DEVELOPMENT OF A DISTRIBUTED HYDROLOGICAL MODEL FOR FLOOD FORECASTING AND IMPACT ASSESSMENT OF LAND-USE CHANGE IN THE INTERNATIONAL MOSEL RIVER BASIN

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ABSTRACT A distributed hydrological model for simulation of the rainfall-runoff process in the Mosel River catchment is under development. The research project has several objectives: development of a hydrological model allowing short-term and long-term simulation and application for real time flood forecasting, specification of the impact of landuse changes and identification of the hydrological effects of potential climatic changes. The model is structured in a modular way; for every component of the water balance certain modules are defined and combined into a main computer program. It is based on a geographic information system derived from a digital terrain model, on Landsat satellite imagery and on digitized maps, all having a spatial resolution of 30x30 m². In order to achieve a reduction in computational effort grid elements having equal hydrological characteristics are lumped together into 'hydrologically similar units'.

INTRODUCTION

The Mosel River catchment is an international river basin of about 28 000 km², located in the countries of France, Luxemburg, Belgium and Germany. Extreme floods observed during the last decades lead to the question how human influences affect the water balance during floods and dry periods. Human influences are mainly characterized as climate changes (e.g. a rise in mean air temperature or a shift in the annual rainfall distribution due to an increasing concentration of CO2 and other trace gases in the atmosphere) and as landuse changes, i.e. a change in vegetation cover as a result of forest damages, different agricultural use or urbanization.

A hydrological model capable of simulating the effects of such spatially highly variable changes as well as their effects on floods and droughts should be based on a high resolution in space and different time scales. These tasks cannot be met by a lumped system model, since this is unable to predict the hydrological effects of changes within the catchment.
Therefore a distributed model is being developed, which is based - to a certain extent - on the physical principles of the hydrological processes. For distributed system models information on geological, pedological and topographical characteristics of a river catchment is required in order to derive or measure the necessary parameters. In the past this information was often missing or imprecise, but nowadays satellite data and digital terrain models provide the tool for a more successful application of distributed hydrological models.

In this paper a model is presented which makes use of such data for parameter derivation and as model input. It will further be described how a database is set up which combines remote sensing data (i.e. digitally processed satellite imagery), digital elevation data obtained by means of photogrammetry and conventional data obtained from digitized thematic maps.

GENERAL CHARACTERISTICS OF THE HYDROLOGICAL MODEL

The structure of the model consists of two main components; the first being the flood routing component for the Mosel River and its major tributaries, which is developed at the Federal Institute of Hydrology, Germany and will not be discussed in this paper. The second component consists in the computation of runoff resulting from rainfall in the various subcatchments with the aid of the hydrological model.

![Diagram](image-url)

Fig.1. Illustration of the principle of 'hydrologically similar units'.
Each catchment area is subdivided into square area elements with a grid size of 30x30m², i.e. all information is stored in the format of this spatial resolution. Since such a high resolution cannot be applied to the large catchment of the Mosel River, a special aggregation technique had to be developed, similar to those presented by Fortin et al. (1990) and Knudsen et al. (1986). In order to reduce computational effort grid elements having equal hydrological features are lumped together into 'hydrologically similar units' (HSUs).

In order to determine the hydrological features for the various catchment characteristics (e.g. vegetation cover, soil type, meteorological zone, elevation, slope and exposition) certain 'classes' were defined. Hydrological units then consist of a number of grid elements all having the same combination of classes for these characteristics (see Fig. 1). Within the units homogeneous hydrological conditions concerning parameters, input and runoff generating processes are assumed. Although this assumption does not quite satisfy Beven's (1989) definition of the term 'physically based', it can be considered to be a fair representation of the physical principles prevailing in a catchment.

THE GEOGRAPHIC INFORMATION SYSTEM

For the estimation of model parameters from high resolution data of catchment characteristics, it was necessary to set up a regional Geographic Information System (GIS) based on the idea that the data should be referenced in a way which will allow retrieval, analysis and display on spatial criteria as required. The configuration of the GIS is a combination of a management subsystem, a computer hardware subsystem and a computer software subsystem which consist of such modules as data input and verification, data storage and database management, data output and presentation, data transformation and interaction with the user (Burrough 1989).

Data input: the data are acquired from field observations, satellite sensors and existing maps via interactive terminals, digitizers, text files, scanners and magnetic media. Verification is immediately performed in order to identify the applicability of the data and to remove primary errors.

Data storage and database management: the data are stored and managed with reference to their geographic position with a predefined regional coordinate system or reference basis (e.g. Latitude and Longitude, Universal Transverse Mercator, etc.).

