GIS and Modeling in Ecological Studies: Analysis of Beaver Pond Impacts on Runoff and its Quality

Voyageurs National Park, Minnesota, case study.

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NRRI Technical Report
NRRI/TR - 94/01
February, 1994

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Research funded by the National Science Foundation

(DEB - 9119614)

EXECUTIVE SUMMARY.

The ARC/INFO GRID module was used to derive watershed variables for input to AGNPS, a cell-based runoff model that estimates water volume, peak flow, eroded and delivered sediment, chemical oxygen demand, and nutrient export from watersheds (Young et al. 1987). The boundary of a 534 ha watershed in Voyageurs National Park was hand-digitized from 1:24,000 topographic maps, and used to clip elevation data from a 7½ minute U.S.G.S. Digital Elevation Model (DEM) with 30 m mesh-point spacing. ARC/INFO GRID was used to generate slope, slope shape, and field slope length for each of the 90x90 m cells used to subdivide the watershed. A surface runoff network was then generated using the FLOWDIRECTION, FLOWACCUMULATION, and STREAMLINE hydrologic modeling tools in ARC/INFO GRID. Each of the 90x90 m cells was uniquely numbered, and receiving cell numbers were derived for each source cell based on FLOWDIRECTION results. A 1:24,000 land cover map (Allen et al. 1993) was digitized and gridded to derive Manning's roughness coefficient, surface condition constant, and chemical oxygen demand factor for each cell. Detailed soil maps have never been made for the wilderness study site used, so land cover classes were coupled with information about soil series from nearby mapped sites to estimate soil texture, soil erodibility factor, and hydrologic group (to derive SCS curve numbers). The drainage area for each beaver impoundment in the watershed was derived from a digital database of subwatersheds. All variables were exported from ARC/INFO into the Microsoft Excel spreadsheet program, which was used to generate a data file in the appropriate format for AGNPS.

The methodology was applied to the 534 ha, third order stream watershed to determine the influence of beaver ponds on water quality and quantity. Beavers influence runoff by: 1) constructing dams that retard the flow of water, 2) creating ponds that promote sediment deposition and increase phosphorus retention, and 3) changing forest land cover to water and wetland vegetation. We ran the model for a range of storms with average 24-hour rainfalls equivalent to a 1 yr, 2 yr, 5 yr, 10 yr, 25 yr, 50 yr, and 100 yr storm, based on National Weather Service records for the region. Model runs for the beaver-impounded landscape ("with ponds") were compared with those for the same watershed without the influence of beaver ("no ponds"), based on historical vegetation and adjacent forest types.

The "with ponds" scenario resulted in slightly increased water flow at the mouth of the watershed. This is because, assuming that the pond is full, 100% of the rain that falls onto it will flow off of it. This caused a 10% increase in runoff at the lowest rainfall intensity, but only a 1% difference during the 100 yr storm. The runoff contribution of individual cells changed relatively little between the two scenarios, but there were easily discernable differences in accumulated runoff per cell

with distance downstream. Sediment deposition in the beaver ponds also had an effect that accumulated downstream, so that the "with ponds" scenario yielded 7 to 12% less sediment than the "no ponds" scenario, an effect that increased with storm intensity. The model predicted a 4% decrease in watershed nitrogen output with ponds for a 1 yr storm, but there was no effect for storms with a 10 to 50 yr frequency, and a net increase for a 100 yr storm. This implies that while beaver ponds may retain N during low-intensity storms, there may be a flushing of that retained N during high-intensity storms. This pattern is visible on GIS maps for "with ponds" scenario with low intensity storm: higher nitrogen concentrations were observed at the locations, where no ponds were situated, and nitrogen content in runoff had remarkable alterations in cells adjacent to ponds. Chemical oxygen demand (COD) showed the largest effect of any of the parameters predicted: the presence of beaver ponds was associated with a 10 to 17% reduction of COD, depending on the storm intensity. This is because a forest has a lot more primary productivity than a pond, and therefore contributes more organic matter (and therefore COD) to the system.

This model-based approach provided insight into the landscape scale influence of beaver ponds that could not have been derived using conventional field techniques. The modeling was done at a spatial level of detail that would have been impractical using manual data entry to AGNPS. Automating the derivation and interchange of variables with a GIS made this research possible.

ACKNOWLEDGEMENTS

Bob Young, Basil Meyer, John Witte, and Mike Koehler of the USDA Agricultural Research Service in Morris, MN provided valuable assistance with AGNPS. Research support from the National Science Foundation (DEB-9119614).

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1. INTRODUCTION.

Integration of environmental modeling and Geographical Information Systems (GIS) is one of the most rapidly developing branch of sciences, related to natural resources management. Current work at the Natural Resources Research Institute of the University of Minnesota (NRRI) focuses on the problems of ecosystem dynamics determined by changes of hydraulic regimes and nutrient cycles. One of the complicated problems facing the scientists is to determine and forecast impacts of beaver ponds on ecosystems. Number of beaver ponds drastically increased in Northern Minnesota in recent decades, producing a variety of direct and indirect impacts on forest ecosystems, hydrology and landscapes. Assessment and forecasting of these impacts involve analysis of interrelated natural processes and multiple temporal and spatial sets of data.

When addressing the problems of runoff and water quality assessments in a changing environment, the following general questions arise:

1. What are the relative hydrological impacts of different landscape features ?

2. Which process simulation models could be appropriate for studies of input-output relationships between climate and hydrology in dynamic landscapes ?

3. What are the related parameters to describe these processes with desired accuracy and efficiency ?

4. How to determine and analyze values of spatially distributed parameters corresponding to landscape changes ?

5. What are the procedures to relate the detected changes in hydrology and water quality to the landscape changes taken place on the watersheds ?

Numerous studies deal with estimates and modeling of hydrology and material fluxes in a watershed scale. The general opinion is that changes in land use, climate, atmospheric deposition to terrestrial ecosystems are able to cause significant alterations in streamflow and water quality downstream (Howarth et al., 1991). The magnitude of loading from various areas varies considerably depending on land use and hydrological conditions. The loading of sediment may vary from zero or a few kilogram per hectare per year from forest land and pasture on permeable soils or some low-density suburban residential areas to several hundred tons per hectare per year from construction sites, mining or congested nonmaintained urban centers (Novotny and Chesters, 1981). However, quantitative spatial estimates of particular impacts are difficult to obtain due to the complexity in the terrestrial cycle.

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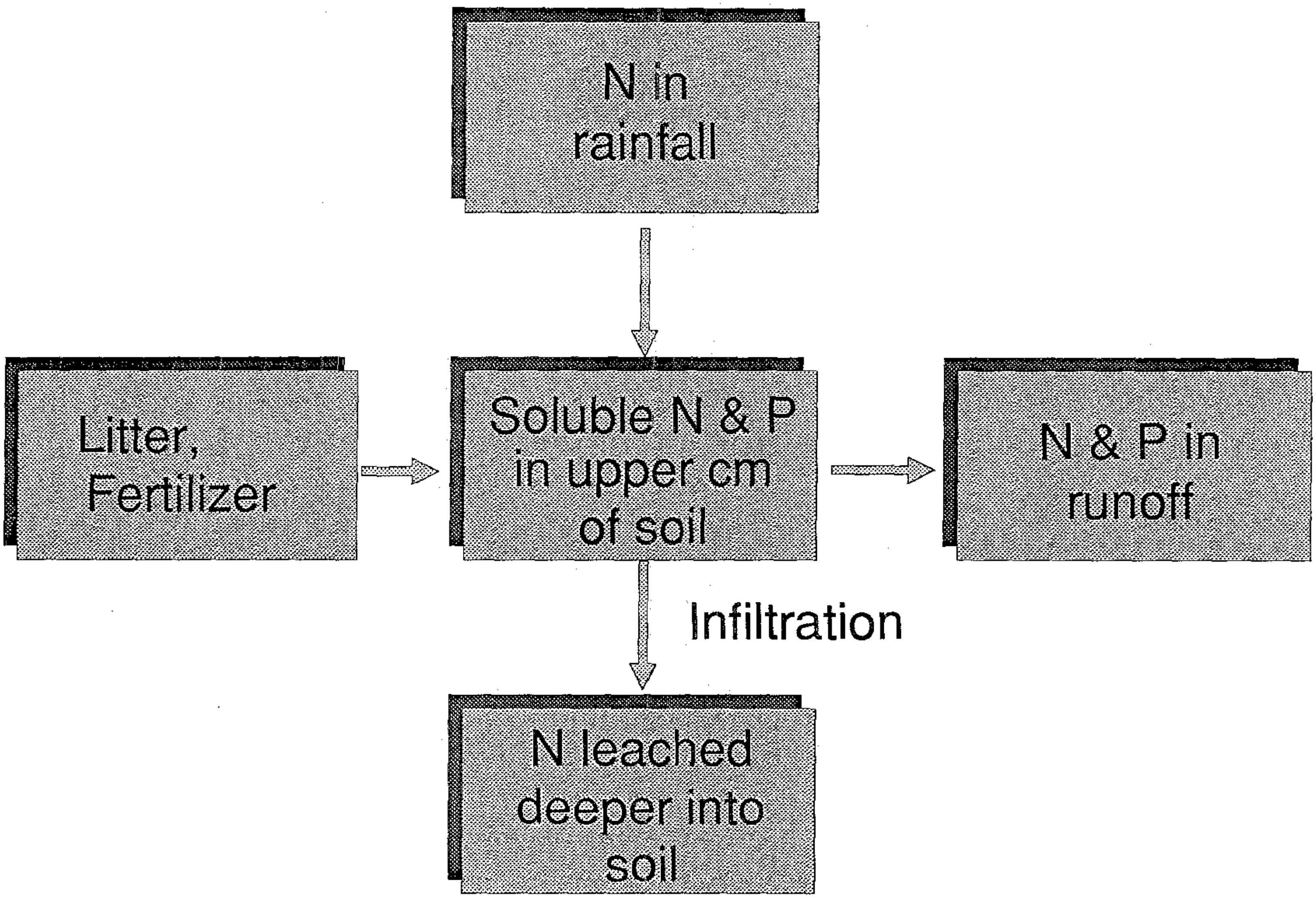
Figure 1. **Fluxes of nutrients in watershed systems.**



2. METHODOLOGY.

Recent developments in the integration of environmental modeling and GIS make it possible to use digital databases of landscape characteristics (streams, topography, land cover) to predict water and nutrient flow through the landscape. However, the use of modern tools has to be directed by knowledge of process, governing fluxes of materials in natural systems. Schematically these fluxes are shown on figure 1. Generally, three basic directions are developing in the studies of these processes.

2.1. Aggregated assessments of fluxes on watersheds, based on hydrochemical studies of streamflow, statistics and "black box" models.

Analysis of field data from 928 U.S. watersheds by Omernik (1977) revealed relationships between land use and water quality. Mean concentration of both total phosphorus and total nitrogen were nearly nine time greater in streams draining agricultural lands than in streams draining forested areas. The nature of chemicals also varied by land use. Inorganic nitrogen made up a larger proportion of total nitrogen concentration in streams from watersheds having larger percentages of agricultural land. The inorganic nitrogen component increased from about 18% in streams draining forested areas to almost 80% in streams draining agricultural watersheds. The inorganic (orthophosphorus) portion of the total phosphorus component stayed roughly at the 40% to 50% level regardless of land use type (Omernik, 1977).

Based on this type of approach important nation wide estimates were derived to illustrate the damage caused by nonpoint source pollution to the environment and national economy. According to Duda (1993), agricultural activities in the USA produce four times more pollution than municipal point source discharges. Sediment pollution alone imposes high monetary costs, with at least $6.2 per year in offsite damages to water users, recreation, reservoirs, waterways etc.

Basin scale estimates give the values of average loads from diffuse pollution sources. For example, loadings from watershed to the Great Lakes in mid-seventies were estimated as (kg/ha-yr): total phosphorus - 0.40, soluble orthophosphate - 0.10, suspended solids - 310, total nitrogen - 6.4, chlorides - 74 (Novotny and Chesters, 1981).

The "black box" models could be applied to large geographical areas to estimate the flows of materials based on certain aggregated assumptions. Studies in the Mississippi basin (Gildea et al., 1986) treated the whole river basin as a coarse network (resolution 0.5 degree). Land uses, distinguished for 1374 cells of the basin, gave characteristics of nutrient budgets in agro-ecosystems, expressed as functions of fertilizer input. For forested and grassland ecosystems, nutrient budgets were assigned based on literature data. The resulting assessments of nitrogen flows in the basin compared pre-settlement and contemporary scenarios. According to these estimates, the terrestrially mobilized total N loads varied by subwatersheds from 35 to 480 Mg/yr with the increase over the pre-settlement period from 23.2% to 500%.

In this type of approach hydrological process simulation is replaced by bulk estimates of fluxes between aggregated cells. Factors which impact runoff and its quality on the watersheds are not considered separately.

2.2. Process based simulation modeling.

Mathematical modeling is applied to determine factors controlling runoff and fluxes of material on watersheds. The numerous models, developed by many authors (DeCoursey, 1991; Nazarov, 1988; Novotny and Chesters, 1981), are based on fundamental water balance equations.

Surface runoff

$$R_s = P - S_i - S_d - f\,\Delta t \qquad (1)$$

Interflow (lateral soil water movement)

$$R_i = (f - ET)\Delta t - S_s - q_g \qquad (2)$$

Groundwater (base) flow

$$R_g = Q_g - S_g - Q_d \qquad (3)$$

where:

- R_s = volume of the surface runoff (cm) in a time interval Δt
- P = precipitation volume (cm)
- S_i = change in the available interception storage (cm)
- S_d = change in the available depression surface storage (cm)
- f = infiltration rate (cm/hr)
- ET = evapotranspiration rate from the soil zone (cm/hr)
- S_s = soil moisture storage change (cm)
- q_g = groundwater recharge (cm)
- R_i = interflow volume (cm)
- R_g = groundwater flow contribution (cm)
- S_g = groundwater storage change (cm)
- Q_d = geological water loss (cm)
- Δt = time interval (hr)

The models, describing mass transfer of chemicals on watersheds transport. This is because the primary transport mechanism is the movement of water. Hydrodynamic models are built on equations of convection and dispersion for moving water solutions. These processes can be represented by ordinary differential equations as:

$$dS/dt = I - Q \qquad (4)$$

where S is the amount of water solution stored in a particular object, I is the inflow rate, Q is the outflow rate, and dS/dt is the rate of change of storage with respect to time in response to inflow and outflow (Maidment, 1993). The components of equations represent separate chemical and physical transformations of the substances.

