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RHINEFLOW: an integrated GIS water balance model for the river Rhine

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Abstract This paper presents the GIS-based RHINEFLOW model. This model describes the changes in the water balance compartments of the river Rhine on a monthly time basis. The model is build with the PC RASTER package as an integrated part of a GIS. PC RASTER is a set of utilities for hydrological and geomorphological modelling that can be linked to a raster GIS. With these utilities water balances can be modelled on each of the cells of the raster system. A geomorphologically based routing model allows the surface water computed from the water balance to drain down to the outlet of the catchment. The utilities allow for evaluation of model results including their spatial and temporal distribution. The RHINEFLOW model performs well in calculating the monthly discharge of the river Rhine and its tributaries.

INTRODUCTION

Geographic Information Systems are very suitable for storing, analysing and retrieving the information needed for running hydrologic models. GIS can hold many data on the, albeit static, distribution of land attributes which form the control parameters, boundary conditions and input data for the model (Burrough, 1989). However, with most GIS it is usually necessary to export the maps from the GIS and convert them into input data sets for the model, which is run seperately. The results can be brought back into the GIS for further analysis. Especially when running several models for a certain analysis, or using different sets of input maps when analysing different scenarios, this ad hoc approach is cumbersome and for routine research the models should be an integral part of the GIS. A useful general approach would be to extend the GIS with a (limited) set of general tools that can be used to build hydrologic models to meet the users requirements. Instead of implementing a limited number of specific solutions for geographic problems, the GIS is a toolbox, with which an experienced user can build solutions for numerous spatial problems. This is basically the approach used by Tomlin (1983) when designing the Map Analysis Package.

CONCEPTUAL MODELLING AND GIS

A GIS toolbox to be used for hydrological modelling must at least contain procedures to:

(a) *procedure A:* read input data for a certain location (x) and time step (t);

(b) *procedure B:* carry out the necessary calculations to determine the water balance at (x,t). For spatially distributed water balance modelling, the flow direction at all locations must be known since the water balance at location x may also depend on the water production in the neighbourhood;

(c) *procedure C:* perform some output operations to enable others (users or models) to use the results of the model.

The GIS toolbox PC RASTER PACKAGE, contains the following programs for hydrological modelling (procedures A, B and C).

Procedure A

Procedure A is represented by an input module (TIMEINP). This module reads input data from time series. Input comes from ASCII data files that store values for a certain input (e.g. precipitation, temperature) for the time interval used in the model. TIMEINP reads the values for these inputs sequentially from these datafiles, and produces raster maps with the (distributed) value for the inputs for a time t.

Procedure B

Procedure B is represented by:

(a) a raster map calculator CALC. This module can evaluate almost any arithmetical point-operation on gridded map-data. It has a list of built in functions, such as LN (natural logarithm), SQRT (square root), which can be applied to the raster maps. Logical functions can be implemented with MIF (IF Map ... THEN .... ELSE....) using operators LT (less than), GT (greater than), EQ (equals);

(b) the program WATERSHED. This program enables the user to extract drainage patterns , a Local Drain Direction matrix (LDD), from elevation data and use these patterns for the geomorphologically based routing modules. The basic concepts for drainage pattern analysis were taken from published descriptions of recursive basin delineation given by Marks *et al.* (1984) and publications by Jenson & Domingue (1988) and Morris & Heerdegen (1988). The approach followed is discussed extensively in Van Deursen & Kwadijk (1990) and Van Deursen (1993);

(c) the module ACCU. This is a tool to route water through the local drain direction matrix (LDD). In a water balance model such as RHINEFLOW the inputmap for this module contains surface water calculated for each cell. The outputmap will contain the surface water accumulated through the Local Drain Direction Matrix.

Procedure C

Procedure C is represented by:

(a) the module DISPLAY, which is used for display of any of the maps through the model timeinterval;

(b) the module TIMEOUT which is used to create timeseries of the results of the model.

