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CHANGES ON FLOOD CHARACTERISTICS DUE TO LAND USE CHANGES IN A RIVER BASIN

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Abstract. Recent extreme flood events in the center of Europe have originated public discussion on the question whether the frequency and severity of floods and conditions for flooding have been increasing and the extent to which they have been at least partially man-made. This paper presents results of a research project, in which the impact of land use changes on flood hydrographs is investigated. A distributed rainfall-runoff model, whose parameters are determined on the basis of satellite imagery, digital terrain models, and digital maps, is developed and its validity is demonstrated for a subcatchment within the international Mosel River basin. Two types of land use changes are investigated: the increased urbanization and forest disease leading to large scale forest death. Two scenarios are considered for the test catchment: a) the urbanized area is significantly increased and b) all trees above 400 masl are assumed to be dead. It is shown how such land use changes can be generated on maps and how the parameters of the hydrological model change according to such land use changes. For a selected historical flood the impact of the changes on the flood hydrograph are presented. In both cases a) and b) flood conditions became more severe, i.e. the rising limb became steeper, the peak considerably higher, and the flood volume significantly larger. In conclusion both types of land use changes produce a significant deterioration of flood conditions.

1. INTRODUCTION

At the beginning of the year 1993 and again at the beginning of 1995 severe floods occurred in the river Rhine and its tributaries as well as in the river Meuse, which caused severe damages and loss of lives. The fact that two such severe floods occurred within a period of two years caused considerable public interest and extensive discussions in the media and the political environment. Two delicate statements were repeated again and again in the press and in many TV and radio discussions:

(a) during recent times we observe an increasing frequency of severe floods,
(b) the increasing frequency and intensity of floods is man made, e.g. by landuse changes, a climate change, etc.

Under the impression of the 1995 flood event and its resulting public discussions politicians became alert that a sensitive situation had developed. Statements by German state ministers, the Federal Minister for the Environment, and ministers and top politicians of the other river Rhine countries promised to take care of the problem and make decisions and provisions for an improvement of this situation. Many meetings were organized by the European Union, the German Parliament, and the International Commission for the Protection of the River Rhine (IKSR), during which the flood situation was discussed and potential measures for the improvement of this delicate situation were suggested. Many of these meetings produced mainly "hot air", but some others were obviously searching for a real solution to the flood problems. One of the most promising activities can be seen in the framework of the IKSR, which formed a new project group "Action Plan for Floods". The intended improvement of the international flood situation in the River Rhine basin requires long term high investment activities at an international level.

While in the media it was claimed frequently that the two large floods in 1993 and 1995 where "floods of the century", computations by the authors‘ institute showed that both floods had a recurrence interval of the order of 30 to 40 years. Thus the floods were severe, but not extreme. Nevertheless it is true that the damages caused by these floods were extremely high, i.e. higher than those observed in the past.

Therefore, the following question immediately arose: how much of those severe flood conditions were actually caused by anthropogenic activities? It may be shown that anthropogenic activities may cause an increase in flood height and flood damage. This is due to three reasons:

- during the last decades more and more infrastructure measures were located in the narrow river valleys, including those areas which had been reserved as flood plains. This subjected more valuable infrastructure to flood damage, even if flood frequency and intensity had not raised,

- structural river training works, particularly in the upper Rhine area including dikes and barrages as well as large-scale landuse changes in the river catchment areas changed flood conditions,

- flood prone weather conditions occur more frequently in winter than in previous decades, a fact, which some people declare as the beginning of a climate change.

These facts have been known qualitatively for some time already. However, the question of how or which anthropogenic activities on a river or within a river catchment area cause individual impacts on flood conditions has not been investigated extensively, yet. This paper deals with the quantification of the hydrological impact of landuse changes within a river catchment. First, a special type of a hydrological rainfall-runoff model will be presented, which allows quantification of landuse changes and their impact on flood conditions. Subsequently examples will be given that quantitatively show how flood conditions react to specified landuse changes for a river basin in West Germany.

2. HYDROLOGICAL MODEL DEVELOPED TO IDENTIFY THE IMPACTS OF LANDUSE ON FLOOD CONDITIONS

The physically based rainfall-runoff model developed at the author's institute is structured to allow most model parameters to be estimated with the aid of readily available information: maps, digital terrain models, remote sensing data etc.. The idea here is that a model whose parameters depend entirely on catchment characteristics will be able to quantify the impact of landuse changes within the hydrological model parameters. Thus it will enable one to determine the changes that may be expected in flood hydrographs due to changes in landuse because of long-term developments (e.g. forest diseases or reforestation of agricultural areas) or short-term developments (e.g. urbanization, industrialization, and highway or airport construction).

In the model, precipitation falls onto the ground after interception storage is filled. The infiltration process is modeled following the principle of Green and Ampt. The infiltrated water enters storages, which in turn govern the vertical fluxes (shown in the upper part of Fig. 1). They produce surface runoff (RO), interflow (RH), and percolation (VER) into the groundwater. For each specified soil texture a "Hydrologically Similar Unit" (HSU) is generated and lateral fluxes are represented by two-dimensional transfer functions as shown in Fig. 1 (bottom right).