In general form, changes of soluble and absorbed matter are taken into account. In most water quality simulation models (CREAMS, AGNPS, GWLF, ANSWERS) the fluxes of material appear at dissolved phase in surface and subsurface runoff, and at solid phase in sediment transport (Knisel, 1980; Young, 1987; Smith and Ferreira, 1989; Haith et al., 1992; Priazhinskaya, 1992).

A variety of models were developed by scientists to predict runoff and its quality in watersheds. Simulation is based on climatic, physiographic, soil, land use, vegetation and other data. The majority of such models are locally based and tested, and the diversity of approaches to model development indicates the complicated nature of hydrological processes.

Depending on theoretical assumptions and details of hydrological and chemical processes involved, the complexity of models and their input requirements vary. Models are highly dependent on the availability of spatial data, and their practical application for heterogeneous watersheds is limited entirely by this factor. In the absence of GIS some modelers developed separate procedures to simulate spatial processes, like flows between cells on a watershed in AGNPS (Young et al., 1986), or within a structured channel network, draining uniform subwatersheds (Nazarov, 1988).

Tradeoffs between accuracy and availability of both reliable models and input data are inenviable when implementing a practical case study and water runoff simulation on watersheds. Each particular case study imposes certain limitations on the complexity of process description. Input data and resources availability are the important constraints for the ultimate choice between desirable models.

2.3. Linking GIS and models

GIS and environmental modeling, when combined, allow to describe spatial environment. GIS can serve as a common data and analysis framework for environmental models (figure 2). But GIS and environmental modeling grew up separately, so their computer programs have very different data structures, functions and methods for inputing and outputing spatial information (Maidment, 1993).

In attempt to overcome existing gaps the concept of "unit loads" is often applied. It offers a relatively simple method for quickly deriving a rough estimate of average long-term (i.e. annual) diffuse loading within large, diverse watersheds. GIS technology is used to obtain an accurate description of how

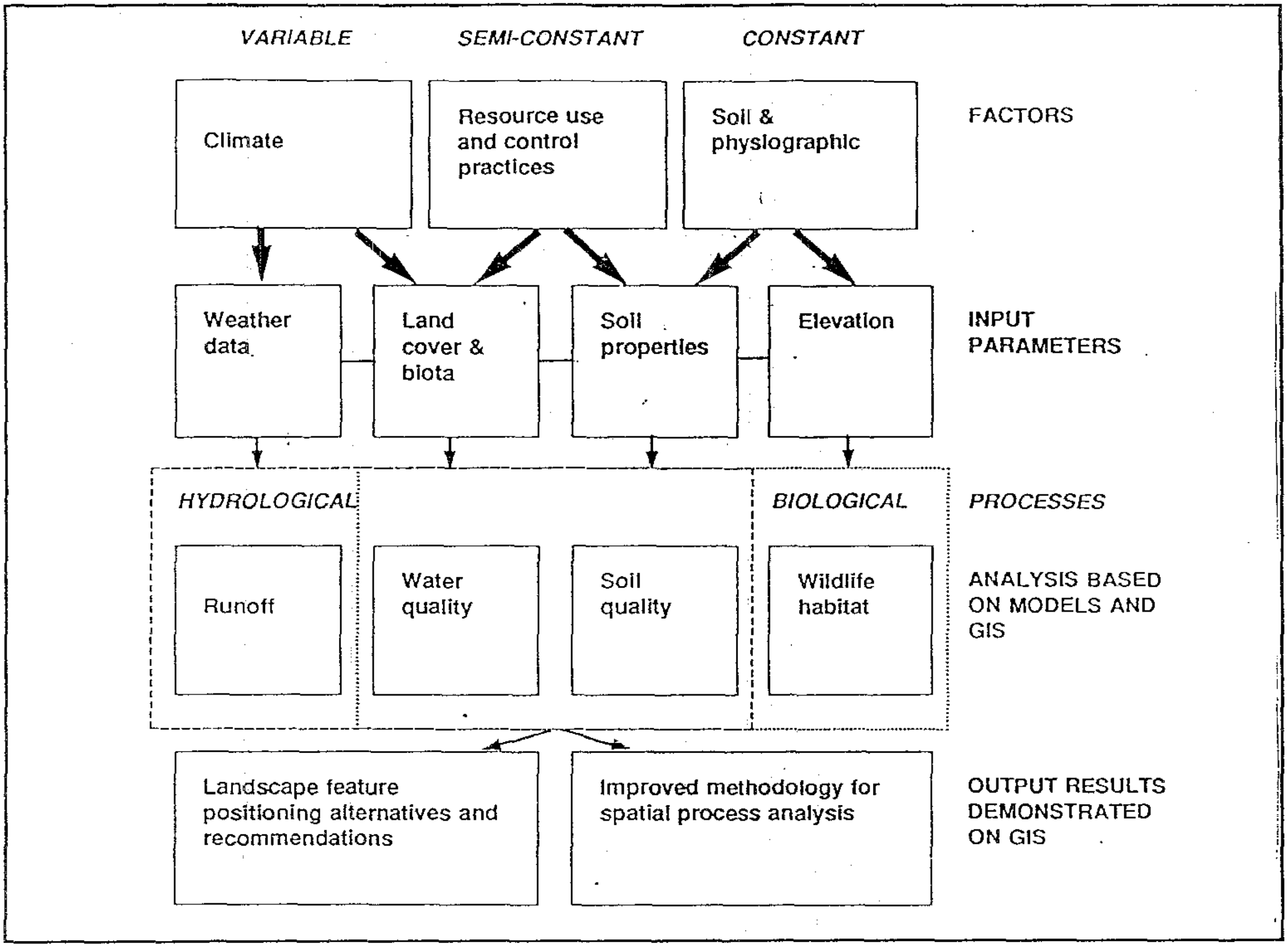


Figure 2. **Conceptual framework of linking GIS and models for environmental management.**

specific combinations of critical geographic attributes are distributed over the drainage basin. Phosphorus loads in the Owasco Lake watersheds were determined by Heidtke and Auer (1993), based on this concept, using Universal Soil Loss Equation (USLE) and urban runoff loading functions. A similar example is provided by Tim et al. (1993), when estimating soil erosion, sediment and phosphorus pollution for the Nomini Creek watershed in Virginia. Phosphorus transport, **TP**, in each hydrologically homogeneous land cell, **i**, was calculated on the basis of the average P content, **Pc**, in the surface soil layer, **Pc**, the sediment yield, **L**, obtained from the modified USLE, and the P enrichment ratio, **ER**. Thus

$$TP_i = \Sigma\ Pc_i * L_i * ER_i \qquad (5)$$

However, the above mentioned approach, though capable to produce watershed scale estimates with reasonable efforts, sacrifices many important details and the dynamics of hydrological processes.

GIS demonstrates the higher accuracy and abilities to analyze processes in detail when applied at studies of separate landscape components, like relief. In studies performed by Mitasova (1993) the detailed surface modeling and computation of topographic potential for erosion and deposition were implemented. The cell resolution from 2 to 10 m was obtained after resampling of standard USGS 30 m DEM. The erosion potential, **E**, was computed within GRASS GIS as the change in sediment transport capacity, **s**, in the direction of flow $E = dT/ds$. It was estimated by a directional derivative of the surface $T = g(x,y)$ in the direction of flow, given by aspect (Mitasova, 1993).

New, more powerful GIS tools are being developed rapidly. The later version of ARC/INFO GRID 7.0 has abilities to incorporate certain dynamic characteristics in surface hydrological modeling. The function, called *Flowlength*, implements the time-area and distance-area diagrams for the watershed. The time of travel to the outlet in each cell is calculated and the time-area map is created. With GIS GRID capabilities for rainfall mapping, the uniform spatial rainfall distribution is no longer necessary so that two subscripts are needed to characterize rainfall, P_{ij}, where P_{ij} is the average excess rainfall over all cells in isochrone zone **i** during time interval **j**. Direct runoff Q_n at time $t = n\Delta t$ is given by summing the runoff contributions from each of the applicable isochrone zones suitably lagged in time:

$$Q_n = \sum_{i=1}^{n} P_{ij} A_i / \Delta t \ , \text{ where } j = n-i+1 \qquad (6)$$

A_i in this equation (6), suggested by Maidment (1993), represents the incremental areas of GRID time-area diagram.

It seems that the current potentials of GIS for spatial/dynamic processes modeling are beyond the most optimistic outlooks.

Smart-pixel technology, applied in computer understandable terrain model (CUTM), combines GIS, image processing and expert system technologies (Shattuck, 1993). The goal of CUTM is to provide the dynamic representations of the physical, biological and chemical processes on the earth surface by means of scene modeling. Each point of the synthetic image is tied to a knowledge base in an object-oriented program structure. For example, in the case of hydrological studies it could be snowmelt simulation. As environmental events are modeled, each pixel in this rasterlike structure reacts under rules to global conditions, such as the current weather, and interacts with local conditions (its neighboring pixels). All spatial data are gathered into a single composite matrix.

What is still behind and slows down the promotion into practice of these advanced technologies, is that the existing data bases are often uncompleted. If some layers of data lack the resolution necessary to conduct detailed investigations, the most sophisticated tool becomes only as accurate as the least detailed data section. It is particularly true, when the integration of data from scattered sources is essential, like for any watershed scale hydrological and water quality study. The input data include precipitation, elevation, soils, vegetation, surface geology, land uses etc. The common case is, for example, when along with detailed GIS compatible elevation data from DEM, soil maps are either not available at the same scale, or do not contain vital information, needed to determine some parameter values for the process based hydrological models. The unavailability of spatially distributed geochemical data to ascertain initial concentrations for nonpoint source pollution modeling is also the general case. Hence, the equity and uniformity of heterogeneous data bases is always the consideration, guiding the choice of methodological tools for the research.

3. CASE STUDY WATERSHED

The analysis of hydrological impacts of beaver ponds was implemented for a case study watershed in the Voyageurs National Park in Northern Minnesota. This territory is situated in the boreal coniferous forests zone. Soils are formed on glacial and post glacial lucastrine sediments with outcrops of bedrock. Wetlands and beaver impoundments are common. The landscape of the area has been changed significantly in recent decades due to increased beaver population, more dams and ponds created, and related changes in biological communities. Further trends of ecosystem developments could be forecasted with more knowledge accumulated about watershed hydrology, wetland dynamics and material fluxes within and between ecosystems.

The current problems of ecosystem studies in the park focus on determination of the influence of beaver ponds on water quality and quantity. Beavers influence runoff by: 1) constructing dams that retard the flow of water, 2) creating ponds that promote sediment deposition and increase phosphorus retention, and 3) changing forest land cover to water and wetland vegetation.

Detailed simulation and GIS studies were performed at the Finlander Bay third order stream watershed. Its area is 534 ha, the location in the Voyageurs National Park is shown on the figure 3. Natural conditions of this small watershed are representative for the rest of the territory.

4. DESIGN OF SIMULATION STUDIES

Since the background experience of GIS application to environmental research is limited, there no standard approaches which provide explicit guidelines for a specific regional case study. The methodological rules are still to be developed and tested. The methodology of linking GIS with models, explored in the course of this project, could contribute to the further development of GIS based environmental studies and their practical application to natural ecosystem management.

Spatial accuracy of hydrological modeling in this study was supported by GIS ARC/INFO 6.1 software on work stations with grid capabilities. GIS was used to interpret and to implement graphical and numerical analysis of digital elevation maps (DEM) and to derive from them spatially distributed parameters for watershed runoff modeling, such as stream channel network allocation, slopes, aspects (flow directions), slope shapes, channel slopes etc. In addition to that a variety of soil, land use and vegetation data could be also stored and retrieved from GIS at certain stages of watershed runoff and water quality modeling.

Still, the researcher could face a number of certain technical problems when implementing step-by-step analysis and transfer of GIS derived parameters as input parameters to hydrological models on cell-by-cell base, as well as when presenting simulation output results on GIS. State of the art procedures were developed to achieve full compatibility of certain inputs and output and to maintain flow of data between GIS and models.