Data output and presentation: data output and presentation are in the form of visual displays, prints, plots as well as magnetic media.

Data transformation: data transformation thus enables the maintenance of data matching, updating, analyzing and manipulating in order to extract desired information (e.g. catchment physiographic characteristics and hydrological parameters, etc.).

Interaction with the user: the designed GIS enables the user to have a direct contact with the computer. So the user is always informed about what is going on with the aid of interactive operation.
THE DATA STRUCTURE OF THE GIS

The data structure is built with an "overlay" concept, i.e. the real world is portrayed by a series of overlays in each of which one aspect of reality has been recorded, e.g. topography by Digital Elevation Model (DEM), landuse by classified satellite data, soil type by digitized soil map and vegetation by Normalized Difference Vegetation Index (NDVI) and Leaf Water Content Index (WCI) as well as Leaf Area Index (LAI), etc. The event dependent data (e.g. rainfall, temperature etc.) are also represented as time variant overlays.

The digital elevation data (with an accuracy of 1 decimeter) are provided in vector format with grid lengths of 40m, each data set covering an area of 12x12km$^2$ which is a grid element of the Gauss-Krüger coordinate system. The data are verified, filtered to remove the overlaps and mosaiced to the smallest rectangle bounding the catchment under study. As Remote Sensing (RS) data Landsat 5 TM scenes (with a resolution of 30x30 m$^2$) are used (e.g. of 22 August 1984) which are geometrically corrected via the collection of Ground Control Points (GCP's) and referenced primarily to the Gauss-Krüger coordinate system for further use. The soil information is obtained from a digitized Soil Map of the state of Rheinland-Pfalz (1:250 000) with a resolution of 50x50 m$^2$ and a digitized Soil Map of the EEC (1:1 000 000) with a resolution of 200x200 m$^2$, both available in raster as well as vector format. The catchment boundary is digitized and stored as a separate overlay. All these data are converted to a common 30x30 m$^2$ grid (i.e. Landsat TM spatial resolution) in order to be used for the estimation of model parameters.

ESTIMATION OF MODEL PARAMETERS

On the basis of the above discussed catchment data, model parameters are estimated by data transformation (analysis and manipulation).

Model Parameters derived from Satellite Imagery

Several model parameters can be derived from satellite data with the aid of the following catchment characteristics.

Land Use: for land use classification the available TM data have been routed through a principle component transformation (without the use of Band 6 which has a resolution of 120x120 m$^2$) and the resultant first three components (PCT 1, representing brightness, PCT 2, greenness and PCT 3, wetness) are used to select training areas which can easily be identified up to twenty classes with the aid of existing maps and field survey and are combined into eight land use classes according to their significance for hydrological processes, e.g. interception, surface runoff, evapotranspiration, etc. A supervised maximum likelihood algorithm is used for the classification. An example is presented in Fig. 2a.

Vegetation Index: the various types of vegetation are identified with the aid of land use classification, while the state of the vegetation maturity can be
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indexed by vegetation indices. The NDVI is used for this purpose, which is calculated as the ratio of the difference between radiance in the near infrared and in the red, i.e. \( NDVI = \frac{NIR - RED}{NIR + RED} \) (Tucker, 1979), where NIR: radiance in the Near Infrared, e.g. Landsat TM band 4, spectral range 0.76-0.90mm and RED: radiance in the red e.g. Landsat TM band 3, spectral range 0.63-0.69mm.

Leaf Water Content Index: the absorption by vegetation in the short wave infrared is due to absorption by water in the leaves and hence measurements in this spectral band will provide a measure of the amount of available water stored in the leaves (Hunt 1987, cited by Finch 1990). Vegetation having a large capacity to store water in the leaves exists only in areas with abundant water supply. The Leaf Water Content Index can be defined as \( WCI = \frac{NIR - SWIR}{NIR + SWIR} \), where NIR: radiance in the Near Infrared, e.g. Landsat TM band 4, spectral range 0.76-0.90mm and SWIR: radiance in the short wave infrared, e.g. Landsat TM band 5, spectral range 1.55-1.75mm.

The application of NDVI and WCI allows interpretation of the data in terms of response of vegetation to the supply of subsurface water.