The characteristics of the reservoirs shown in Fig. 1 depend on the storage capacity of the soil (which is not homogeneous within a HSU) and on the vegetation. Furthermore the Green and Ampt infiltration approach requires uniform characteristics for pore storage volume and hydraulic conductivity. This requires subdivision of the catchment into areas of similar soil structure (HSU's). Then the storage capacity distribution function depends on the soil type; for instance it is much flatter for loam soil than for sand. Figure 2 shows such distribution functions of the soil storage capacity for different textures in the Prüm river catchment area in Germany. For model operation it is necessary to replace the empirical histograms in Fig. 2 by linear or non-linear mathematical functions that are fitted to the histograms. As can be seen from Fig. 2, soil texture class (loamy sand, loam, silty clay loam, and clay) can be fitted with a specific distribution function of the soil storage capacity. Since it is the intention of this paper to identify the hydrological impact of landuse changes, distribution curves like those in Fig. 2 play an important role. Changes in landuse within the catchment area will change those distribution curves, which in turn influence the modeling results.

Construction of the soil storage capacity distribution curves shown in Fig. 2 is based on information obtained from two sources: (1) Landsat satellite imagery, and (2) digitized soil maps. The seven channels of the Landsat imagery are used in order to perform a landuse classification of the catchment area. This is not done as an average, but on the basis of Landsat pixels (30 x 30 m), i.e. we know the landuse classes for each area element within the river basin. From the five landuse classes chosen for this procedure, it is possible to identify the root depths of the vegetation cover for each pixel in the river basin. From the digital soil maps having a resolution of 50 x 50 m the soil porosity can be inferred for each pixel. By merging the information on root depths and soil porosity, it is possible to compute the soil storage capacity for each pixel as the product of root depth x soil porosity. Figure 3 shows 3 maps of the catchment of the river Nims in Germany, showing soil porosity (left), root depth (center), and soil storage capacity (right).

It is beyond the scope of this paper to go into more details of the rainfall-runoff model used in this effort. The accuracy of the model performance is adequate as can be shown from a typical example of runoff computation for a special flood and its comparison with the observed runoff hydrograph as given in Fig. 4.

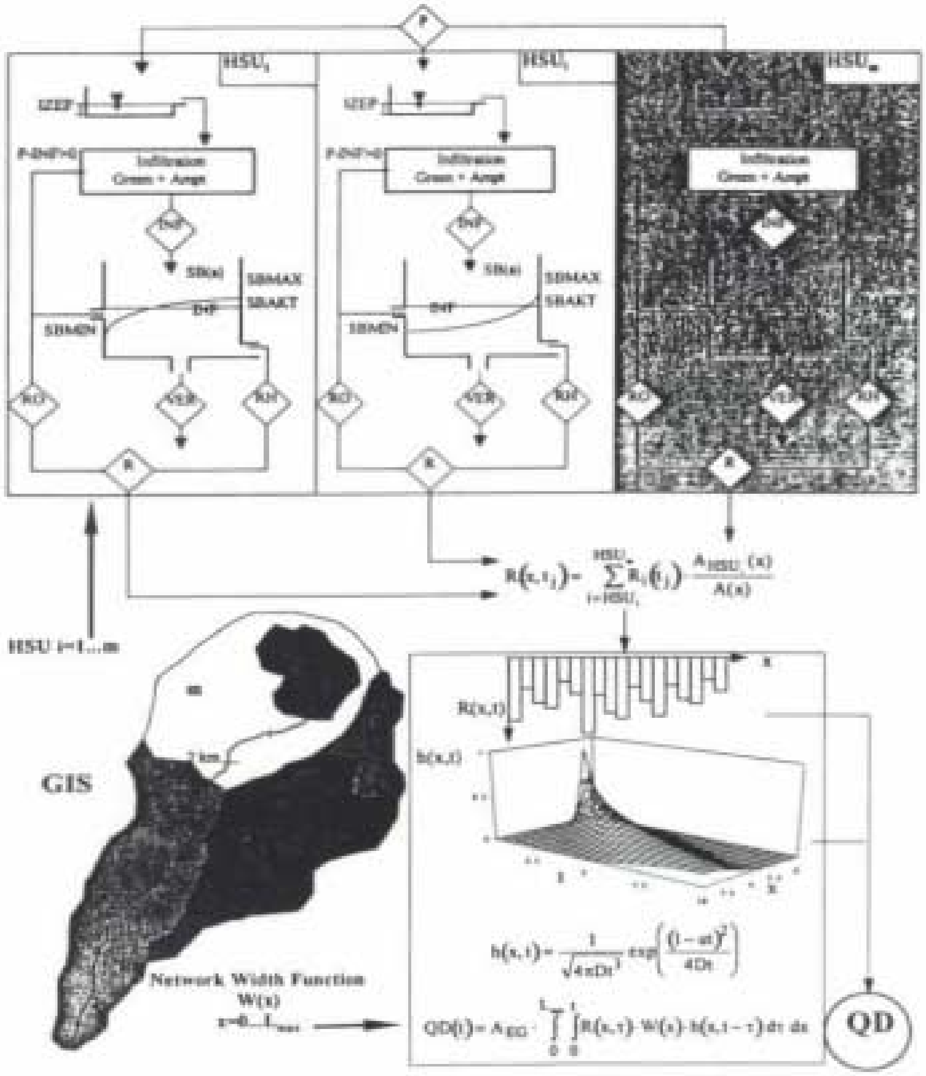


Fig. 1 Rainfall-runoff model with different HSUs for the runoff production model (top) and runoff concentration model (bottom right) both parameterized with the aid of GIS.