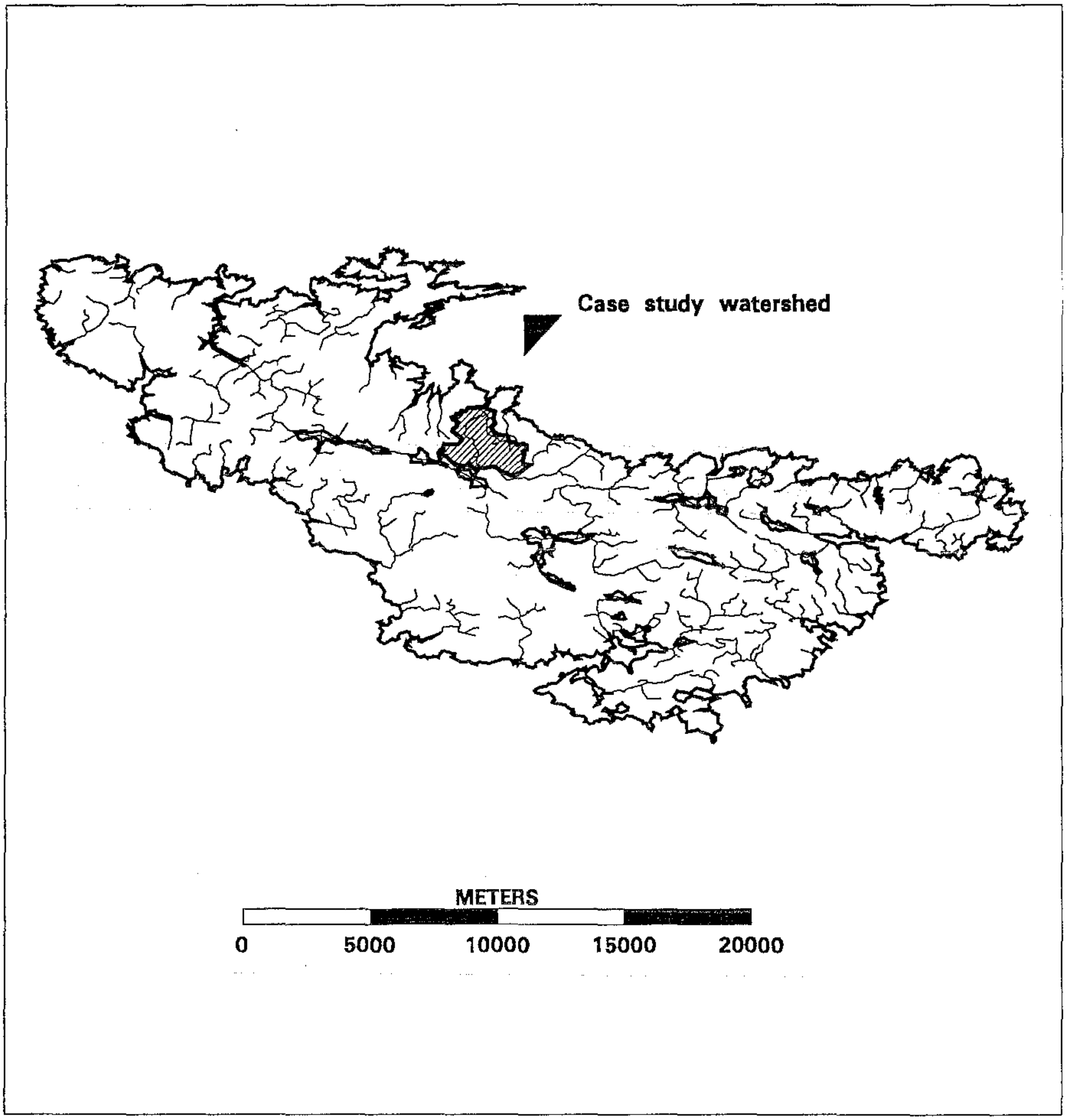
The following essential steps for integrating GIS and hydrological modeling were outlined in the course of this study:

1. Input data quality assessments and comparative spatial analysis of parameter sets prior to storing in the parameter library.

2. Generating and modification of input data based on computation procedures and graphical tools of GIS.

3. Scenario based analysis for environmental forecasting and decision making with generation of scenario related input parameter sets and analysis of corresponding outputs on GIS.

Figure 3. Location of Finlander Bay case study watershed at the Voyageurs National Park, MN



4. Interactive spatial analysis of intermediate and final output results of simulation, model validation studies and sensitivity analysis with graphical representation of input - output parameter relationships by means of GIS.

5. Detection of hot spots and problem zones with regard to specific criteria and tasks, emerging in environmental research and decision making.

The methodology outlined was tested for the above mentioned case study watershed. In the course of this study model runs for the beaver-impounded landscape were compared with those for the same watershed without the influence of beaver. The obtained simulation results were analyzed to define major impacts of beaver population on watershed hydrology and water quality. The general flows of information, integrated by GIS, and their relationships to watershed system features and processes are presented in figure 2.

5. MODEL DESCRIPTION

AGNPS watershed runoff and water quality model, developed by Agricultural Research Service for South Western Minnesota (Young et al, 1986) was chosen for this study. Authors admit, that the reliability of water runoff quality / quantity predictions, based on this model, is limited by the input data. On-site hydrological observation studies are currently on the way at the Voyageurs park, which are aimed to fill the existing data gaps. The general goal of this study was to develop and demonstrate linkages between standard GIS technique and hydrological models, using AGNPS as the typical model example.

The following features of AGNPS model are beneficial for this study:

1. Cell based structure of input data, which provides the relative compatibility with GIS.

2. General similarity of requirements to input data with other models of this type, which provides the opportunity for further testing of different models with the data base, originally developed on GIS for AGNPS.

3. Explicit procedures present in the model to evaluate impacts of impoundments on watershed runoff, which is essential for the case study watershed with a large number of beaver ponds on its territory.

AGNPS also has several disadvantages:

1. The lack of process based descriptions of water and sediment runoff. Basic calculations in the model are implemented with empirical Hydrological Curve Numbers and Universal Soil Loss Equation.

2. The single event based approach used in the model does not allow to simulate long term dynamics of runoff and related processes.

3. The evapotranspiration and related plant growth processes are beyond the scope of the model. So far the important processes, caused by climate impacts on vegetation growth and forest ecosystems behavior, as well as the influence of forest vegetation on water runoff, could not be considered and related to hydrological simulation input and output data in more comprehensive ecosystem studies.

4. The most of attention in the model is concentrated on the detailed description of agricultural management impacts on runoff and its quality. However, the case study watershed is primarily the forested and these capabilities of the model could not be demonstrated.

6. INPUT DATA QUALITY ASSESSMENTS AND SPATIAL ANALYSIS

Spatial representation of major parameter values and visualization of intermediate and final simulation results is helpful for better understanding of watershed processes.

In environmental studies model parameters are commonly estimated based on separate cartographic sources, literature, expert judgments, and the interpolation of point observation data. Separate layers of special data are stored on GIS. However, when the integration of these data occurs (i.e., to study the spatial allocation of water and material flows in the watershed scale), the spatial relativity analysis of parameter values is an important task. Landscape features (soils, vegetation, underlying rock etc.), represented by certain parameters in simulation modeling, are interrelated and allocated in natural systems based on geographical regularities. Experienced soil scientists, for example, could provide general outlines for soil allocation based on analysis of local maps of Quaternary sediments. Vegetation association pattern is closely related to the chemical and physical soil properties and ground water availability in the root zone. In its turn, surface and ground water hydrology is governed by climate and landscape feature patterns.

The assessments of input data quality could be performed by GIS tools. Inconsistencies often happen when various input parameters originate from different sources of data. Also, a common case is when local gaps of data could be determined. Identification of problem areas could be easier found with the help of GIS.

The major technique for the data exchange between simulation models and GIS is the transfer of data to and from GIS attribute data tables. The routine procedures were programmed, as well as standard spread sheet softwares (EXCELL an LOTUS) were used. GIS visualization, overlay and attribute table calculation procedures were applied to process the data. The proximity analysis and interpolation of existing data by means of GIS were used to fill the data gaps.

Basic standard procedures to derive model input data from GIS ARC/INFO proved to be helpful in the case study. The input data for the AGNPS model are structured on cell-by-cell basis with the explicitly determined links of water and chemical fluxes between each of cells. So far, the essential part of pre - modeling studies consisted of input data processing and transformation according to the model requirements to its input data structure.

At the beginning the relationships were difined between the land cover types, which were previously outlined for the Voyageurs National Park from remote sensing data, and the land cover related paraleters of AGNPS. These relationships are shown in the table 1.

The example of the whole set of AGNPS input parameters is presented in the table 2.

Table 1.

Relationships between land cover types and AGNPS parameters

Land cover	Curv #	Soil text	Mann coef	COD fact	K fact	C fact	P fact	SCC
Water	100	0	0.99	0	0	0	0	0
Wetland	85	3	0.99	25	0	0	0	0
Peat	85	4	0.99	25	0	0	0	0
Meadow	78	3	0.13	60	0.28	0.01	1.0	0.59
Forest	77	1	0.08	65	0.28	0.01	1.0	0.59
Bedrock	100	1	0.03	65	0.28	0.01	1.0	0.01

Table 2.

Example of input data for the AGNPS model.

AGNPS Variable	**Wetland**	**Upland Forest**
Cell number	135	153
Receiving cell number	118	152
SCS Curve Number	100	77
Land slope, %	0	3

AGNPS Variable	Wetland	Upland Forest
Slope shape	1	2
Aspect	1	7
Slope length, ft	0	125
Channel slope, %	0	3
Manning coefficient	0.99	0.08
Soil erodibility factor (K)	0	0.28
Cover/management factor (C)	0	0.01
Practice factor (P)	0	1
Surface condition constant	0	0.59
Soil texture	0	1
Fertilization level	0	0
Fertilization availability	0	0
Chemical oxygen demand (COD)	0	65
Impoundment factor	1	0

Watershed data are constant for the whole series of model runs and are entered from the keyboard. Number of cells was derived from GIS. In the case study example the folowing watershed data were used:

1. Watershed name, which indentifies input and output data files for the watershed: FINBAY

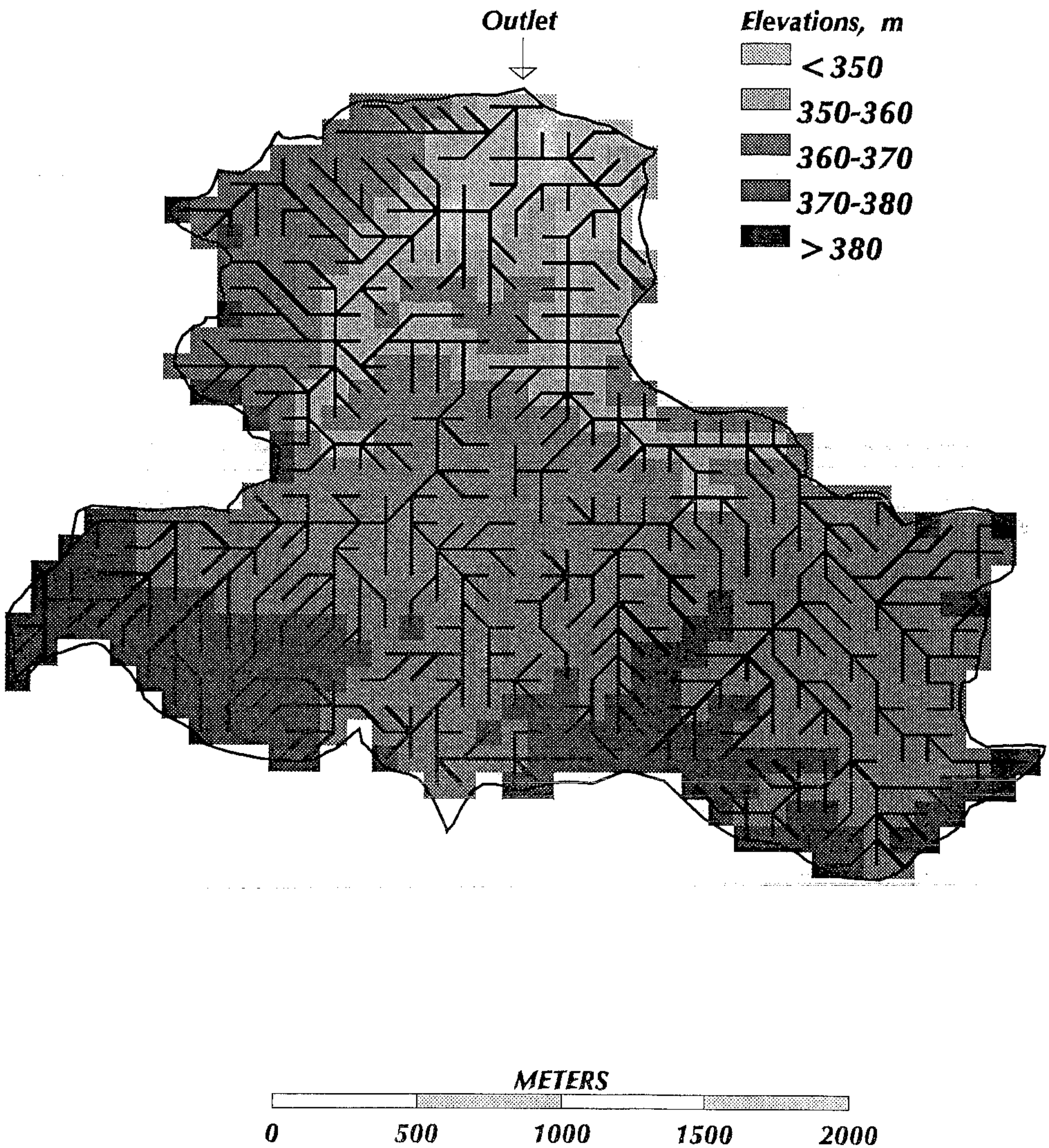
2. Area of each cell: 90 by 90 m, or 2.0014825 acres

3. Number of cells: 659

The primary step to create the input data set for further simulation is to define a cell grid with the satisfactory resolution and to derive from this grid the cell numbers.

The initial input for the GIS analysis was provided from a raster DEM with cell resolution of 30 by 30 m. The elevations in the case study watershed varied within the range of 350 - 400 m. To perform further analysis with AGNPS, which has a limitation of 1900 cells in a single watershed, it was assumed, that the resolution of cells 90 by 90 m could be sufficient for the case

Figure 4. Relief of Finlander Bay watershed with stream network, generated from the digital elevation map.



study goals.

The original TIN lattice elevation watershed cover WATERSHED.lat was transformed to a grid with integer values (figure 4). The initial procedures in GRID could be implemented with the original 30 m cell size to eliminate extra errors, produced from calculations with larger cells. The integer type of values is required by the consequent GRID transformation commands. Two ways could be used in ARC/INFO 6.1 to transform the lattice with floating points to grids with integer values:

```
Arc: gridascii WATERSHED_LAT WATERSHED_ASC
Arc: asciigrid WATERSHED_ASC WATERSHED_INT INT
```

or

```
GRID: WATERSHED_INT = int (WATERSHED_LAT)
GRID: buildvat WATERSHED_INT
```

The general requirement for the cell numbering in AGNPS is that cells are numbered consecutively beginning at the cell in the northwest corner and sweeping from west to east and north to south.