MODELLING THE RIVER RHINE DRAINAGE BASIN

In this part we will examine the steps needed to build a spatially distributed water balance model, called RHINEFLOW, for the river Rhine drainage basin

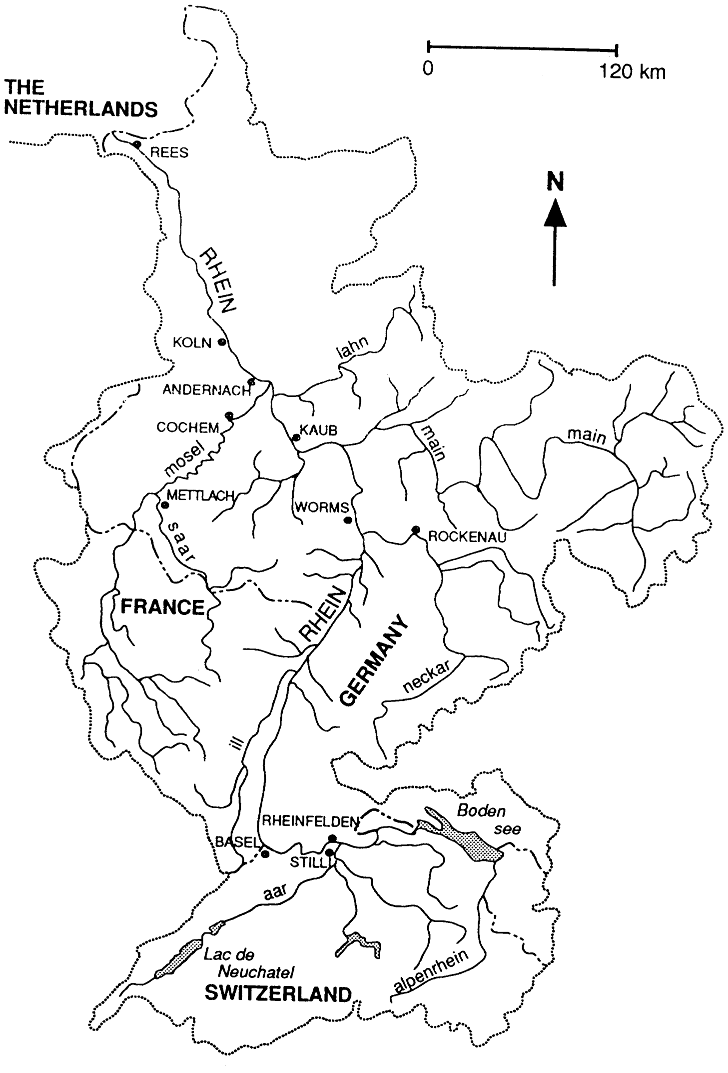


Fig. 1 Catchment of the river Rhine.

(Fig. 1). The model has been designed to investigate possible changes in the water balance compartments in the river Rhine basin, due to climate change. RHINEFLOW is written with the syntax developed for the PC-RASTER PACKAGE. Figure 2 shows a flow diagram of the model. The entire model takes up only 40 lines of code. The model runs on IBM PC-AT or compatible computers.

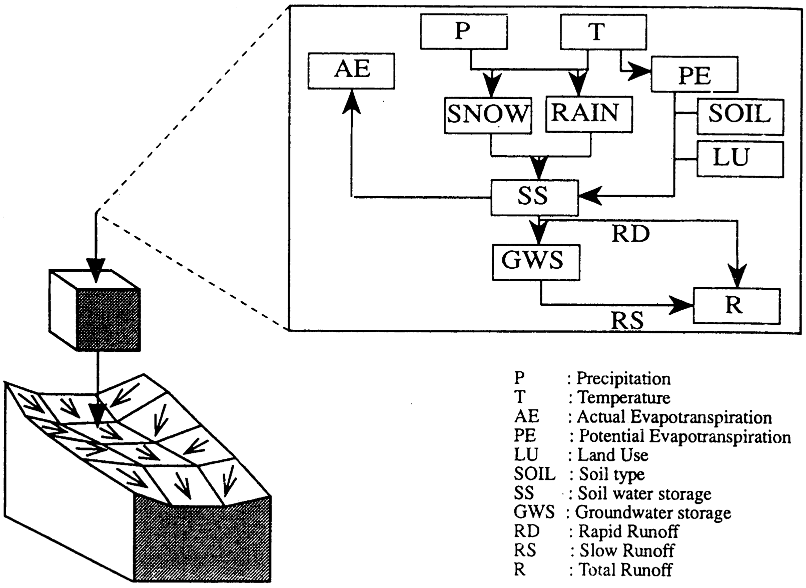


Fig. 2 Flow diagram of the RHINEFLOW model.