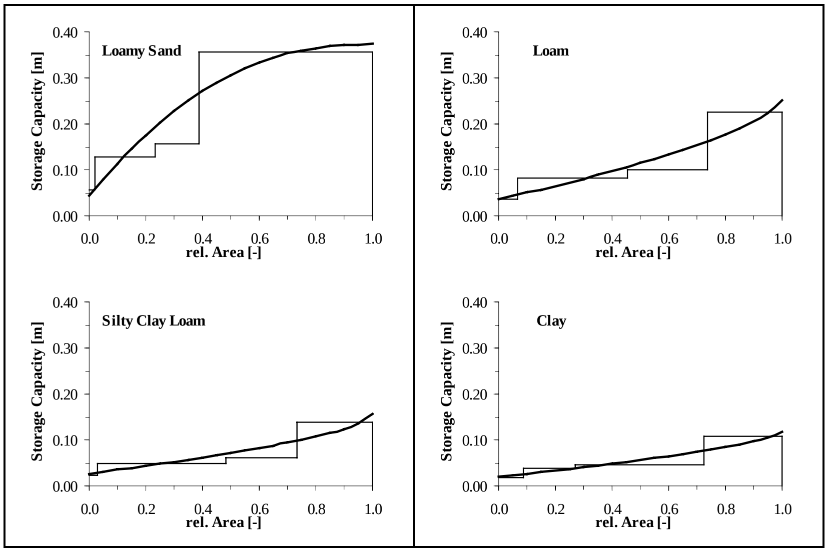


Fig. 2. Areal distribution function of the storage capacity for the upper soil layer for all 4 HSUs in the catchment Alsdorf/Nims (264 km^2).

3. SPECIFICATION OF LANDUSE CHANGES

3.1 INCREASE OF URBAN AREAS

In the modeling effort discussed above, landuse changes must be specified quantitatively for all pixels within the catchment area, for which a change has occurred or is assumed to occur in the future. For example, if a city is expected to grow in the future by 20 %, then a number of pixels (representing 20 % of the existing pixels classified as "urban") which used to be greenland agricultural area or forest have to be changed into urban pixels. A procedure was developed that aggregates these new urban pixels around the city limits of the existing urban areas. This way these future urbanizations look realistic in the map. Alternatively specific areas can be made urban, if the location of future developments is already known. Figure 5 shows a map of the Nims catchment for a chosen reference case (situation of 1989) when the fraction of built-up area was 5.8 % and a scenario of potential future conditions under which the built-up area increased up to 23.6 %. This landuse change alters the storage capacity distribution curves. Figure 6 shows the storage capacity for the reference case of 1989 and for the case of the increased urbanization. Comparison of the storage capacity distribution curves shows that, particularly for the texture "loamy sand", the areas with very low storage capacity have increased. This is due to the fact, that the increased urban areas are impervious and thus have a near zero storage capacity. A similar pattern can also be observed for the texture "loam", while for the other two textures (silty clay loam and clay) almost no change can be observed. This is understandable as these textures have a very low permeability, naturally.