**Leaf Area Index:** The Leaf Area Index is defined as the area of leaves in a

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*Fig. 2. Catchment characterics derived from satellite imagery and digitized maps, Nims catchment (18.5 km², Mosel tributary), Germany (a) Land use (1, water; 2, built-up area; 3, coniferous forest; 4, deciduous forest; 5 mixed forest; 6, agriculture; 7, pasture; 8, bushes); (b) Soil type (7, representing peaty clay loam; 79, clay loamy sand; 108, peaty clay sand and loam; 123, clay sand and loam).*
given ground area (Running 1986 and Running et al. 1988) and can be estimated with the aid of multitemporal image analysis in relation to field measurements.

**Soil Parameters**

The soil classification is obtained from a digitized soil map and the parameters (e.g. soil moisture characteristics, hydraulic conductivity, etc.) are estimated based on the classification. The soil classification is given in Fig. 2b.

**Physiographic Parameters derived from a Digital Elevation Model (DEM)**

The physiographic parameters which are relevant for the drainage structure of a catchment (e.g. elevation, slope and exposition, etc.) are extracted from an existing DEM. Since a DEM is a digital, discrete representation of the continuous variation of relief in space, the elevations of all grid cells form the altitude matrix. Slope is defined by a plane tangent to the surface as represented by the DEM and comprises two components namely, gradient, the maximum rate of change in altitude, i.e. the degree of slope, and exposition (aspect), the compass direction of this maximum rate of change (Marks et al., 1984). These are derived

![Fig. 3](image-url)

**Fig. 3.** Catchment characteristics derived from a Digital Elevation Model, Nims catchment (18.5 km², Mosel tributary), Germany (a) Slope; (b) Exposition (0° - 360° clockwise starting at north).
Distributed hydrological model for flood forecasting according to an algorithm developed by Neumann et al. (1990). Fig. 3 presents the derived slope and exposition data for a Mosel river tributary.

**HYDROLOGICAL SIMULATION**

For all hydrological units the vertical water budget is computed by mathematical simulation of the processes of interception, evapotranspiration, infiltration and percolation. The outflow from these units is then routed as surface flow, subsurface flow and baseflow to the outlet of the catchment.

For the different components of the water budget certain modules are defined calculating the corresponding hydrological processes, which then are combined in a main computer program. This allows the user to exchange or skip single modules.

With the start of the program first the size and spatial distribution of the hydrological units is determined by a 'base file' read from the data base. This file contains the number of elements belonging to the unit and the combination of the characteristics. When computation of the processes starts, the required parameter sets for each component are taken from parameter files according to this combination. The simulation follows the flow chart of Fig. 4. Precipitation is reduced to net precipitation by a certain amount of water stored in the interception storage. The remaining water then infiltrates into the soil moisture storage, which consists of an upper root zone and a lower soil zone. Precipitation exceeding the infiltration capacity generates surface runoff. Evapotranspiration can occur from plant and soil surfaces and from the upper soil zone. Water percolating further into the soil is subdivided into interflow and baseflow.

![Flow Chart of the Hydrological Model](image)

*Fig. 4. Flow Chart of the Hydrological Model.*
COMPONENTS OF THE HYDROLOGICAL MODEL

Precipitation

A rainfall field of high spatial and temporal resolution as obtained e.g. by radar rainfall measurements would be appropriate as input into the model of high resolution in time and space. At present precipitation input is derived from conventional raingauge measurements since no radar data are available for the Mosel River catchment, yet.

Evapotranspiration and Interception

The retention of rainfall on the vegetation cover is simulated by an interception storage approach. The amount of intercepted water depends mainly on the type of vegetation, the season and the intensity and duration of rainfall. These parameters are taken into account by an interception storage model as developed by Meriam (1960):

\[
\Delta I = \frac{P}{S_{\text{max}}} \cdot (1 - e^{\frac{P}{S_{\text{max}}}}) + \text{LAI} \cdot \text{E}_i \cdot t_e
\]

with
- \(\Delta I\): change in the amount of interception (mm)
- \(S_{\text{max}}\): capacity of the interception storage (mm)
- \(P\): precipitation (mm)
- \(\text{LAI}\): leaf area index (-)
- \(\text{E}_i\): evaporation rate (mm/h)
- \(t_e\): duration of precipitation (h)

The variability of the vegetation type and its seasonal change in interception capacity is considered using the leaf area index with its annual variation. The value of \(S_{\text{max}}\) can be derived from measured parameters (Hoyningen-Huene, 1983), after the landuse has been determined by satellite data. The interception storage is emptied by evaporation.

The estimation of evaporation from plant and soil surfaces is based on daily evaporation rates. Evapotranspiration from the upper soil zone will be computed depending on the vegetation type and the moisture content of the zone.