Water balance modelling

The discharge regime of the Rhine is governed by five major natural storages and controls:

(a) the amount of precipitation and its spatial distribution;

(b) the temperature distribution in the catchment, which mainly depends on the topography. This distribution forms the main control for the amount of snow storage, snow melt and potential evapotranspiration in the catchment;

(c) soil moisture storage which gains water from the surplus of precipitation and looses water to evapotranspiration, to seepage to the groundwater and to the direct runoff;

(d) groundwater storage which gains water from the soil water seepage and looses water to the river baseflow;

(e) the distribution of the land use and soil water storage capacity in the catchment, which control the actual evapotranspiration.

Finally, the discharge regime is not only influenced by the local conditions but is also by the water production in the upstream area:

(f) the spatial connectivity of the geographical sub-elements in the catchment.

Data requirement and data sources

For the RHINEFLOW model a raster GIS dataset was created. The different maps in this dataset were digitized and rasterized to a grid size of about 3x3 square kilometer. Each of these raster cells in the database represents one calculation element in the RHINEFLOW model and is the smallest element in the spatial connectivity analysis. Figure 3 shows a diagram of the data flow.

The following set of data is used as input variables and parameters for the model:

(a) monthly areal precipitation and temperature data for a large number of stations in the Rhine catchment. Temperature data was interpolated to cover the complete grid with the use of elevation data from the digitized Digital Elevation Model (DEM);

(b) a DEM. This DEM was digitized from an elevation map. The digitized elevation map (Fig. 4a) was interpolated using an inverse distance method;

(c) a soil map. The soil type map was relabeled into a soil storage capacity map (SSmax.map) using published data (Groenendijk, 1989);

(d) a land use map. The land use map was relabeled into a cropfactor map. This map was used to adjust the calculated potential evapotranspiration for different crop types;

(e) from the DEM a local drain direction map (LDD) was created using the program WATERSHED. This LDD map represents the drainage pattern of the Rhine catchment. This map is used to route the water produced in each cell (see next section) to neighbouring cells and eventually to the outlet of the basin, thus representing the spatial connectivity of the geographic sub-elements. From this drainage pattern map, WATERSHED can determine the upstream area map, which for each cell represents the number of grid cells draining through that cell. This upstream area map is given in Fig. 4b.

The original maps are all published by the Commission Hydrologique du Basin du Rhin (CHR/KHR, 1977).

The following data set is used for calibration and validation:

(a) monthly discharges for the main tributaries of the river Rhine and 7 stations along the main river. This time series covers periods ranging between 1870-1980 and 1956-1980. These data were derived from the German Hydrological Office (BfG);

(b) average monthly changes in snow water equivalents (SWE) for 30 mountain weather stations in the Alps. These data were derived from the geographical institute at the ETH (Switzerland) (Martinec *et al.*, 1992);

(c) average monthly evapotranspiration for different crop types for several stations in Germany, published data on the average monthly

