentially fitted to empirical data, and distributed process-based models, by gradually allowing the parsimonious model to be spatially differentiated, as the need arises. The core is a 'patch level representation of a daily water balance, driven by local rainfall and modified by the land cover and soil properties of the patch. The patch can contribute to three types of stream flow: surface-quick flow on the day of the rainfall event, soil-quick flow on the next day and base flow, via the gradual release of groundwater. The overall water balance of the model is, summed over space and time:

In	**Out**
+ Rainfall	- Evaporation of canopy intercepted
+ Changes in soil and groundwater storage	- Evapotranspiration from soil surface and by plants
+ Changes in the volume of water in streams and rivers	- River discharge (summed over base , soil quick flow and surfacequickflow)
	- Error term (difference between all in & out terms; negligible if model is correctly implemented)

For the long-term behaviour the changes in soil and groundwater storage, as well as changes in the volume of streams and rivers will be negligible, while the error term should be negligible at all times if the model is correctly implemented.

On shorter time scales, however, the changes in storage in soil, groundwater, streams and rivers are critically important for the variability in (daily) river flow as reflected in the 'hydrograph'. If measured data for river discharge are entered, a direct comparison of measured and simulated river discharges can be made (Fig. 3.36).

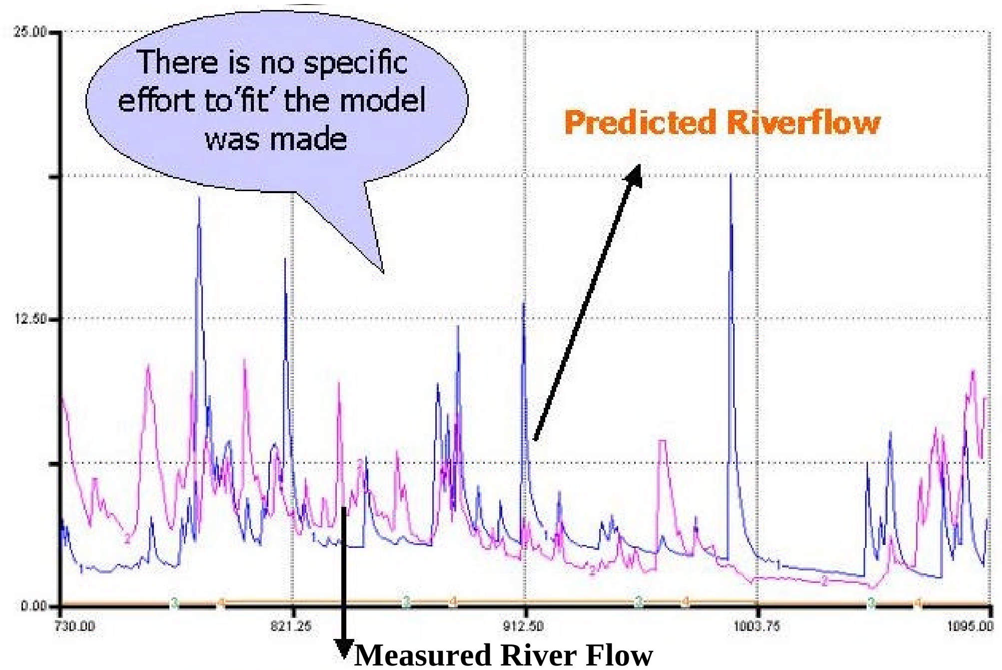


Figure 3.36. An example of a hydrograph as output of the model for one year of simulation