To provide the ground for next steps of analysis and stream network simulation based on elevations, minor errors in the DEM must be corrected. Otherwise, sinks are capable to break the further created stream network into pieces. The involved GRID procedures are:

Finding sinks:

```
SINK = sink (FLOW_DIR90)
SINK_AREA = watershed (FLOW_DIR90, SINK)
SINK_MIN = zonalmin (SINK_AREA, ELEV_90)
SINK_MAX = zonalfill (SINK_AREA, ELEV_90)
SINK_DEPTH = SINK_MIN - SINK_MAX
```

As a result of the above procedure the value of z-limit is obtained as a maximum absolute value in sink_depth.vat table.

Next step is filling sinks:

```
fill ELEV_90 FILLED1 sink < Z-LIMIT > FLOW_DIR1
```

Then the procedure is repeated from the beginning to check if sinks exist for "FLOW_DIR1" GRID:

```
SINK1 = sink (FLOW_DIR1)
SINK_AREA1 = watershed (FLOW_DIR1, SINK1)
SINK_MIN1 = zonalmin (SINK_AREA1, FILLED1)
SINK_MAX1 = zonalfill (SINK_AREA1, FILLED1)
SINK_DEPTH1 = SINK_MIN1 - SINK_MAX1
fill FILLED1 FILLED2 sink < Z-LIMIT > FLOW_DIR2
```

etc.

For filling all sinks 'z-limit' in the last expression had the value 'z-limit + 1'.

Filling sinks in digital elevation maps is an example of input data GIS pre-processing prior to simulation. Many other specific examples of input data error identification with GIS could be relevant here. I.e., Manning coefficient values for AGNPS were corrected after overlay and checking for consistency with other GIS data, characterizing land cover.

7. GENERATING AND MODIFICATION OF INPUT DATA BY COMPUTATION PROCEDURES AND GRAPHICAL TOOLS OF GIS.

Special procedures in GRID ARC/INFO 6.1 are created for hydrological modeling. The software allows to interpret and to implement graphical and numerical analysis of digital elevation maps (DEM) and to derive from them spatially distributed parameters for further watershed runoff modeling.
In other words, GIS provide the tool to retrieve a variety of data (slopes, aspects, stream network and even several stream flow characteristics) from a single set of data (elevations) contained in DEM. In the course of the study, the optimal procedures could be developed, which will allow the most economical ways of input data processing for permanent storage in the parameter library. For temporal goals and routine data retrieve, standard procedures could be developed to convert and modify major basic data with regard to specific tasks.

Some of GIS ARC/INFO procedures, capable of modifying, transforming, and generating new data sets from initial sets of base input data, were used in the current study. The most essential for hydrological modeling are calculation of parameter values, generating stream network from the initial digital elevation map, and determination of soil property parameters based on relationships with other land cover characteristics.

7.1. ASPECTS and RECEIVING CELLS

Flow direction and flow accumulation routines were run on the depressionless DEM. These routines were used in conjuction with creating a theoretical stream network. This was used to look for errors. Once this was done slope was determined. Flowdirection gave us recieving cell numbers which AGNPS needs to track flow. Since the recieving cell was one of the eight surounding cells it was easy to write an AML to find all receiving cells based on the identity numbers from the identity coverage. The AML used is below:

```
&set cols := 42
DOCELL
     if (flowdir == 1) receive = id +1
          else if (flowdir == 2) receive = id +1 + %cols%
```

```
        else if (flowdir == 4) receive = id + %cols%
        else if (flowdir == 8) receive = id -1 + %cols%
        else if (flowdir == 16) receive = id -1
        else if (flowdir == 32) receive = id -1 - %cols%
        else if (flowdir == 64) receive = id - %cols%
        else if (flowdir == 128) receive = id +1 - %cols%
        else receive = 0
    end
    flowdir = flow direction grid
    receive = output receiving cell grid
    id = grid with unique id numbers
    cols = number of columns in id grid
```

A second docell aml was used to change flow direction numbers derived in GRID to those used in AGNPS. The relation of aspects and flow directions codes in AGNPS and ARC/INFO is show below.

AGNPS

8 ↖	1 ↑	↗ 2
7 ←	0	→ 3
6 ↙	5 ↓	↘ 4

ARC/INFO

32 ↖	64 ↑	↗ 128
16 ←	0	→ 1
8 ↙	4 ↓	↘ 2

The "aspect" command in grid assigns the aspect values in the related .vat table in degrees from 0 to 360. With the relationship between AGNPS and ARN/INFO aspects and flowdirections shown above, the actual ARC/INFO ASPECT command was not used.

The "aspect" command in grid could be also chosen to assign the aspect values. The supplementary calculations are implemented to modify the ARC/INFO grid, which contains floating point values in accordance with AGNPS requirements to input data. The reference table "aspect.dat", relating ARC/INFO aspect values in degrees to AGNPS units, is used at this step. The "aspect.dat" table, created by any text editor, is as follows:

ARC/INFO			AGNPS
-1	-1	:	0
0	22	:	1
22	67	:	2
67	112	:	3
112	137	:	4
137	202	:	5
202	247	:	6
247	292	:	7
292	337	:	8
337	360	:	1

The command to modify aspect values in the desired way is:

Grid: ASPECT30 = reclass (WATERSHED_ASP ASPECT.dat)

The similar procedure, as resampling mentioned above, is implemented to get aspects for 90 m size cells.

Grid: ASPECT90 = resample (ASPECT30, 90, cubic)

To combine the aspect values, contained in ASPECT90.vat table, with cell number, determined earlier, the function is used:

Grid: ASPECT-CELL = COMBINE (CELL, ASPECT90)

The .vat table of ASPECT-CELL grid contains both cell numbers and aspects values for a case study watershed.

To join CELL numbers and ASPECT values in a single attribute table, as well as all the other parameter values, derived from GRID, the function 'combine' is recommended in ARC/INFO, which works similar to 'or' function.

Combining Grid information became harder than it should have. The COR and CON commands combine grids in ARC/INFO. However, there were bugs in these commands as of release 6.1.1. Joinitem commands were used instead. This took more time but every grid database was combined.

ARC/INFO procedures, outlining basin boundaries and calculating subwatershed areas for assigned drainage outlets, were also used. The drainage area for each beaver impoundment in the case study watershed was derived from the original digital elevation database (figure 5).

7.2. CURVE NUMBERS

Other AGNPS parameters, which do not have special calculation ARC/INFO procedures, like aspects, are also determined based on existing GIS and quantitative relationships, assigned by experts. Detailed soil maps have never been made for the wilderness study site used, so land cover classes were coupled with information about soil series from nearby mapped sites to estimate soil texture, soil erodibility factor, and hydrologic group (to derive SCS curve numbers).

The example below describe the technique of expert estimates in the determination of Hydrological Curve Numbers.

Curve numbers (CN) show the relative value of impacts of the soil cover complexes on runoff. The following values are recommended for the forested watersheds by Chow (1964). CN are derived from tables in this handbook on the page 22-47 - 22-50 with regard to hydrological condition class (HCC) (table 3). HCC could have 5 types related to the humus content in the soil profile (inches).

Figure 5. **Subwatersheds, draining to beaver impoundments at Finlander Bay watershed, as outlined on GIS.**

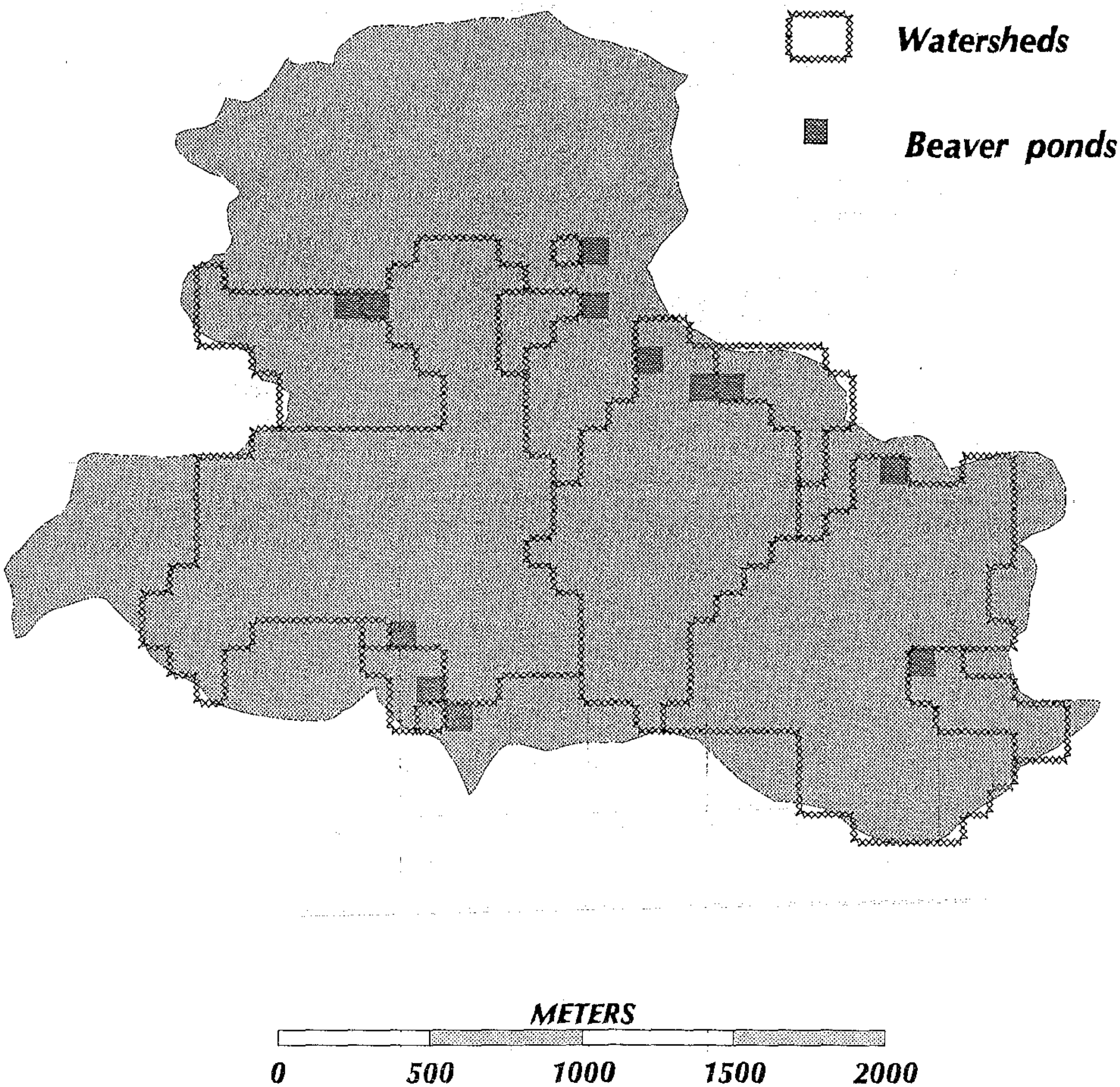
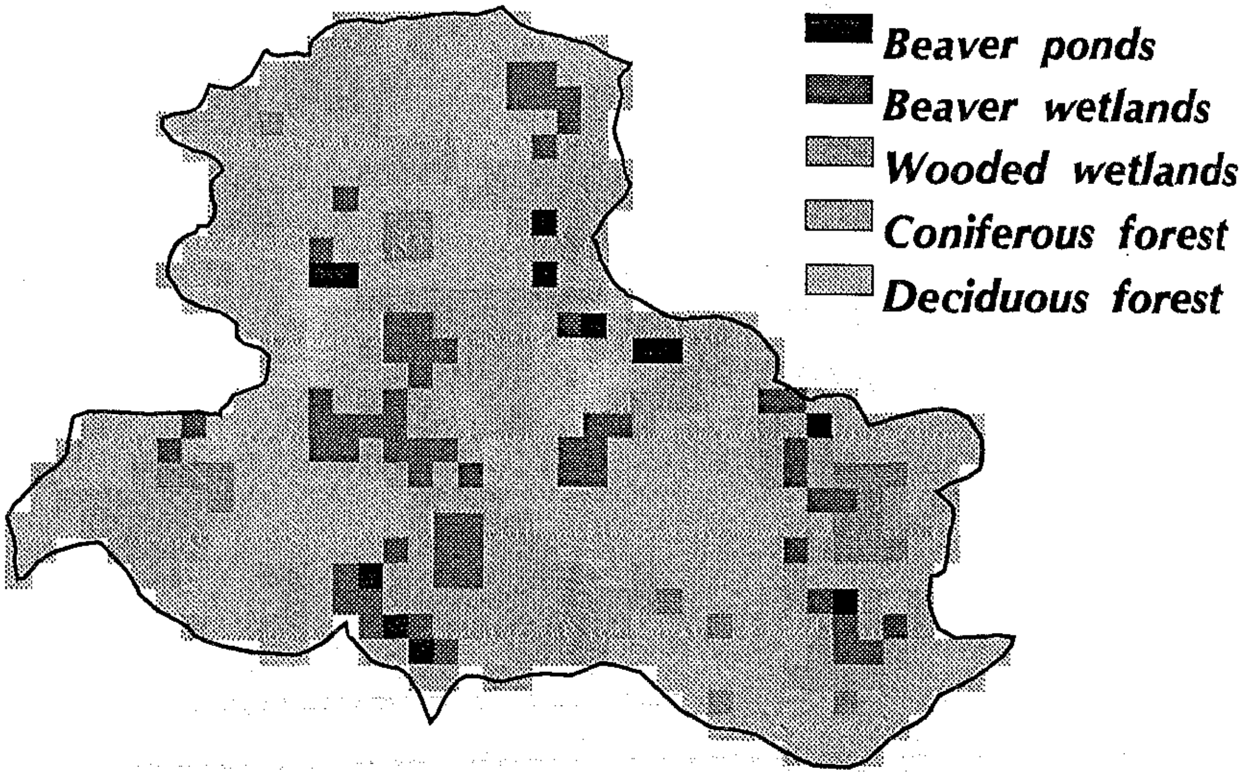


Figure 6. Land cover map of Finlander Bay watershed, as defined from contemporary and historical remote sensing data.