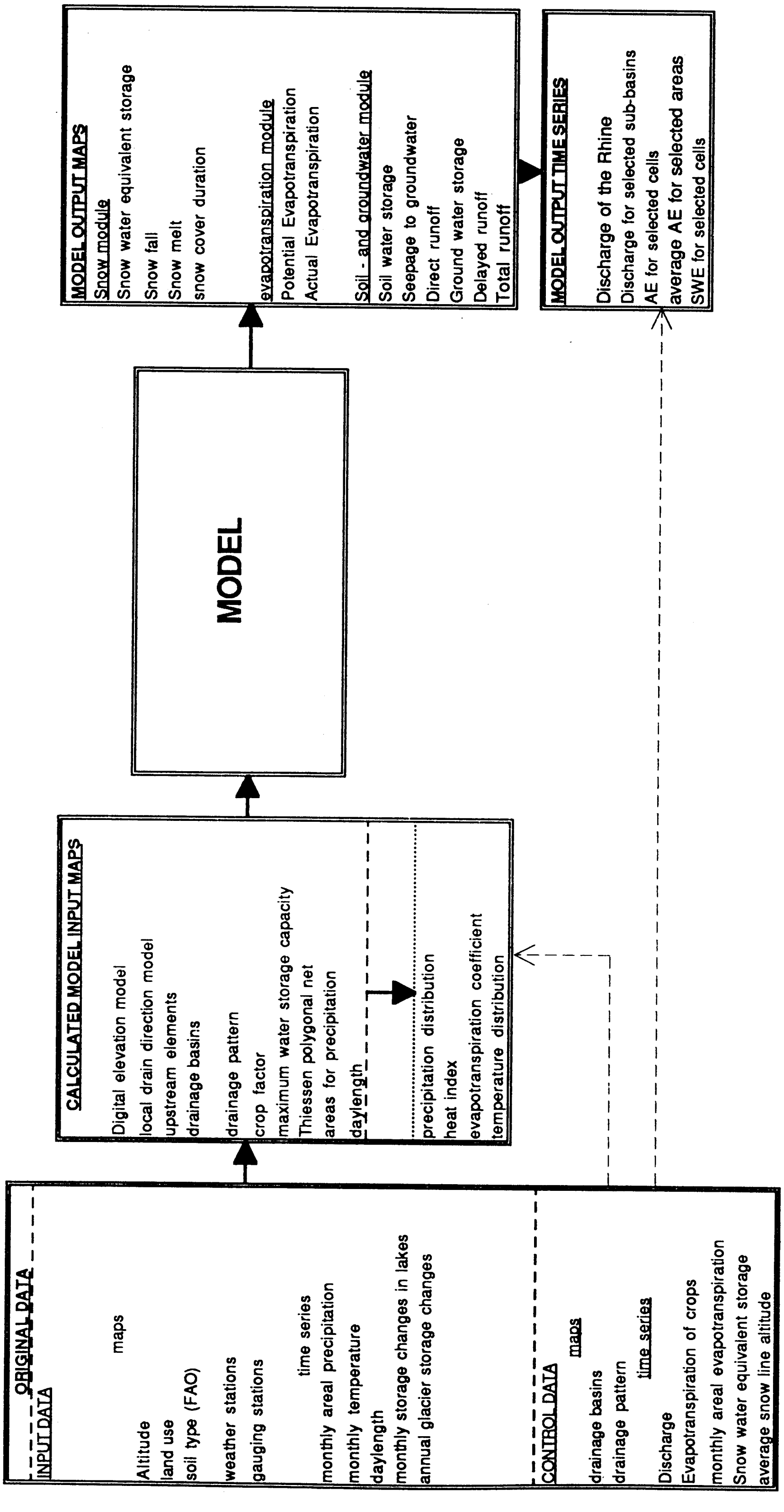


Fig. 3 Data flow diagram of the RHINEFLOW model.