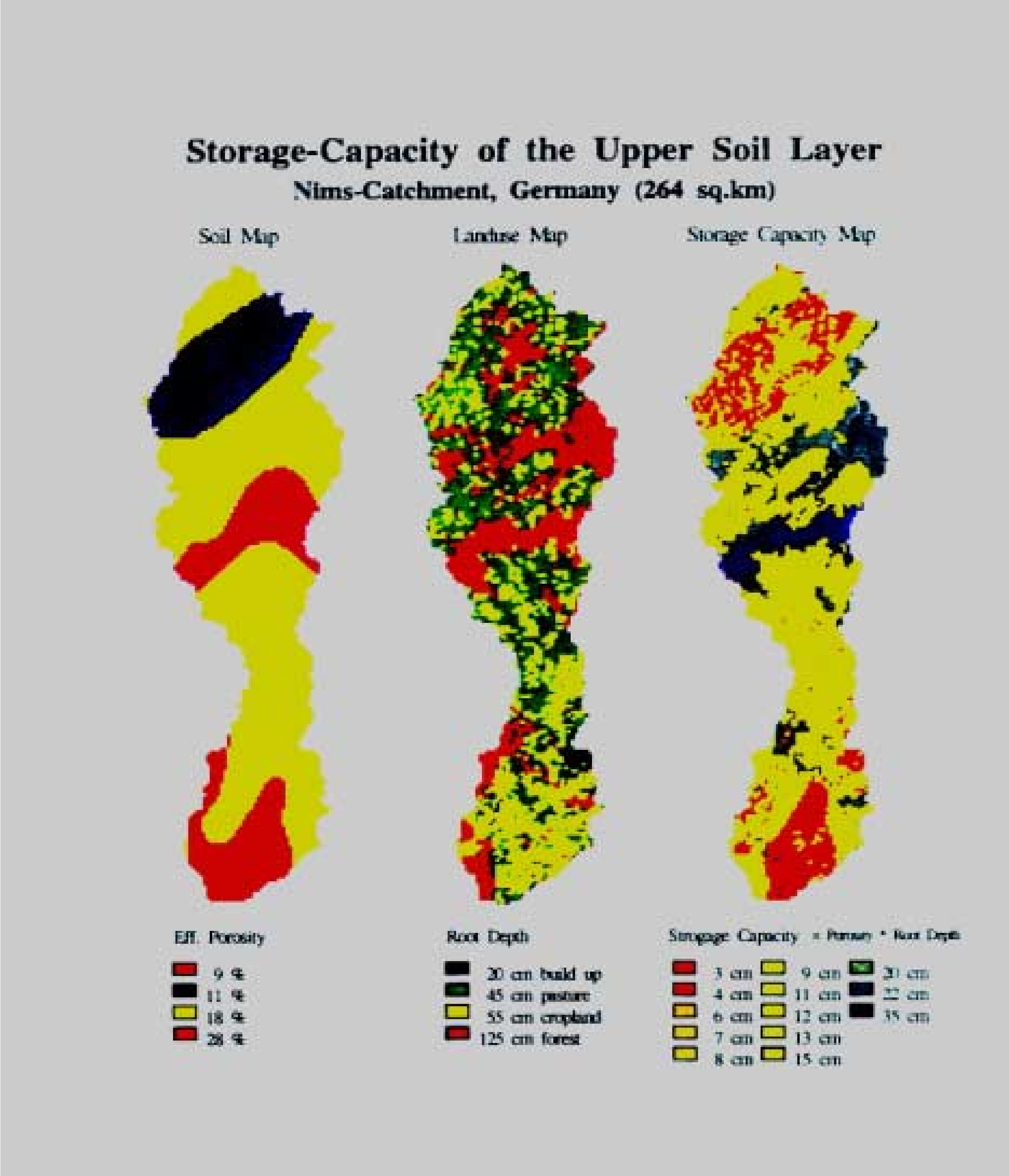


Fig. 3. Map of maximum soil storage capacity developed from Landsat imagery (for root depth) and digitized soil map (for soil porosity). Prüm and Nims catchment, Germany

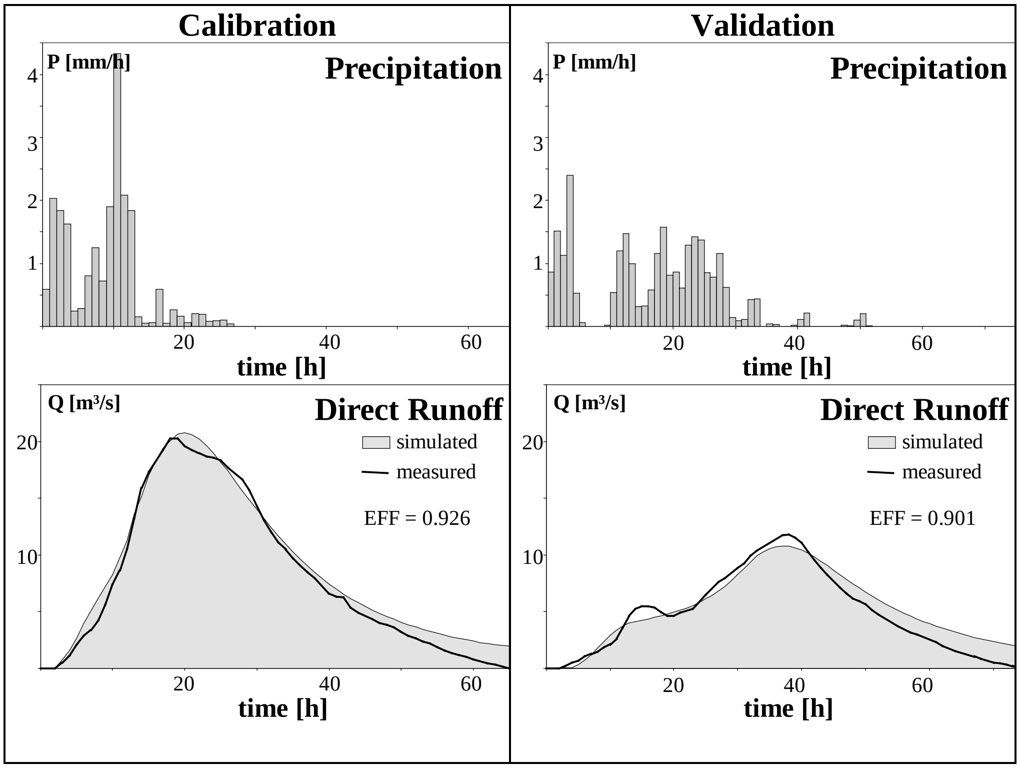


Fig. 4. Examples for the calibration and validation of the model for the catchment Alsdorf/Nims (264km^2), EFF = model efficiency by Nash/Suttcliffe.

3.2 FOREST DISEASES

Another type of landuse change, i.e. the scenario "forest disease", was also investigated because of its growing importance in central and northern Europe. Figure 7 shows two landuse maps of the Nims river catchment. One displays the reference case of 1989, the other the scenario "forest disease", specified in this case to indicate that all trees above an elevation of 400 m are assumed to be dead and replaced by grassland. This is realistic since experience shows that forest diseases are particularly relevant at higher elevations and may reduce the percentage of the forest areas from 30.1 % to 8.6 %. In the context of mathematical modeling, this fact implies that all pixels within the Nims river catchment that are located above 400 m (which is known from a digital elevation model) and are classified as "forest" in the Landsat-based landuse classification are changed from forest to grassland. This reduces the root depths of all these pixels from the values of the relevant forest type to the values of grassland. The consequences of this change can be seen again from Fig. 6. If we compare the storage capacity distribution curves of the reference case versus the forest disease case, we observe a significant change in these curves, particularly for the texture "loamy sand". Since large areas in the Nims catchment are presently forests at higher elevations, these areas lose much of their storage capacity due to the decrease in root depth thereby reducing the storage capacity of the soil significantly. This pattern can also be observed for the textures "loam" and "silty clay loam", although at a lesser significance. For the texture "clay" almost no change can be observed. The landuse classes for the 3 scenarios (reference case, increased urbanization, and forest disease) are given in Table 1.