1. WITH PONDS



2. NO PONDS

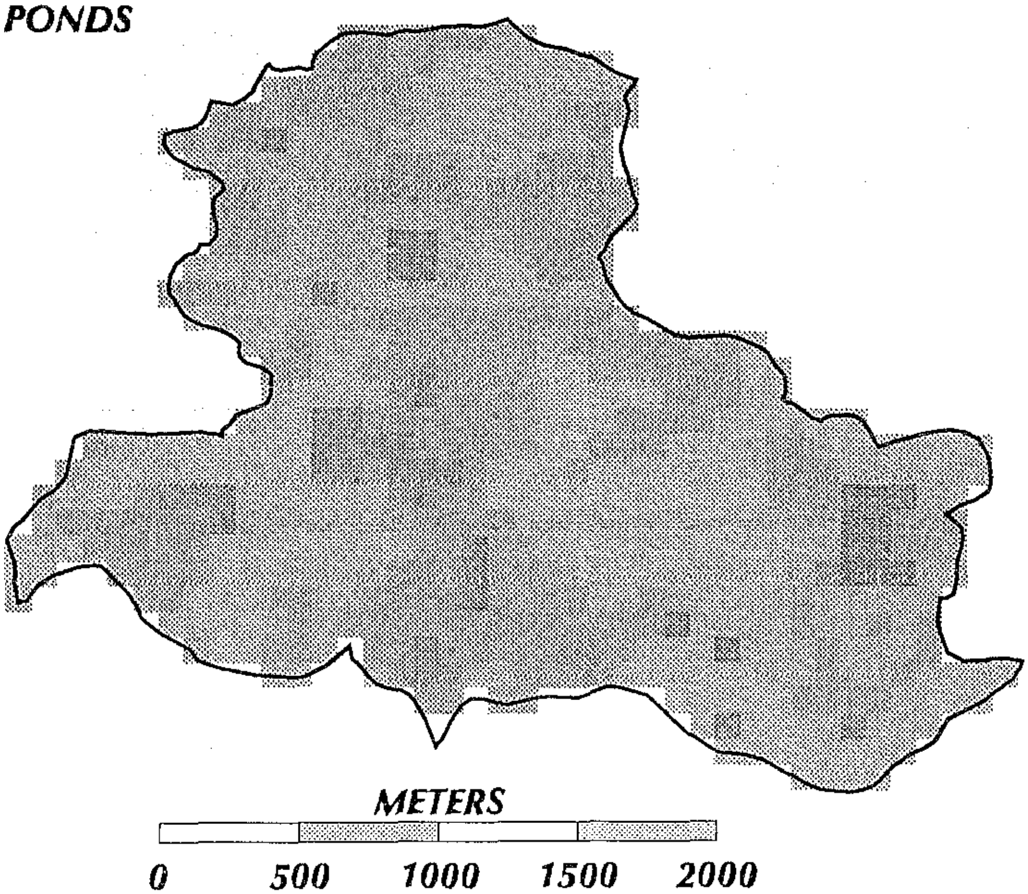


Table 3.

Recommended CN values for the USA forests (Chow, 1964)

HCC	Class	Humus, in	Soil groups A	B	C	D
I	Poorest	1.0 - 1.9	56	75	86	91
II	Poor	2.0 - 2.9	46	68	78	84
III	Medium	3.0 - 3.9	36	60	70	76
IV	Good	4.0 - 4.9	26	52	62	69
V	Best	5.0 - 5.9	15	44	54	61

A 1:24,000 land cover map (Allen et al. 1993) was digitized and gridded (figure 6). The land use coverages for scenarios with and without beaver impoundments were further analysed to derive Manning's roughness coefficient, surface condition constant, and chemical oxygen demand factor for each cell. Detailed soil maps have never been made for the wilderness study site used, so land cover classes were coupled with information about soil series from nearby mapped sites to estimate soil texture, soil erodibility factor, and hydrologic group (to derive SCS curve numbers) (Lewis, 1973; Anonymous, 1973). To determine CN value for each cell relevant CN values were assigned for forest land use types, depending on soil humus content and drainage conditions, as shown in the table 3 (figure 7). The change of drainage conditions, resulted in more wetland area with new beaver pond construction, was also taken into account, when generating CN values for land use patterns, corresponding to each particular scenario, considered for simulation. In the similar way, using expert reationships with land cover data, soil texture and soil nutrient availability values were determined (Minnesota Soil..., 1981; Soil Taxonomy, 1975; Watt, 1965) (figure 8).

Table 4.

The effect of channel slope value on the watershed erosion as calculated by AGNPS.

Finbay watershed, with ponds. Rainfall 2.00 inches, EI = 10.
Cell# 30

Channel Slope	Sediment above cell	Sediment within cell	Sediment yield, t	Deposition %
0.0	20.78	0.01	21.86	-5
0.1	20.78	0.01	24.66	-16
0.3	20.78	0.01	22.53	-8
0.5	20.78	0.01	21.86	-5
0.8	20.78	0.01	21.38	-3
1.2	20.78	0.01	21.07	-1

Channel slope was the only variable derived manually; it was measured from 1:24,000 U.S.G.S topographic maps using a template

Figure 7. Soil Conservation Service Hydrological Curve Numbers at Finlander Bay watershed.

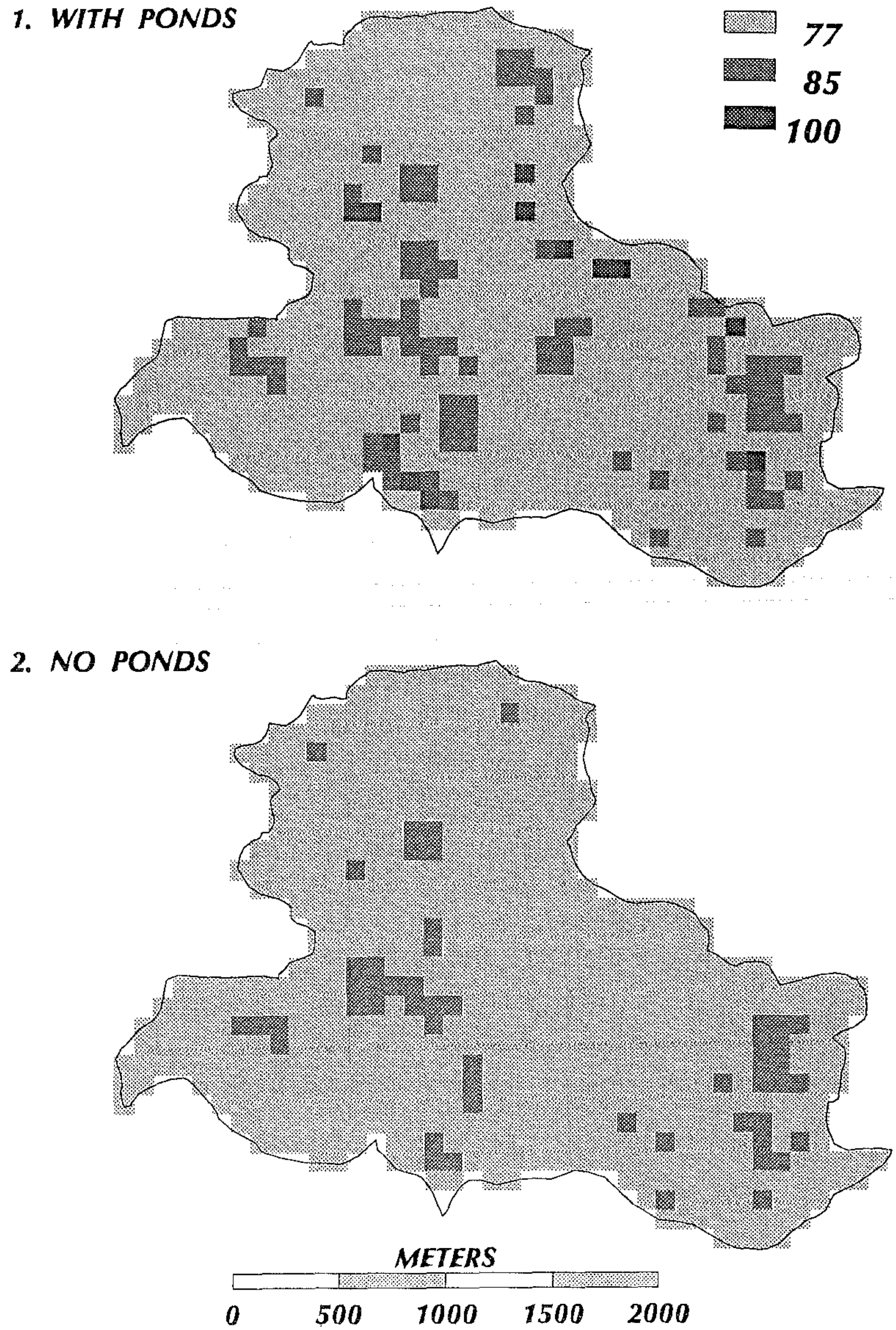
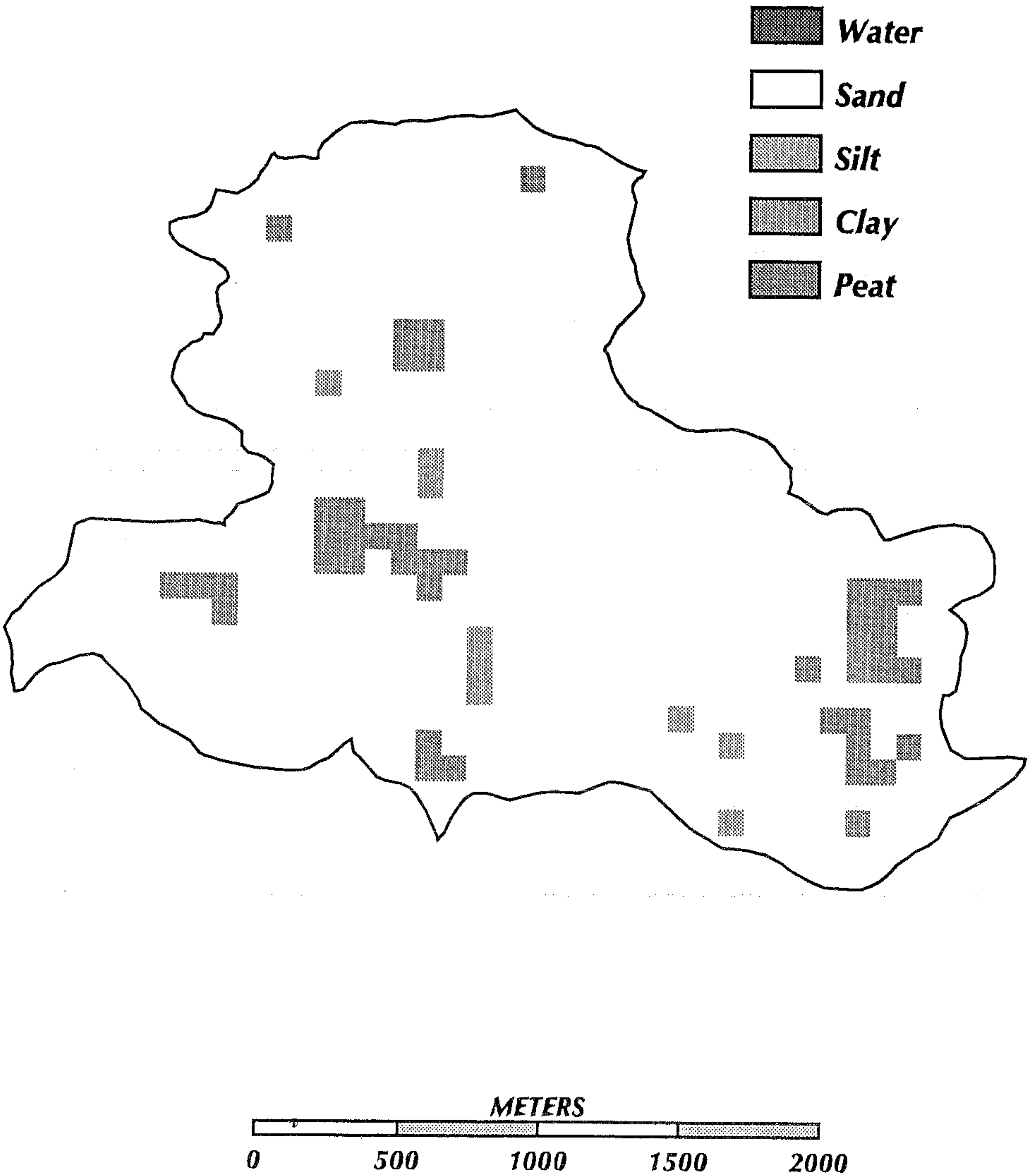


Figure 8. Soil textures at Finlander Bay watershed.



of the watershed grid generated with ARCPLOT. However, in further simulation it turned out, that channel parameters caused errors in total sediment yield estimates by AGNPS.

Slight changes of a channel slope value in a single cell produced a noticable effect on the total erosion yield of the whole watershed. All other parameters remained unchanged. The example is presented in the table 4.

To eliminate the undesired effects of channel parameters on the output results of sediment yield and total erosion all channel cells were assumed as having undefined channels. This has been done temporary untill the updating of AGNPS model will bring more accurate calculation for stream channel erosion processes.

All variables were exported from ARC/INFO into a spreadsheet program EXCEL, which was used to generate a data file in the appropriate format for AGNPS. In future studies internal GIS capabilities for input data management and processing could be explored to convert and transfer input parameters sets between various simulation models.

As a rule, different models have specific requirements to the presentation of input data. For example, AGNPS input data are provided on cell-by-cell base, when each square cell of equal size is described by a permanent set of input parameters. Other hydrological models, which use almost the same input parameter sets, are, however, tuned for parameter input by uniform subwatersheds or homogeneous physiographic units of unequal size. Without GIS there is no easy way to exchange input data between these models.

8. SCENARIO BASED ANALYSIS

The typical problem facing the environmental researcher, is how to obtain the reliable environmental forecasts by simulation modeling within the current uncertainties of many data. It is especially common when describing stohastic climate and hydrological processes, or unknown trends of human impacts on environmental systems. Scenario based approach is widely applied in these situations.