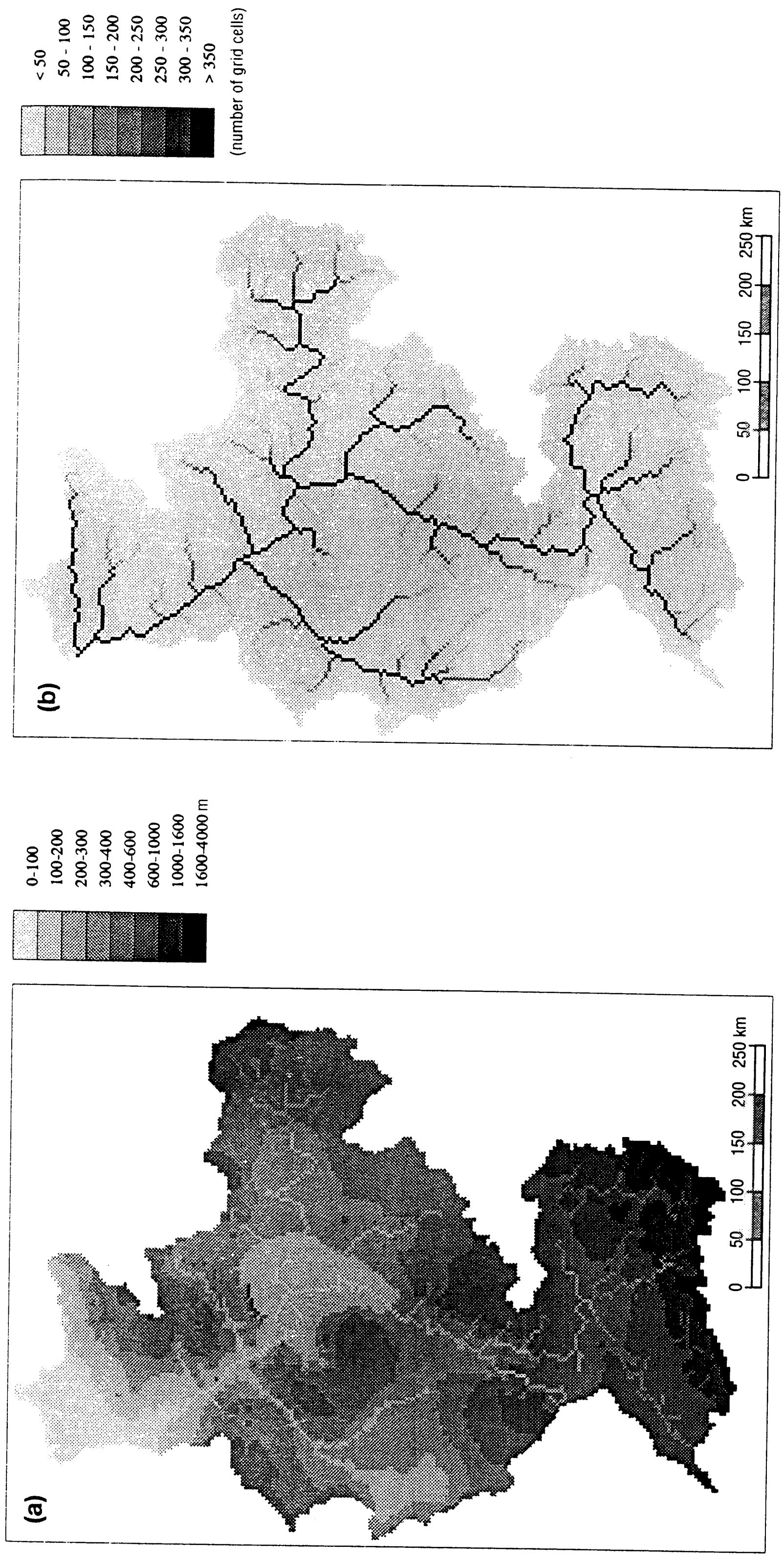


Fig. 4 (a) digital elevation model (m); (b) calculated upstream area map (number of grid cells).

evapotranspiration in the middle and lowland area (CHR/KHR, 1977) and published data on the evapotranspiration in the Alpine area (Schädler, 1985).

All meteorological data were obtained from German and Swiss meteorological Offices (DWD and SHA, respectively).

Model calculations

Evapotranspiration and soil moisture The Potential Evapotranspiration (PE) is estimated on a monthly basis using a Thornthwaite approach, corrected for different types of land use (Thornthwaite & Mather, 1957; Kwadijk & Van Deursen, 1993). From the PE the actual evapotranspiration (AE) and soil storage (SS) were calculated as follows:

(a) if P>PE then AE=PE and SS is filled until it reaches field capacity (SSmax). The water surplus above the field capacity storage (SPW) is assumed to drain to the groundwater;

(b) if P<PE then SS is estimated with a Thornthwaite-Mather approach:

$$SS = SSmax \times EXP(-APWL/SSmax) \tag{6}$$

$$AE = P + dSS \tag{7}$$

in which APWL is the Accumulated Potential Water Loss, this is the sum of monthly water shortages during a dry period.

The results are formed by maps in which all raster cells contain a value that is an estimate for the local potential and actual evapotranspiration and the soil water storage. Consequently these maps show the spatial distribution of AE and soil water storage for the drainage basin in the month of concern.