Infiltration

The infiltration is calculated for the pre-ponding and ponded state using the well-known Green and Ampt equation as presented by Mein and Larson (1973) and later extended for the computation of infiltration during an unsteady rain (Chu, 1978):
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\[ f(t) = i(t) \]  \hspace{1cm} (2)  

for pre-ponding conditions and

\[ f(t) = K_s \left( 1 + \frac{\psi}{F} \cdot \Delta \Theta \right) \]  \hspace{1cm} (3)  

for ponding conditions

with:
- \( f(t) \) infiltration intensity (mm/h)
- \( i(t) \) precipitation intensity (mm/h)
- \( K_s \) saturated hydraulic conductivity (mm/h)
- \( \psi \) average suction at the wetting front (mm)
- \( F \) infiltrated volume (mm)
- \( \Delta \Theta \) moisture deficit (-)

This approach represents the actual infiltration process in a simplified way based on physical measurable parameters (Rawls and Brakensiek, 1989). Tests of the model have shown satisfactory results with less computational requirements compared to other infiltration models.

Surface Flow

Surface flow is computed as infiltration excess while the surface is under ponded conditions. Since input data for hydraulic approaches to model overland flow are hardly available and have to be estimated to a large extent, a conceptual technique was chosen.

Subsurface flow and baseflow

Below the upper soil zone (i.e. the root zone) the infiltrating water quantity represents the input into the soil moisture storage from which interflow and groundwater recharge are generated. This lower soil zone is represented by a single reservoir with two outlets. The diversion into interflow and baseflow depends on the current water content of the storage, the volume of infiltrating water, a certain threshold value and the hydraulic conductivity (Boehme-Korn et al., 1981).

VERIFICATION OF THE MODEL

The model as described above has been applied in a preliminary study to the upper part (18.5 km²) of the Nims catchment, a Mosel river tributary in Germany. The precipitation input is taken from the records of one recording rain gauge.
Fig. 5 shows first results of the simulated hydrograph compared to the observed hydrograph of an event in June, 1984. The results are quite satisfying as far as the time to peak and the simulation of the peak flow are concerned. The dynamic behaviour of the observed hydrograph could not well be simulated by the model. This may be a result of the first trial approach treating the whole catchment as one 'hydrological unit', which leads to good results in estimating the amount of the runoff components but neglects the fact that some areas, e.g. the area adjacent to the river, produce runoff immediately while others contribute mainly to interflow. The next trials will use a more detailed structure of HSUs within the catchment, which should provide more realistic results.

Fig. 5. Comparison between computed and observed hydrographs. Flood in June 1984, Nims catchment (18.5 km²), Germany.

CENTRAL QUESTIONS

The most difficult problem caused by the large dimensions of the Mosel river basin was to cope with the enormous amount of data resulting from the high
spatial resolution the model is based on. In order to achieve a reduction in effort of computation and data management the technique of aggregating hydrologically similar elements into 'units' and the application of a GIS are considered to be appropriate tools.

The acquisition of data in the international Mosel river basin is, as far as the determination of the different types of land use is concerned, not a serious problem, since the land use can be derived from LANDSAT imagery. Digitized soil maps and elevation models of the different countries are all based on different sizes of grid elements; with the use of the GIS they are modified to grid elements of identical size. Precipitation and runoff data are being provided by the Federal Institute of Hydrology; so far only the data for the German part of the river basin were acquired.

It is intended to apply the model with an hourly time step for flood forecasting, while the long-term version of the model, based on daily values, should indicate the hydrological effects of land use and climate changes.

CONCLUSIONS

a) The structure of a mesoscale deterministic hydrological model of the distributed system type was described, a model which is still under development for implementation in the international Mosel river catchment.

b) For the estimation of the model parameters satellite imagery of Landsat-TM is used as well as a digital elevation model. Since this type of information provides a very high resolution in space it was necessary to aggregate the small area elements to so-called 'hydrologically similar units'.

c) First results of the application of a simplified version of this model were presented for the Nims river, a small tributary to the Mosel river.

d) In the near future a more sophisticated version of the model will be developed and applied to larger sub-catchments of the Mosel river.

e) Future work will also comprise long term simulation of the runoff process based on daily values and using a better evapotranspiration module.

f) Later the model shall be applied in order to estimate the impact of landuse changes. Here changes of the agricultural use as well as the problem of forest diseases will be analyzed.

g) In the long run it is intended to couple the Mosel river model with an atmospheric general circulation model (AGCM) provided by a meteorological institute. This coupling of the two models will allow to run the model with future scenarios of a changed climate. The impact of climate changes on hydrological processes can then be analyzed with the aid of the two coupled models.

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