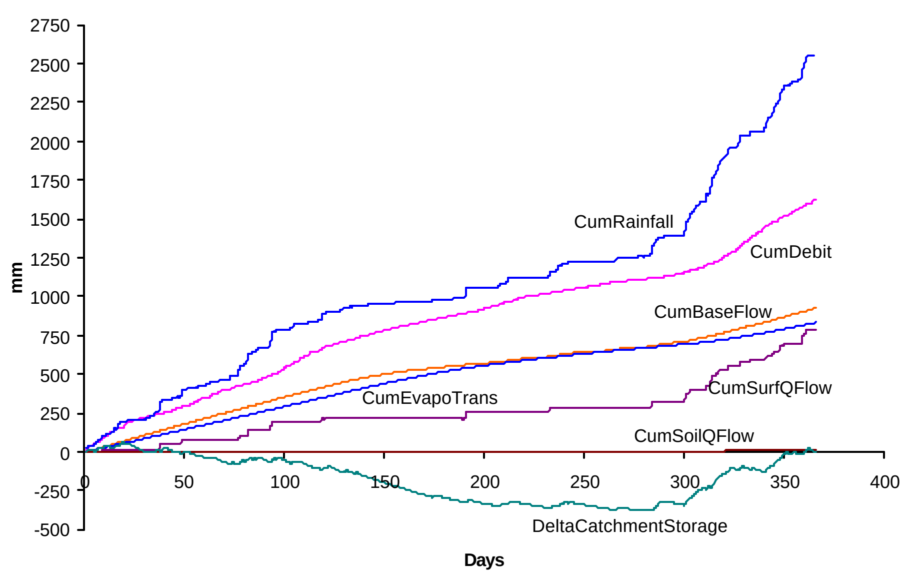


Figure 3.37. Cumulative water balance as output of the model with cumulative river discharge(CumDebit), approximately equal to cumulative rainfall (CumRainfall) minus cumulative evapotranpiration (CumEvapoTrans). The dynamic change in catchment storage (DeltaCatchmentStorage) account for difference between these cumulative terms. Cumulative basedischarge (CumBaseDischarge), surface quick discharge (CumSurfQDischarge) and soil quick flow (CumSoilQFlow) can be calculated in this model.

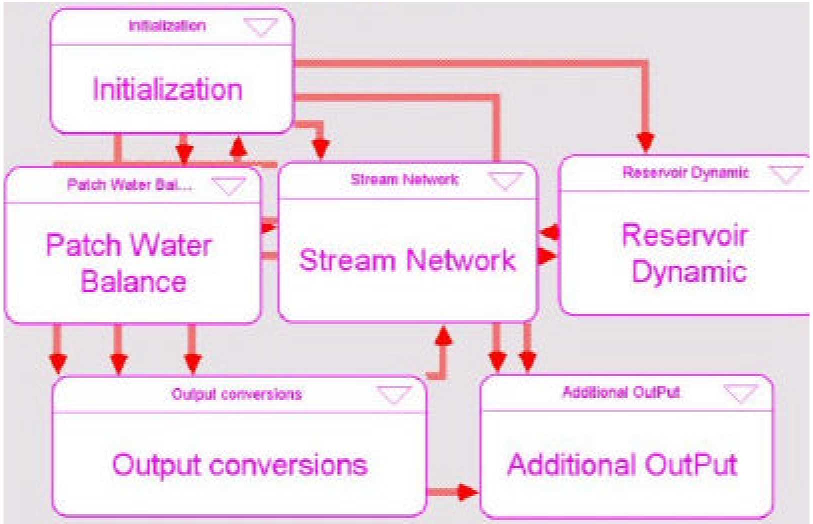


Figure 2.38. Component sectors of the model; the 'reservoir dynamic' section is optional and has not been used yet

Brief description of GenRiver and component processes

A ***river*** is treated as a summation of ***stream***s, each originating in a ***subcatchment*** with its own daily rainfall, yearly land cover fractions and constant total area and distance to the river outflow (or measurement) point. Interactions between streams in their contribution to the river are considered to be negligible (i.e. there is no 'backflow' problem). Spatial patterns in daily rainfall events are translated into average daily rainfall in each subcatchment in a separate module. The ***subcatchment*** model represents interception, infiltration into soil, rapid percolation into subsoil, surface flow of water and rapid lateral subsurface flow into streams with parameters that can vary between land cover classes.

Rainfall

Rainfall at subcatchment level is implemented as daily amounts from long time records for each subcatchment, stored in an Excel spreadsheet. These data can be derived from actual records, or from a 'random generator' that takes temporal patterns (SpatRain, see below) Rainfall intensity is treated as a parameter with a mean and standard deviation that are constants throughout a simulation.

Interception

Storage capacity for intercepted water is treated as a linear function of leaf + branch area index of the land cover, with the option of modifiers for surface properties that determine the thickness of the water film. Interception-evaporation has priority over plant transpirational demand.