Runoff production From the above calculations for individual cells the seepage from the soil is known (SPW). Runoff is seperated into rapid and delayed runoff using a runoff coefficient of 0.2. This is an average value when using the rational method (Ven Te Chow *et al.*, 1988) for runoff seperation. The direct runoff (RS) is assumed to come to discharge within the month of concern. The delayed runoff (RD) is stored as groundwater. The flow from this water balance compartment to the river is described with a linear recession equation:

$$RS = GWSTOR/T \tag{8}$$

in which T is a recession parameter which is calibrated for all tributaries containing a gauging station near their outlet (t), GWSTOR is the volume water stored as groundwater (mm).

Now the water balance for all individual cells of the raster map is known. The geomorphological routing routine (ACCU) routes the water produced through the LDD map (which connects the cells within the watershed with the outlet of the basin). A cell in the resulting DIS.MAP contains the average runoff production for that cell and the cells upstream of (draining to) that cell. With the tool TIMEOUT the calculated runoff series of the cells representing a gauging station can be produced. Figure 5 shows the syntax used to calculate the evapotranspiration, soil moisture and the runoff production.

Snowfall and snow-melt RHINEFLOW calculates snowfall and snow melt with a temperature - index method. It is assumed that all precipitation falls in form of snow if the monthly temperature is below zero degrees Celsius. Snow starts to melt if the temperature rises above zero. Maps showing the spatial distribution of snowfall, water equivalent snow storage (SWE) and the melt water production per cell form the output of this module.

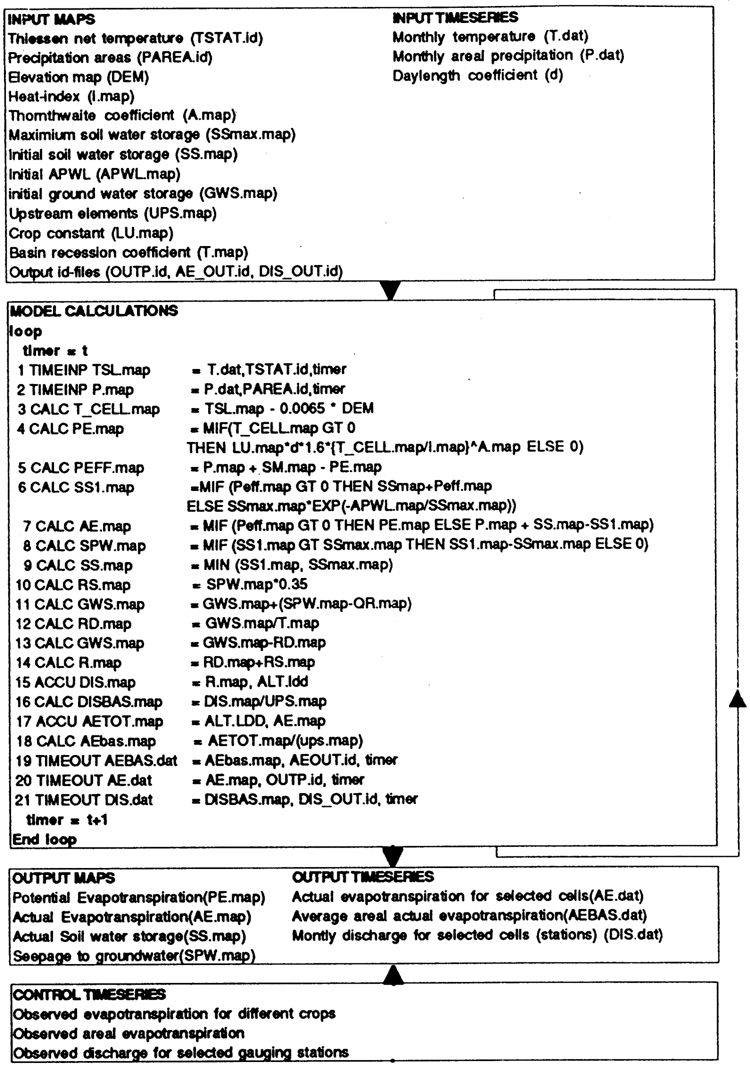
Model results

The RHINEFLOW model produces maps and tables at all calculated timesteps, not only for the runoff at a certain location, but also for the other calculated hydrological variables including their spatial and temporal distribution. As an example, Fig. 6 shows the spatial distribution of the calculated potential evapotranspiration. The RHINEFLOW model was calibrated for the period 1965-1970. The calibrated model was tested for the period 1956-1980. The runoff results have been tested on the goodness of fit using the coefficient of efficiency (Nash & Suttcliff, 1970). This coefficient ranges between -1 and 1, a value of 1 describes a perfectly fitting curve while zero means that the average is an equally good estimate for the runoff as the calculated curve. This test provided results between 0.7 and 0.85. An extensive discussion on the model results is published elsewhere (Kwadijk & Van Deursen, 1993).