Once the input data for the base scenario are inserted into GIS, the unlimited possibilities for the new scenario based data generation and modification could be provided. The same GIS overlay techniques, as described above with the relation to input - output data analysis, are applied for the comparative studies of scenario based outputs. As the ultimate result of this type of studies, the system stability thresholds could be determined, the most vulnerable spots localized, and the best land use, or other natural resources management practices tested.

Scenario based approach was applied to the current study to generate a sequence of moisture conditions for runoff simuation.

In AGNPS precipitation are presented as single events for a 24-hour, 25 year storm frequency. This synthetic value is used since both the annual and the maximum storm values vary at a particular location from year to year. They tend to follow log-normal frequency distribution that are usually well difined by continuous records of from 20 to 25 years (Wishmeier and Smith, 1978).

The reason to do so is because erosion index could not be estimated solely from annual precipitation data. It is the function of intensities of individual rainstorms, and these are not closely related to annual precipitation. Therefore a given annual rainfall indicate only a broad range of possible values of the local erosion index.

The 24-hour storm duration is appropriate for determining both peak discharges and runoff volumes. The intensity of rainfall varies during storms and over geographic regions. SCS developed four synthetic rainfall distributions (I, IA, II and III) . Type IA is the least intense and type II is the most intense short duration rainfall. Type II is representative for Minnesota.

The other input parameter, used in scenario generation, is energy intensity value (EI). This parameter corresponds to rainfall erosion index, used in the universal soil loss equation. The dimension units are foot-tons per acre-inch. The energy intensity values appear along with the rainfall frequency curves in Appendix to AGNPS. The value of EI for a given rainstorm equals the product, total sum energy (E), hundreds of foot-tons per hour, times the maximum 30-min intensity (I30), inches per hour.

Table 5

Rainfall event scenarios, used for AGNPS simulation.

Frequency, year	24-hour Rainfall	EI
1	2.0	10
2	2.3	13
5	3.0	24
10	3.5	34
25	4.0	46
50	4.5	59
100	5.0	71

The above table presents 24-hour rainfall and EI data which were assigned for 7 simulation scenarios for the Finbay watershed area (table 5).

The comparison of impacts on runoff and its quality was implemented by AGNPS simulation for 7 indicated above rainfall scenarios, and for two scenarios of watershed land uses, related to beaver ecosystem dynamics. The laters were considered as having and not having beaver ponds within the case study watershed (figure 6).

1. WITH PONDS.
   Current land use pattern was derived from GIS, as digitized based on data of 1988 air photo images. Beaver ponds present on the watershed and parameter sets, corresponding to water and wetland cells are used in AGNPS model for these sites.

2. NO PONDS.
   Past land uses pattern is assumed for runoff simulation, as indicated by 1940 air photo images. Beaver ponds are absent in the landscape and all the water cells on the place of beaver ponds, which present in the land use scenario 1, are converted to land or wetland cells. The corresponding to each land use parameter values are assigned for AGNPS simulation.

GIS and AGNPS input - output data interchanges provided the opportunities for visualization and graphic presentation of numerous results.

9. SPATIAL ANALYSIS OF RESULTS

While performing the simulation model runs, the researcher needs tools to make sure, that the output results have desired quality and are consistent with the tested changes of input. GIS provides this tool. Spatial overlays of input - output data provide convenient ways for:

checking the spatial consistence of output results with the input parameter changes (very often just the territorial visualization of output results by means of GIS assist to easy simulation model errors and bugs identifications);

local identification of spots and zones with specific process features and determination of key factors, or their combinations, contributing to the certain behavior of investigated environmental systems;

sensitivity studies and finding numerical spatial relationships between input - output data;

graphical representation of input - output relations, simulated by models.

GIS supported analysis of AGNPS simulation output results was performed in the current study at the Finlander Bay watershed. The output results show the variety of impacts of beaver ponds on watershed hydrology and water quality, as it is illustrated by figures 9 - 20 and Table 6 and 7. In general, the observed trends were in producing more runoff and less pollution due to beaver ponds. However, the degree of beaver pond impacts varied for various output parameters.

Table 6

The output results of runoff and water quality simulation on Finlander Bay watershed.

Rain, inch	Runoff, inch	N in sediment, lb/acre	N, dissolved, lb/acre	N concentration, ppm	P in sediment, lb/acre	P, dissolved, lb/acre	P concentration, ppm	COD ppm	Sediment yield, t/acre
				WITH PONDS					
2.0	0.53	0.04	0.11	0.92	0.02	0.01	0.05	49.44	6.56
2.3	0.71	0.04	0.15	0.91	0.02	0.01	0.05	50.98	7.83
3.0	1.17	0.06	0.23	0.89	0.03	0.01	0.05	53.10	10.69
3.5	1.53	0.07	0.30	0.88	0.03	0.02	0.05	53.99	12.65
4.0	1.91	0.07	0.38	0.87	0.04	0.02	0.05	54.63	14.54
4.5	2.31	0.08	0.45	0.86	0.04	0.03	0.05	55.11	16.37
5.0	2.72	0.09	0.53	0.86	0.04	0.03	0.05	55.48	18.17
				NO PONDS					
2.0	0.48	0.04	0.10	0.96	0.02	0.01	0.06	59.44	7.05
2.3	0.65	0.05	0.14	0.93	0.02	0.01	0.06	59.77	8.50
3.0	1.11	0.06	0.23	0.90	0.03	0.01	0.06	60.24	11.75
3.5	1.48	0.07	0.29	0.88	0.04	0.02	0.06	60.45	13.97
4.0	1.87	0.08	0.37	0.87	0.04	0.02	0.06	60.60	16.11
4.5	2.27	0.09	0.44	0.86	0.04	0.03	0.06	60.72	18.33
5.0	2.69	0.10	0.52	0.85	0.05	0.03	0.05	60.81	20.61

Table 7

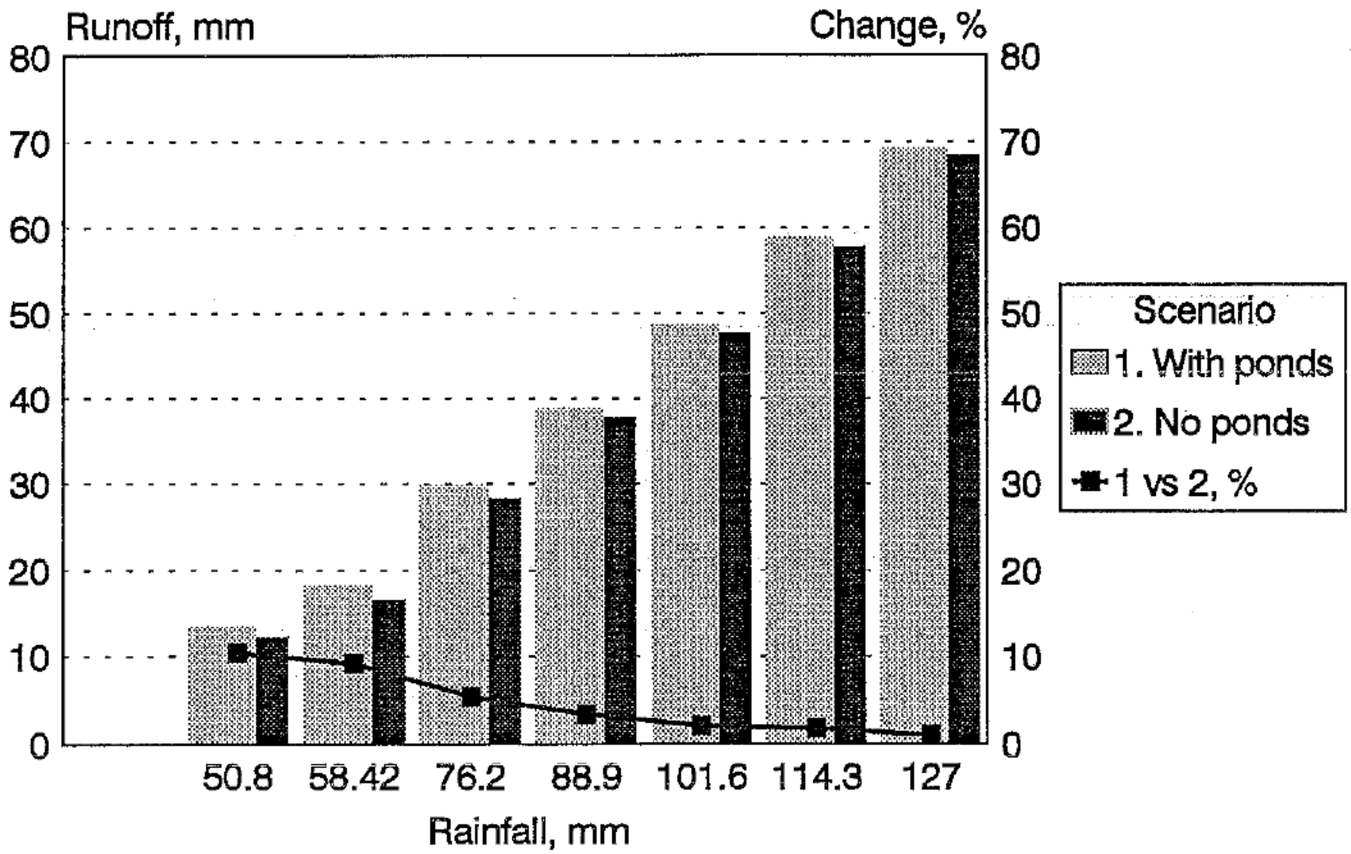
Impacts of beaver ponds on runoff and its quality. "With pond" as compared to "no ponds" scenarios. Finlander Bay watershed, %.

Rain, inches	Runoff	N in sediment	N, dissolved	N concentration	P in sediment	P, dissolved	P concentration	COD	Sediment yield
2.0	10.4	0	10.0	-4.2	0	0	-16.7	-16.3	-7.0
2.3	9.2	-20.0	7.1	-2.2	0	0	-16.7	-14.7	-7.9
3.0	5.4	0	0	-2.1	0	0	-16.7	-11.9	-9.0
3.5	3.4	0	3.4	0	-25	0	-16.7	-10.7	-9.5
4.0	2.1	-12.5	2.7	0	0	0	-16.7	- 9.9	-9.8
4.5	1.8	-11.2	2.3	0	0	0	-16.7	- 9.3	-10.7
5.0	1.1	-10.0	1.9	1.1	-20	0	0	- 8.8	-11.8

Figures 9-13 present rainfall scenario output results as simulated by AGNPS. Figures 14-20 show spatial allocation of these outputs at the case study watershed for scenarios with and without beaver ponds.

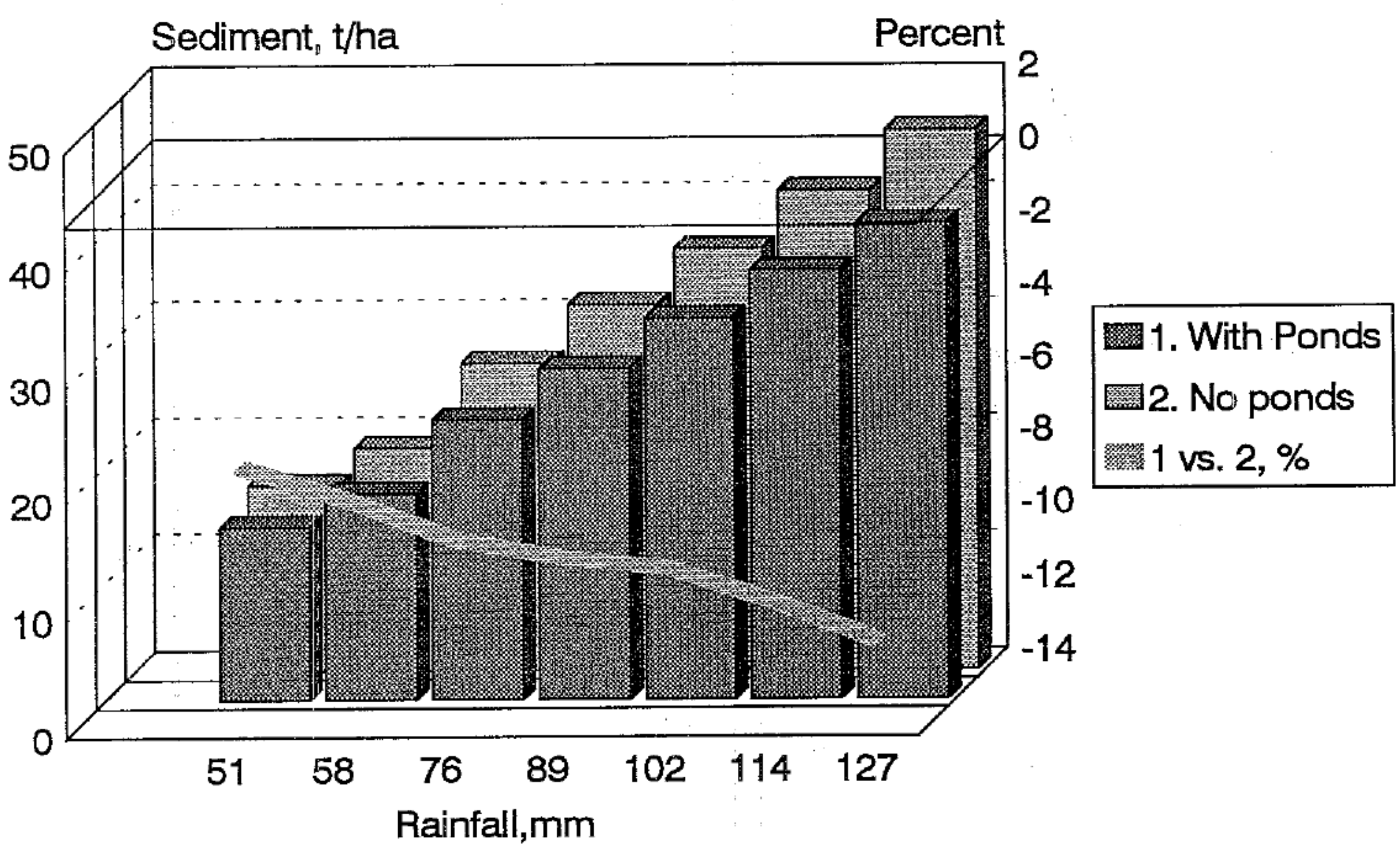
The total watershed runoff produced per single event was increased almost linearly - from 0.5 to 2.7 inch as caused by the increase of rainfall from 2 to 5 inch, respectively (Table 6). The "with ponds" scenario resulted in slightly increased water flow at the mouth of the watershed. This is because, assuming that the pond is full, 100% of the rain that falls onto it will flow off of it. This