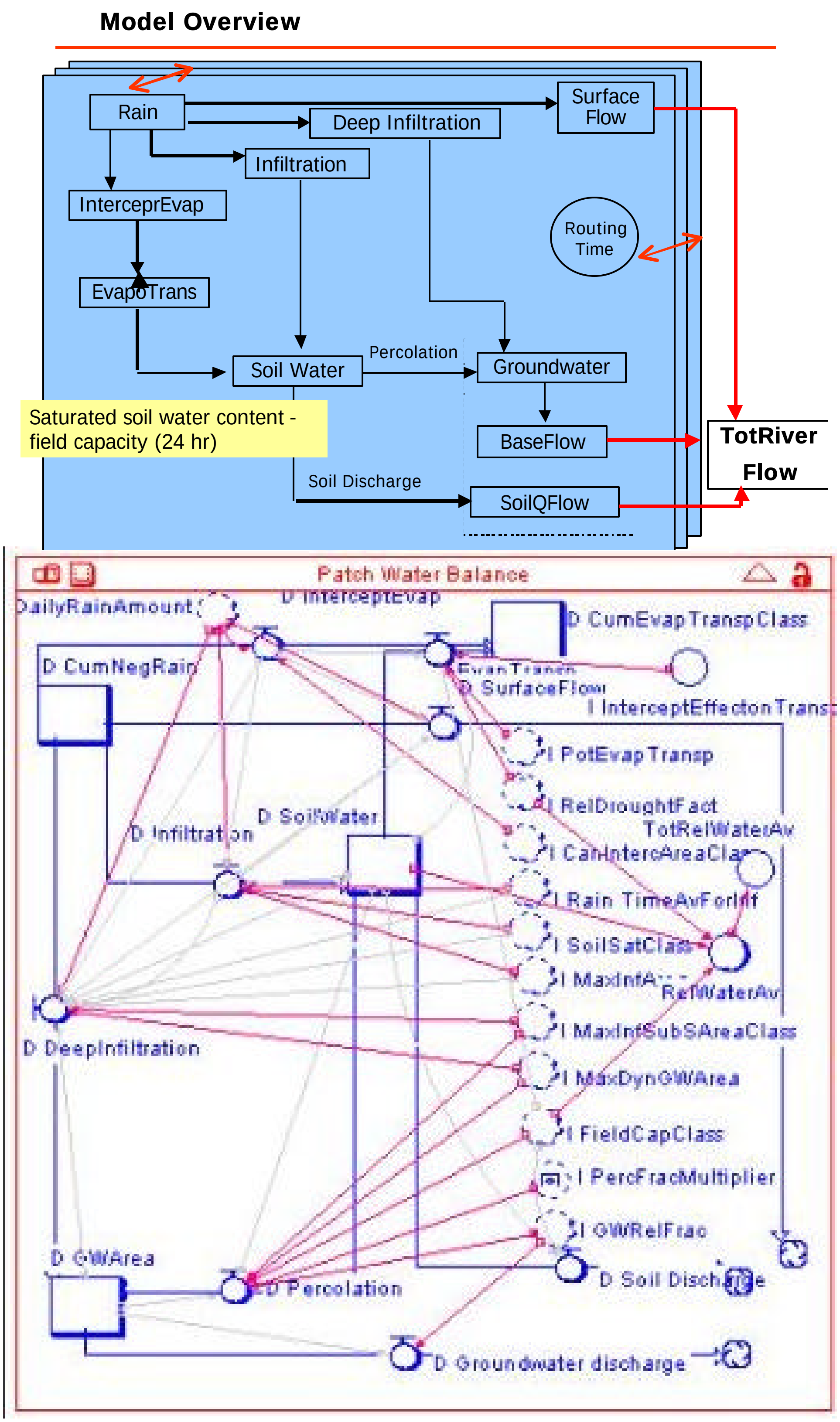


Fig. 2.39. Implementation of the patch level water balance model of GenRiver

Surface infiltration/runoff

The description of the infiltration process is similar to that in WaNuLCAS and the parameterization can be derived for a wide range of land cover types (and histories) from tests with that, more detailed model. Infiltration is calculated as the minimum of the daily infiltration capacity times the fraction of a day that is available for infiltration (the latter reflects rainfall intensity as well as the local storage capacity of the soil surface) the amount that can be held by the soil at saturation minus the amount already present ***plus*** the amount that can enter the groundwater within a day (which in itself is the minimum of the potential daily transport rate and the difference between maximum storage capacity of groundwater and the current amount) If the first constraint is active, the model generates 'infiltration limited runoff', in the second case 'saturation overland flow'. The sum of both is included as 'surface quick flow'.

Evapotranspiration

Total evapotranspiration is driven by potential evapotranspiration (Penman-Monteith type) and (partially) met by:

- intercepted water
- land cover, with a drought-limitation proportional to soil water content relative to field capacity below a (vegetation dependent) threshold potential relative evapotranspiration per land cover type (per month) (a monthly multiplier on potential daily evapotranspiration, reflects overall phenology)
- soil surface evaporation (not explicit – to be included in the land cover/vegetation properties for transpiration)

Soil water redistribution

During a rain event the soil may get saturated, but within one day it is supposed to drain till 'field capacity' (with an operational definition of the soil water content 24 hours after a heavy rainfall event). The difference between saturation and field capacity can be either:
used for transpiration (but canopy intercepted rainfall takes priority to meet the demand)
drain to the groundwater reserve, calculated as the minimum of the amount that can be transported downwards and the fraction of soil water that will drain on any given day
drain to the rivers as 'soil quickflow': any water left above field capacity by the two preceding processes

Groundwater release to streams (baseflow)

Surface quickflow, soilquickflow and baseflow all feed into streams. For each subcatchment a 'Routing' function determines the time delay before the water passes by a defined measuring point (currently the outflow from the catchment).

Distance (routing distance)

Distance from the mid point of each sub-catchment to any number of observation point . This parameter will derive the routing time for each sub-catchment to each of the observation point, while excluding sub-catchment downstream of the observation point.