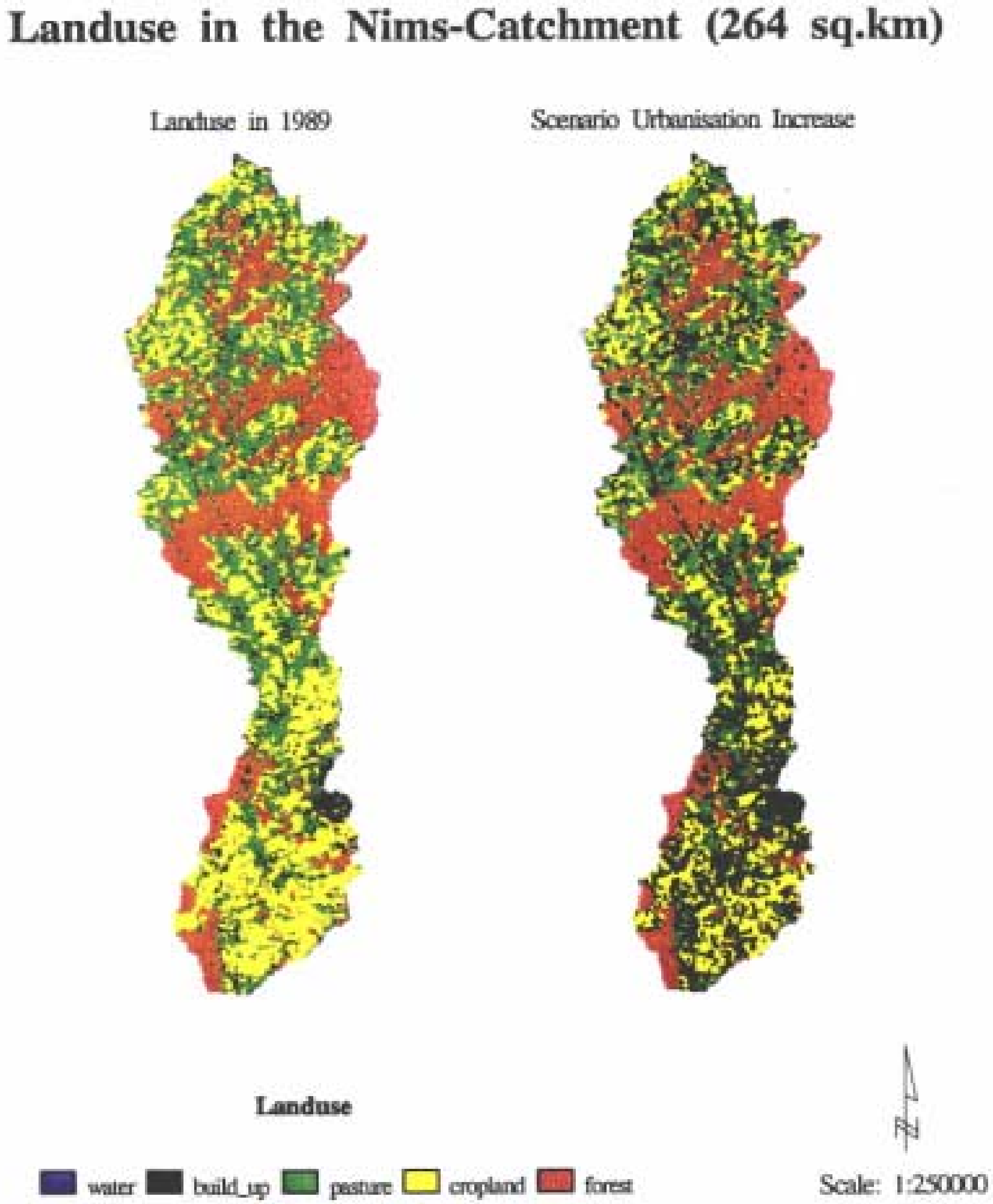


Fig. 5. Landuse classification of the Nims river catchment for a reference case of 1989 (urbanization = 5.8 % of area) and a scenario of increased urbanization (23.6 %).