CONCLUSIONS

Conclusions drawn from the river Rhine example show that even with these simple approaches the RHINEFLOW model is able to describe monthly changes in the water balance compartments for both the entire basin and its tributaries quite accurately. Since the topographical and climatological characteristics of the tributaries are different, the model seems accurate over a wide range of both climate and other environmental conditions. This allows the conclusion that the model can be used to estimate possible changes of the river Rhine discharge to a change in temperature and precipitation.

The Rhine study shows that the PC RASTER PACKAGE offers a general approach for modelling different kind of processes, and includes the possibility to combine detailed spatial resolution with simple (conceptual) models. The toolbox allows validation of water balance models not on



INPUT MAPS

Thiessen net temperature (TSTAT.id)

Precipitation areas (PAREA.id)

Elevation map (DEM)

Heat-index (I.map)

Thornthwaite coefficient (A.map)

Maximium soil water storage (SSmax.map)

Initial soil water storage (SS.map)

Initial APWL (APWL.map)

initial ground water storage (GWS.map)

Upstream elements (UPS.map)

Crop constant (LU.map)

Basin recession coefficient (T.map)

Output id-files (OUTP.id, AE_OUT.id, DIS_OUT.id)

INPUT TIMESERIES

Monthly temperature (T.dat)

Monthly areal precipitation (P.dat)

Daylength coefficient (d)

MODEL CALCULATIONS

```
loop
  timer = t
 1 TIMEINP TSL.map        = T.dat,TSTAT.id,timer
 2 TIMEINP P.map          = P.dat,PAREA.id,timer
 3 CALC T_CELL.map        = TSL.map - 0.0065 * DEM
 4 CALC PE.map            = MIF(T_CELL.map GT 0
                          THEN LU.map*d*1.6*{T_CELL.map/I.map}^A.map ELSE 0)
 5 CALC PEFF.map          = P.map + SM.map - PE.map
 6 CALC SS1.map           =MIF (Peff.map GT 0 THEN SSmap+Peff.map
                          ELSE SSmax.map*EXP(-APWL.map/SSmax.map))
  7 CALC AE.map           = MIF (Peff.map GT 0 THEN PE.map ELSE P.map + SS.map-SS1.map)
  8 CALC SPW.map          = MIF (SS1.map GT SSmax.map THEN SS1.map-SSmax.map ELSE 0)
  9 CALC SS.map           = MIN (SS1.map, SSmax.map)
10 CALC RS.map            = SPW.map*0.35
11 CALC GWS.map           = GWS.map+(SPW.map-QR.map)
12 CALC RD.map            = GWS.map/T.map
13 CALC GWS.map           = GWS.map-RD.map
14 CALC R.map             = RD.map+RS.map
15 ACCU DIS.map           = R.map, ALT.ldd
16 CALC DISBAS.map        = DIS.map/UPS.map
17 ACCU AETOT.map         = ALT.LDD, AE.map
18 CALC AEbas.map         = AETOT.map/(ups.map)
19 TIMEOUT AEBAS.dat      = AEbas.map, AEOUT.id, timer
20 TIMEOUT AE.dat         = AE.map, OUTP.id, timer
21 TIMEOUT DIS.dat        = DISBAS.map, DIS_OUT.id, timer
  timer = t+1
End loop
```

OUTPUT MAPS

Potential Evapotranspiration(PE.map)

Actual Evapotranspiration(AE.map)

Actual Soil water storage(SS.map)

Seepage to groundwater(SPW.map)

OUTPUT TIMESERIES

Actual evapotranspiration for selected cells(AE.dat)

Average areal actual evapotranspiration(AEBAS.dat)