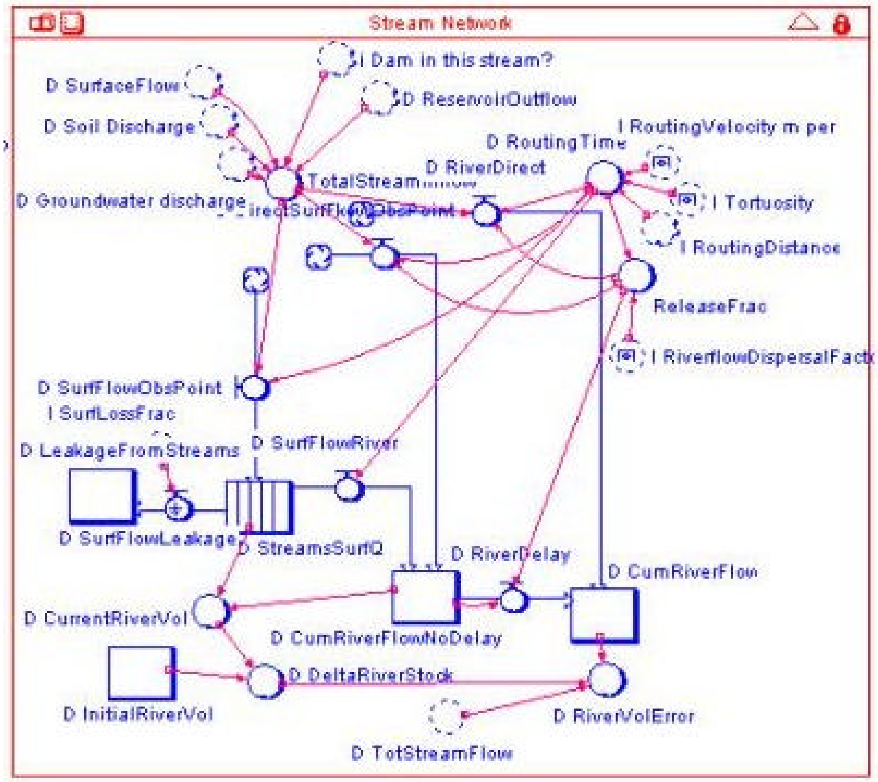


Figure 2.40. The routing section of the model causes a delay in the arrival at specified measurement points of water delivered to the streams in the patch model, as well as an attenuation of peaks

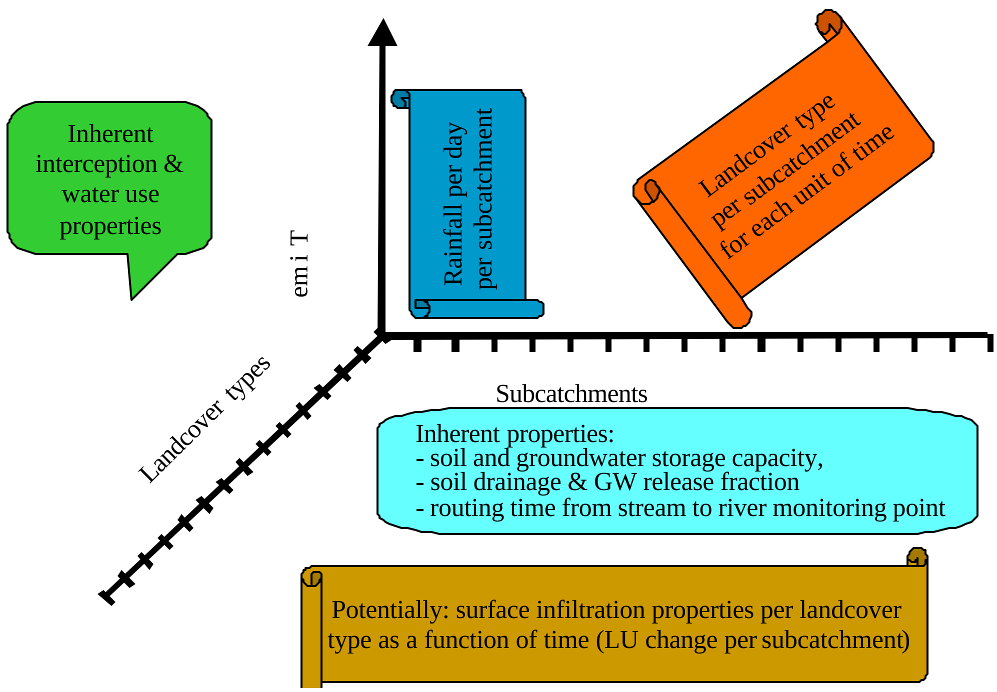


Figure 2.41. Array dimensions is used in the model