Figure 9. Runoff alterations under changing rainfall



AGNPS simulation results

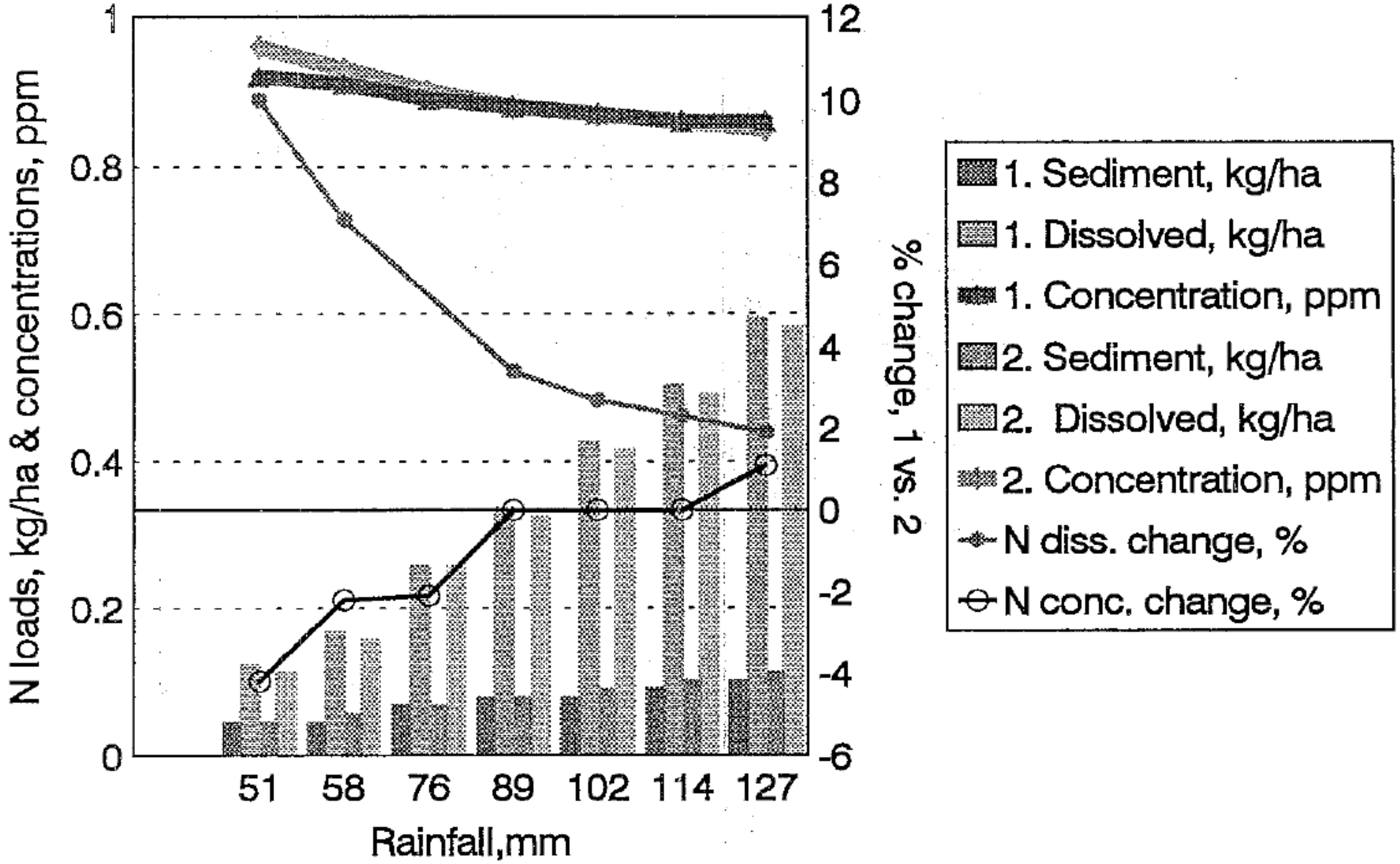
Figure 10. Sediment load alterations under changing rainfall



AGNPS simulation results

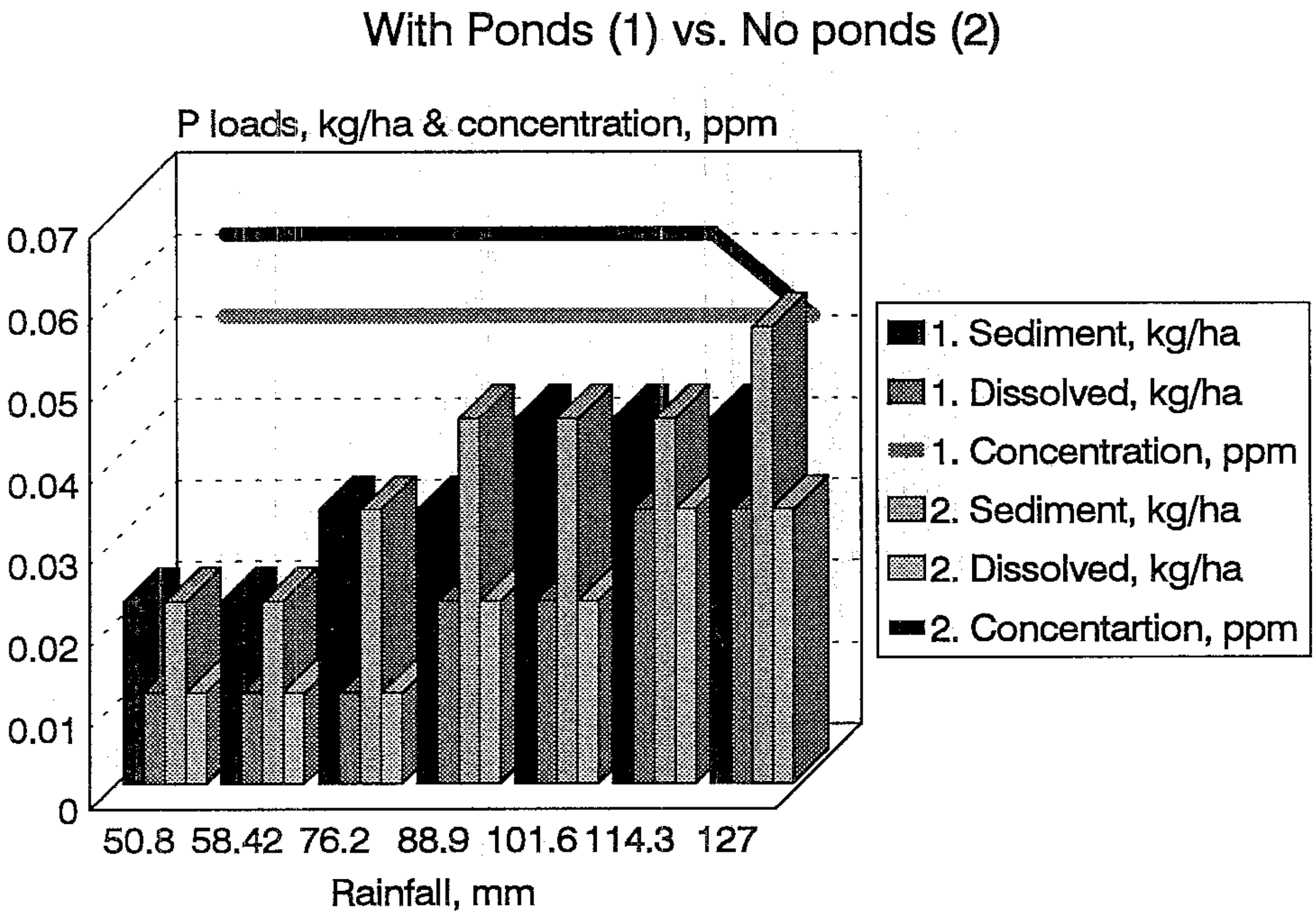
Figure 11. N load alterations under changing rainfall

With Ponds (1) vs. No ponds (2)



AGNPS simulation results

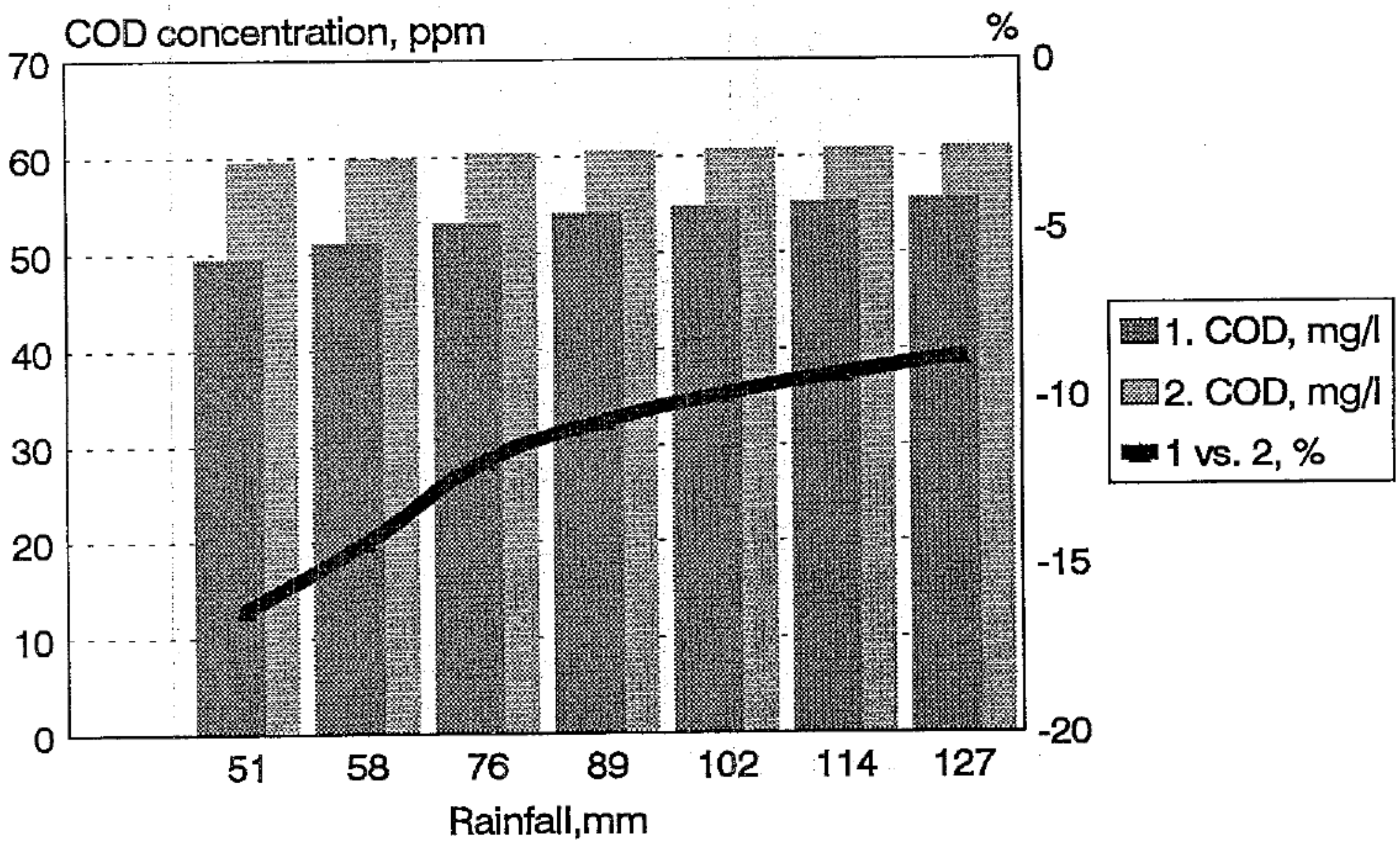
Figure 12. P alterations under changing rainfall



AGNPS simulation results

Figure 13. COD alterations under changing rainfall

With Ponds (1) vs. No ponds (2)



AGNPS simulation results

Figure 14. Spatial distribution of runoff generated within cells at Finlander Bay watershed.