Montly discharge for selected cells (stations) (DIS.dat)

CONTROL TIMESERIES

Observed evapotranspiration for different crops

Observed areal evapotranspiration

Observed discharge for selected gauging stations

1 Temperature (sea level) data file is converted to a temperature map

2 Areal precipitation data file is converted into a precipitation map

3 Cell temperature=temperature at sealevel- (altitude_temperature coefficient * altitude)

4 Potential evapotranspiration = if temperature > 0 celsius then: F(Temp, landuse,daylength) Else: 0

5 Available water= precipitation + meltwater - potential evapotranspiration

6 Soil water= if available water more than 0 then initial soil water + available water
Else soil water storage F(maximum soil water storage, APWL)

7 Actual evapotranspiration = if available water > 0 then AE=PE Else precipitation + soil water storage loss

8 Seepage to groundwater = if actual soil water storage > maximum soil water storage then
actual soil water storage - maximum soil water storage, else 0

9 Final soil water storage = minimum between calculated and maximum soil water storage

10 Direct runoff = seepage * seperation coefficient (0.35)

11 Groundwater storage = initial groundwater storage + (seepage - direct runoff)

12 Delayed runoff = groundwater storage / delay factor

13 Final groundwater storage = groundwater storage - delayed runoff

14 Total runoff = delayed runoff + direct runoff

15 Total basin runoff = accumulation of produced runoff for individual cells through the drainage network

16 Average basin runoff = total basin runoff / basin size

17 Total areal actual evapotranspiration = accumulated AE through the drainage network

18 Average basin AE = total basin AE / basin size

19 Generating timeseries of average AE for selected areas

20 Generating timeseries of AE for selected cells

21 Generating timeseries of discharge for selected basins

Fig. 5 Syntax used to calculate the evapotranspiration, soil moisture and runoff.

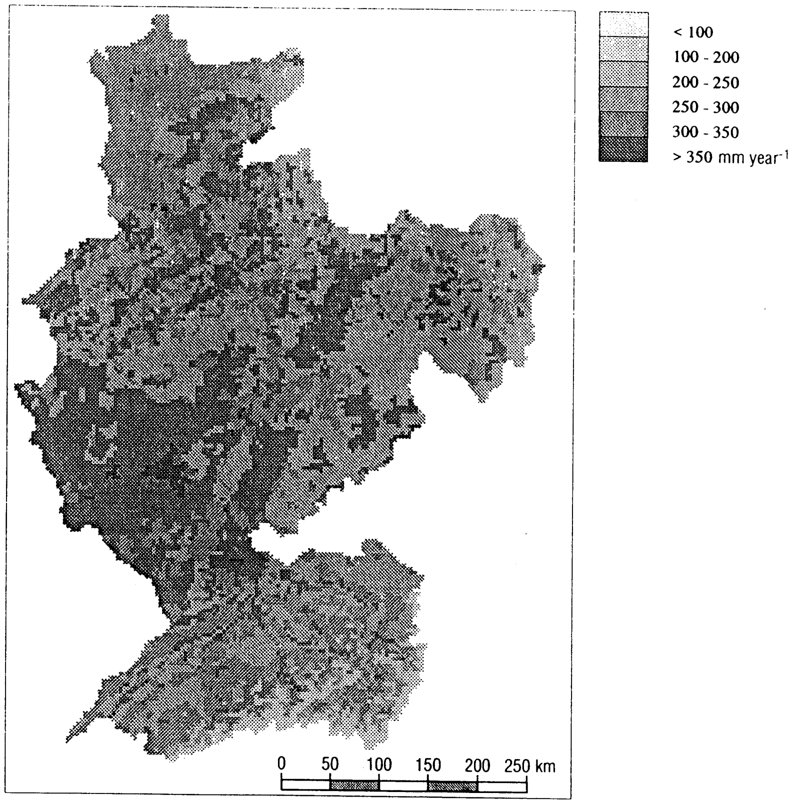


Fig. 6 Map of average calculated potential evapotranspiration (mm).

discharge only but also on the spatial and temporal distribution of other hydrological variables. Since the discharge output can be obtained for any cell along the flow line, it forms a very flexible tool to test the model for the calculated runoff.

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