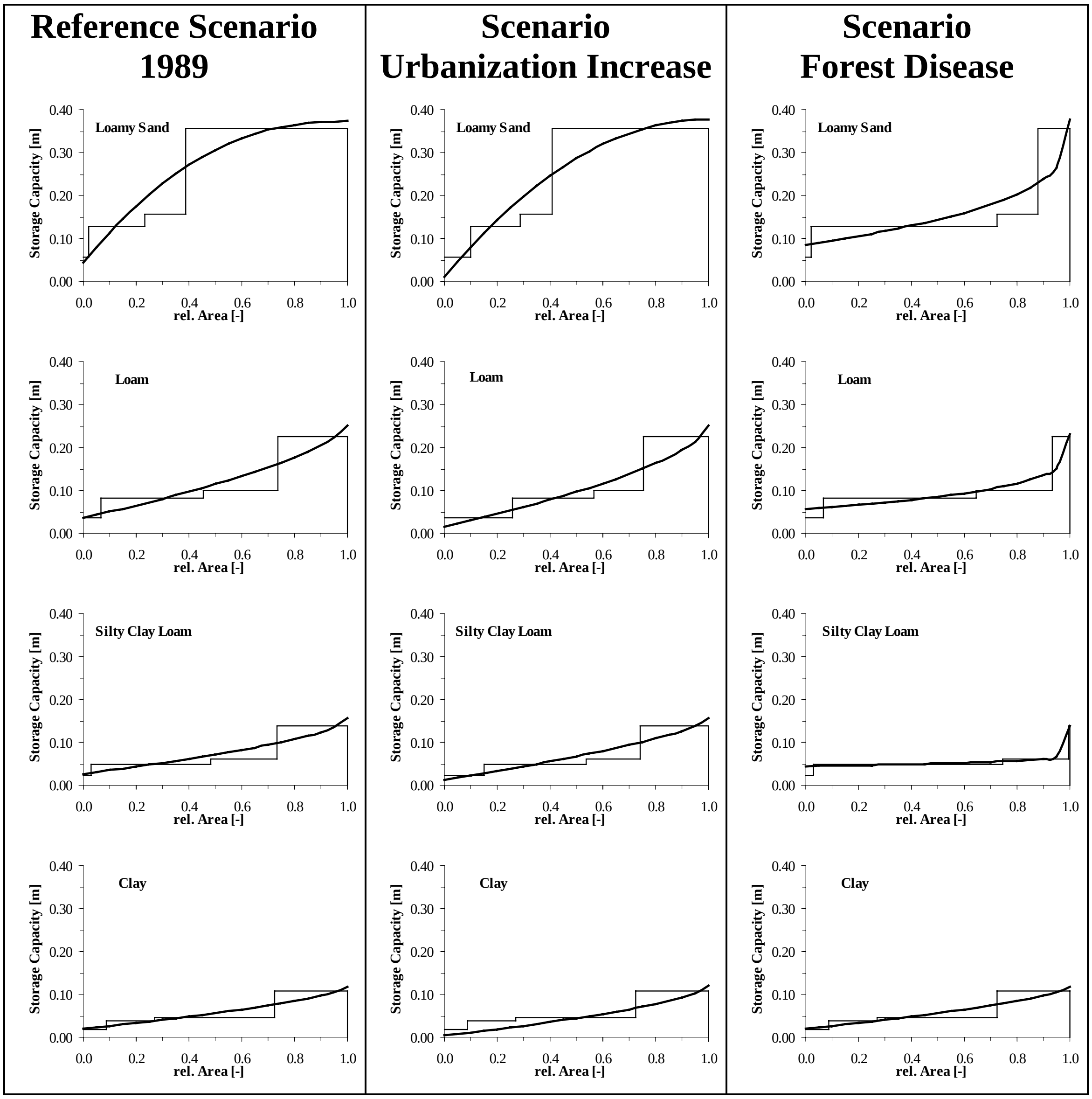


Fig. 6. Soil water capacity distribution curves for the 4 HSU's in the Nims river catchment for 3 cases: reference case 1989, increased urbanization scenario, and forest disease scenario.

Table 1. Landuse classes in the river Nims catchment for three scenarios

	Reference Scenario 1989	Scenario Urbanization Increase	Scenario Forest Disease
Water	0.00 %	0.00 %	0.00 %
Build up Areas	5.79 %	23.63 %	5.79 %
Pasture	35.62 %	28.63 %	57.10 %
Cropland	28.47 %	19.39 %	28.47 %
Forest	30.12 %	28.35 %	8.64 %
	100.00 %	100.00 %	100.00 %

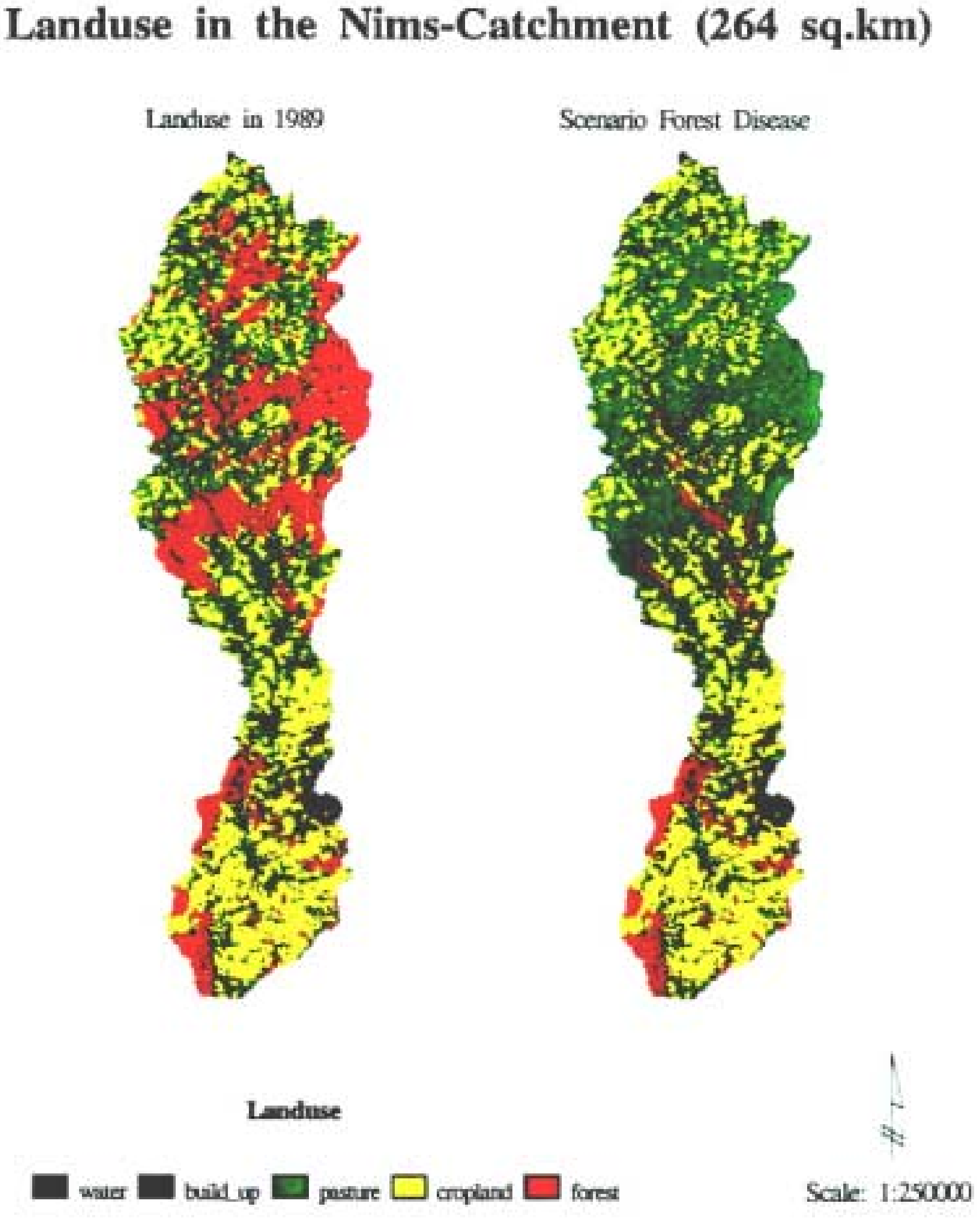


Fig. 7. Landuse classification for the Nims river catchment for a reference case (situation of 1989) versus a forest disease scenario (all trees above 400 m elevation are assumed to be dead)

4. HYDROLOGICAL IMPACT OF LANDUSE CHANGES

The model described in section 2 is applied to the river Nims catchment in order to compute flood hydrographs from precipitation in the following cases (scenarios):

- reference case of 1989
- increased urbanization
- forest disease scenario.

Computations were carried out for a number of severe flood events in the river Nims catchment. So far only preliminary results have been achieved.

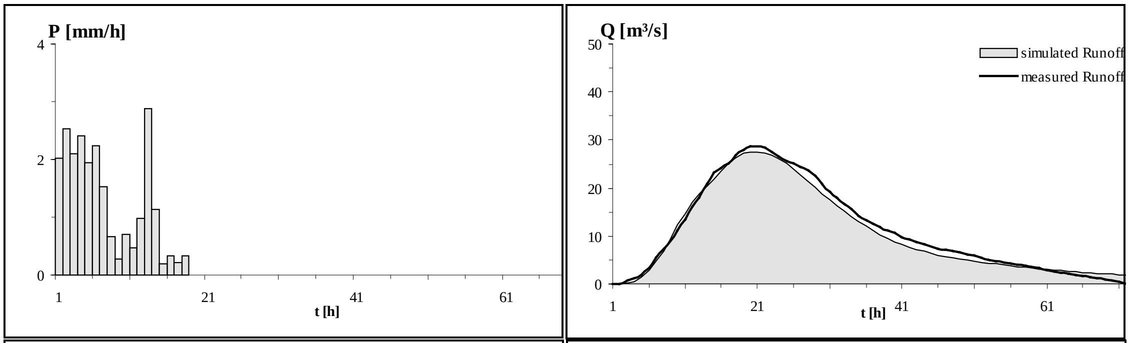
From the soil water capacity distribution curves shown in Fig. 6 it can be concluded already that, as compared to the reference scenario, the urbanization scenario will yield increased flood peaks and increased flood volume due to the fact that the soil water storage capacities have been reduced for the newly built-up areas. This gives rise to increased direct runoff and decreased soil water contents.

Also for the forest disease scenario the lowered soil storage capacities, as shown in Fig. 6, give rise to the expectation of higher flood peaks and volumes. This reduction is less obvious for the left part of the curve but more pronounced in the middle and right parts of the curve. This means that we do not have areas with extremely low soil storage capacity - as seen in the urbanization scenario - but lower storage capacities are maintained over larger percentages of the catchment area. Therefore, the forest disease scenario will also increase flood peaks and flood volumes. Figure 8 compares the computed and observed flood hydrographs for the 3 scenarios during a flood in the river Nims catchment, which occurred in June of 1984.

The upper two diagrams in Fig. 8 show the precipitation and runoff of the flood event and in the right diagram observed runoff is compared to the runoff computed with the aid of the model. It can be seen that there is good agreement. The scenario in the bottom left diagram shows a comparison of the flood hydrographs observed (under 1989 conditions) versus runoff occurring under conditions of the increased urbanization scenario. The rise of the flood hydrograph is much steeper, the peak is higher (about 50 %) and the volume is significantly higher for the urbanization increase scenario. This indicates that increased urbanization, industrialization, or construction of highway intersections or airports leads to a significant deterioration of the flood conditions. However, this result is true only if the catchment areas are not too large and if the ratio of urbanized areas (i.e. sealed areas) to the total catchment area is large, e.g. nearly 25 % as in the example presented in Fig. 8.

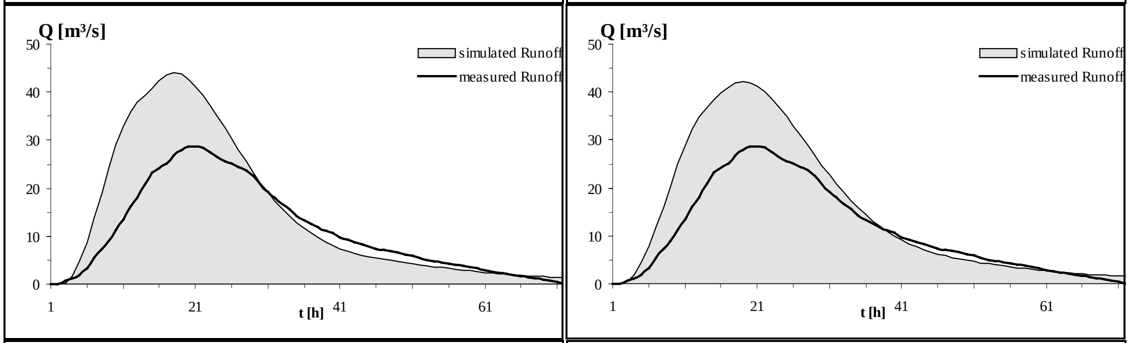
The hydrographs shown in the bottom right diagram of Fig. 8 represent a comparison between the reference case of the 1989 conditions and the forest disease scenario. In this case, we observe a flood hydrograph with a steeper rising limb, a much higher flood peak, and a considerably larger flood volume. This indicates that forest disease leads to a significant deterioration of flood conditions. As indicated before the forested areas decreased from over 30 % to 8.6 %.

For other flood hydrographs simulated under conditions of the three given scenarios, results are similar. At present, not enough results have been computed to allow a statistical analysis.



Precipitation

Reference Scenario 1989



Scenario Urbanization Increase

Scenario Forest Disease

Fig. 8. Observed and computed flood hydrographs simulated for conditions of 1989, the urbanization scenario, and the forest disease scenario, flood of June 1984, Nims river catchment

5. CONCLUSIONS AND SUGGESED RESEARCH TOPICS

At present we observe a growing public discussion on increasing damages and loss of life due to flood events. A thorough analysis of the question, is the increased severity of flood damage due to anthropogenic change and, if so, what are the reasons, is yet to come. In this paper only one reason for deterioration of flood conditions is discussed, i.e. the impact of specific landuse changes on flood hydrographs. A model is presented most of whose parameters are determined on the basis of catchment characteristics. Satellite imagery as well as digital elevation models and digital maps are used in order to identify the parameters of the deterministic distributed rainfall-runoff model. It was shown that historical or predicted landuse changes can be identified on digital landuse maps. Based on this information, changes in model parameters can be determined. In the model used here, landuse changes become apparent in a change of the soil water storage capacity distribution functions. Examples are given that show the impact of two types of landuse changes on flood hydrographs. In both cases, increased urbanization and forest diseases, it could be demonstrated that such landuse changes cause significant increases in flood peaks and flood volumes, both of which must be considered as deterioration of flood conditions.

Based on the experience gained in the research project discussed in this paper as well as in other research projects in a wider area of hydrological modeling, the following proposals for future research projects are suggested:

- Better determination of historical landuse changes in high-resolution hydrological rainfall-runoff models and development and validation of special hydrological models, which are capable of reproducing those landuse changes and their impact on flood conditions.
- Quantification of flood hydrograph changes based on quantitative landuse changes, including a sensitivity analysis of those changes in relation to catchment area size.
- Development of rainfall-runoff models, in which the storage water component (dS/dt) is not considered as a residual of other water balance components, but as the central model component. This requires in-situ measurements of soil moisture and a new structure of hydrological models. The question, how far remote sensing data (e.g. active or passive microwave data) can be used in order to quantify soil water content with a high spatial resolution has to be addressed,
- Thorough analysis of sub-surface flows - vertically and laterally - including the hydraulics of the macro-pore system, to improve the modeling of water transport in the unsaturated soil zone, including the role of air content in the pores of the soil.
- Developments of improved models for real-time flood forecasting and flood warning. In addition to the development of an adequate theoretical model structure, modern electronic input devices must be considered, i.e. groundbased weather radar or satellite imagery. Particular emphasis must be placed on the question of quantitative precipitation forecasting (QPF) in real time and the analysis of the sensitivity of forecast flood hydrographs to imperfect QPF's.

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6. REFERENCES

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