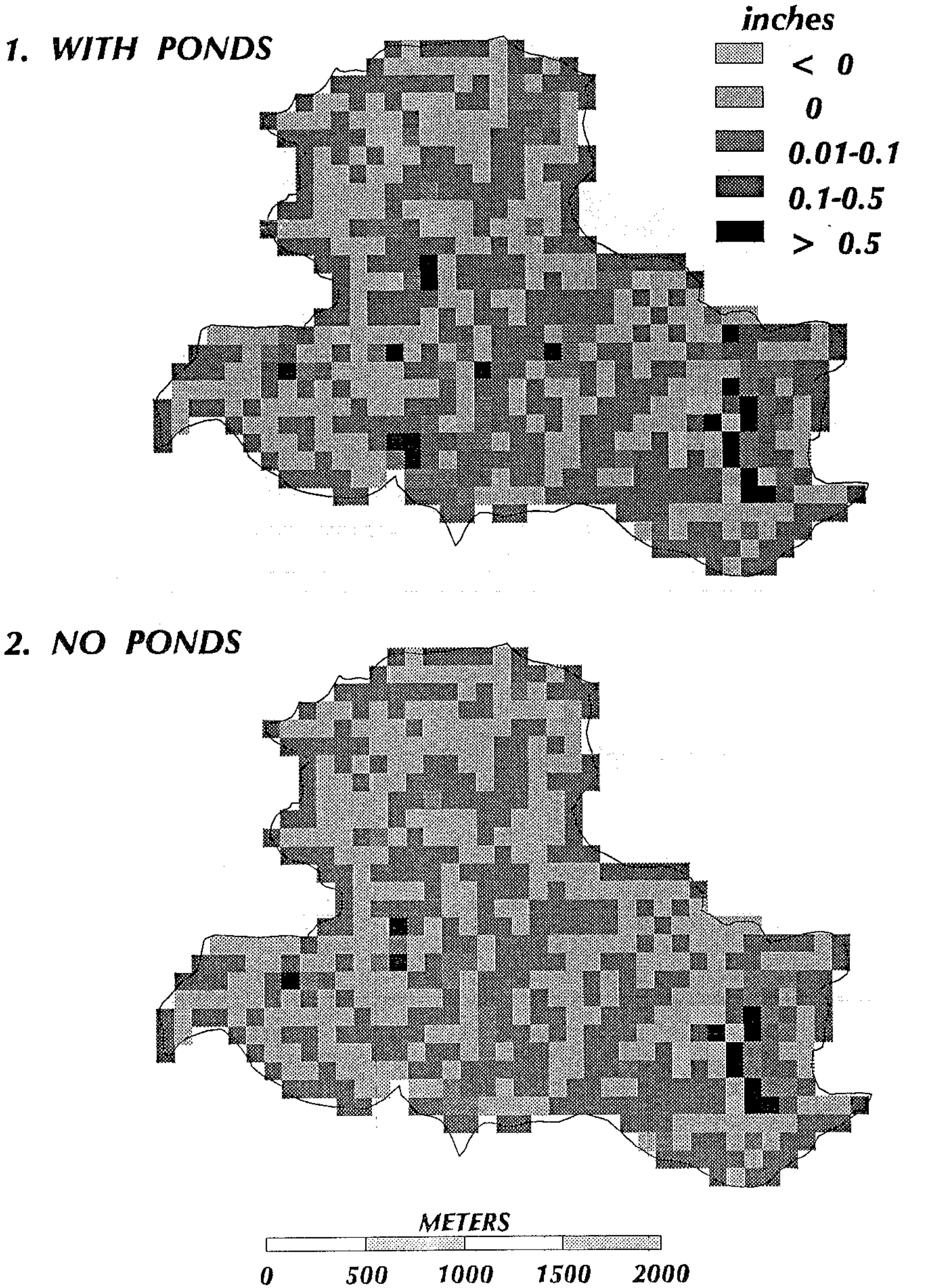


Figure 15. Accumulated runoff within cells at Finlander Bay watershed.

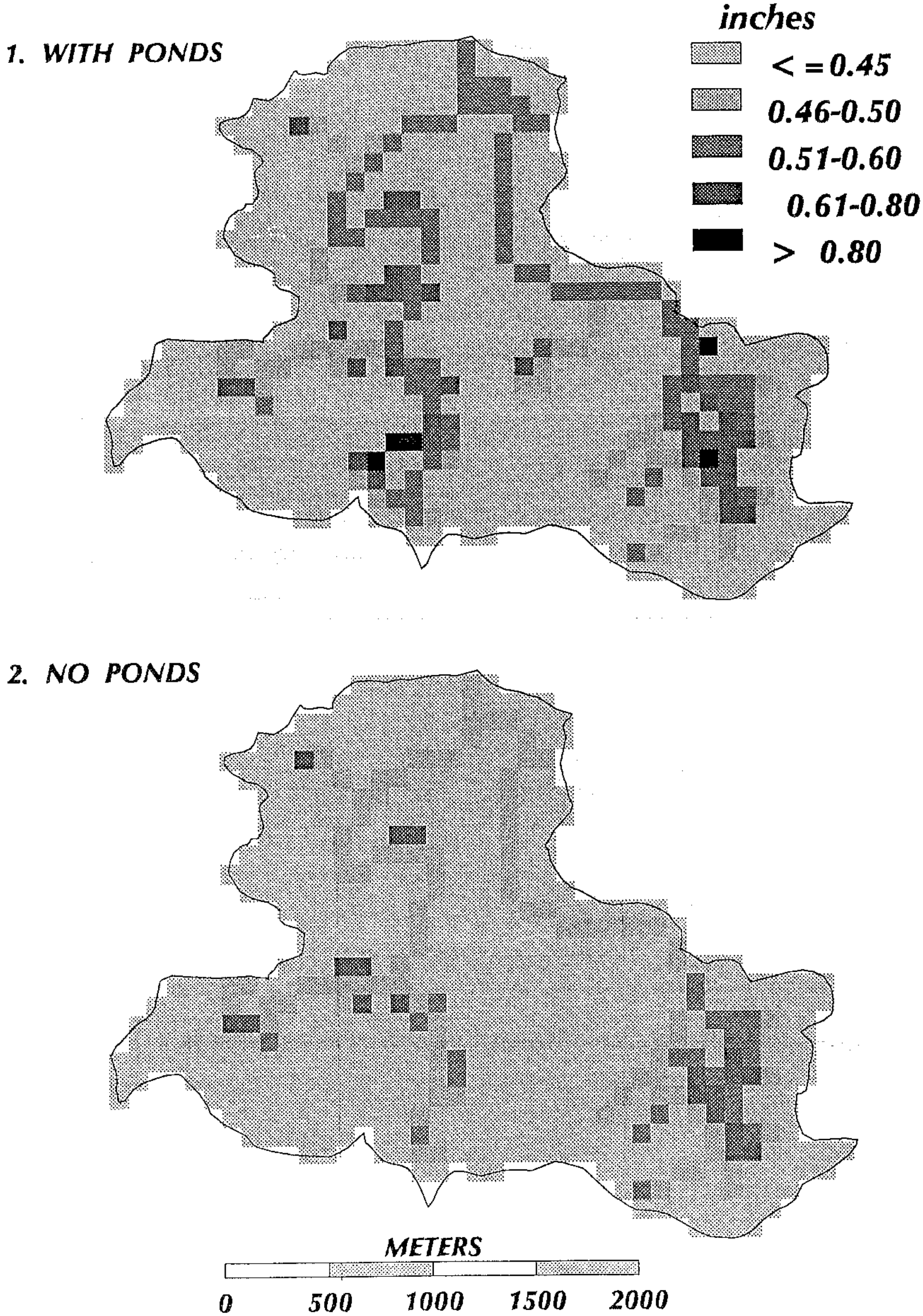


Figure 16. **Sediment yield within cells at Finlander Bay watershed.**

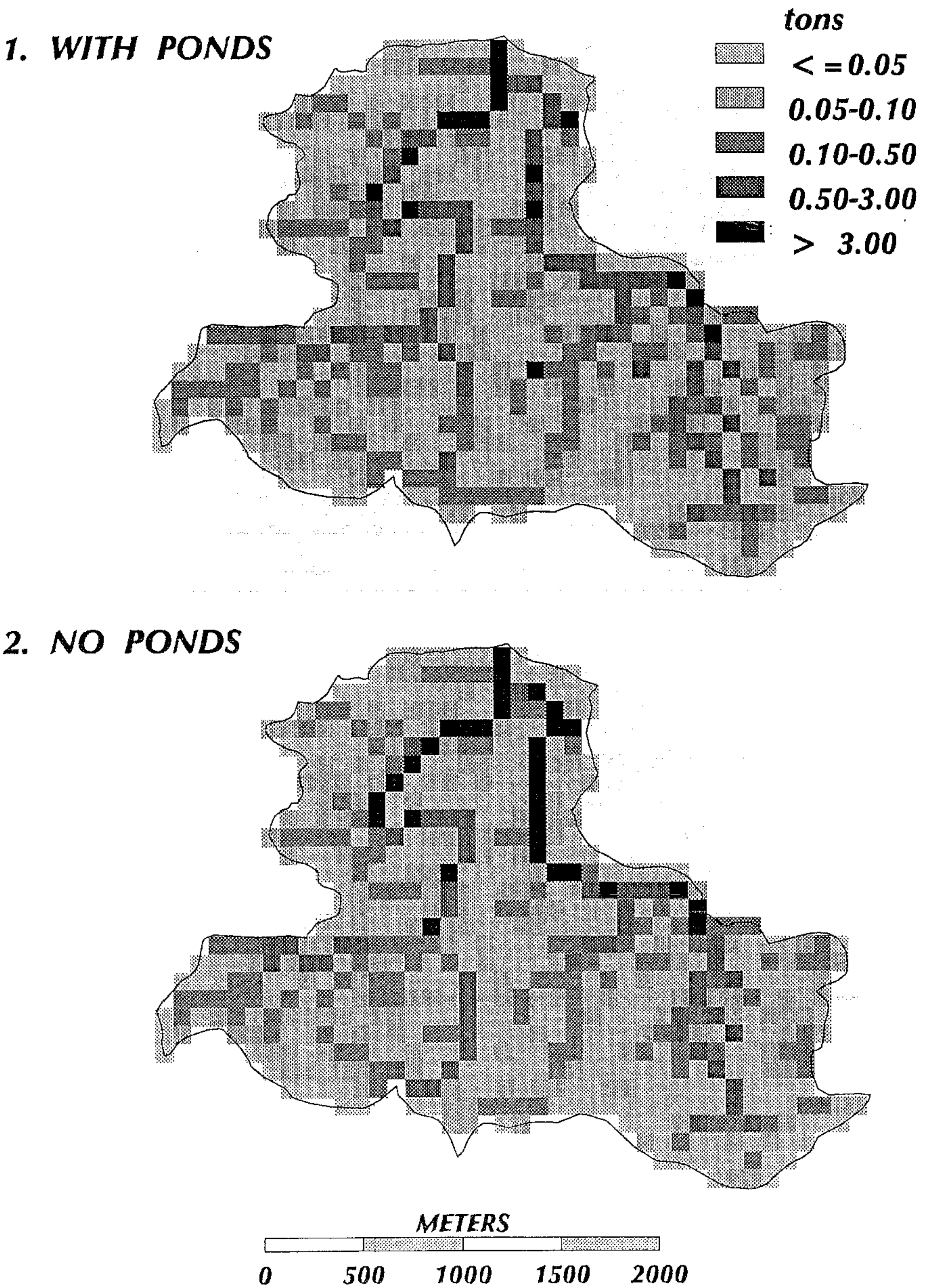


Figure 17. **Deposition of sediment as % ratio to sediment yield generated within cells at Finlander Bay watershed.**

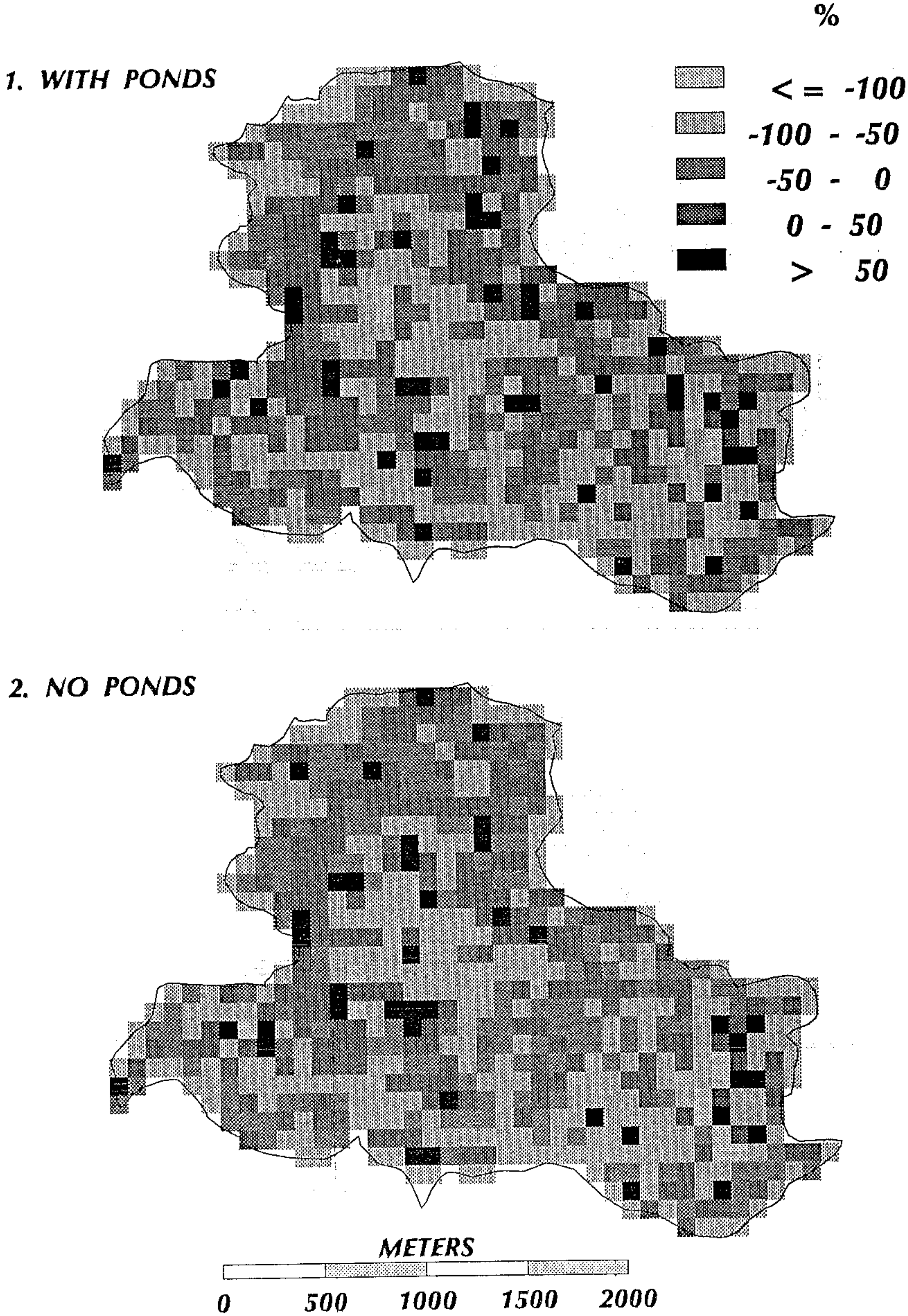


Figure 18. Total soluble nitrogen generated within cells at Finlander Bay watershed.

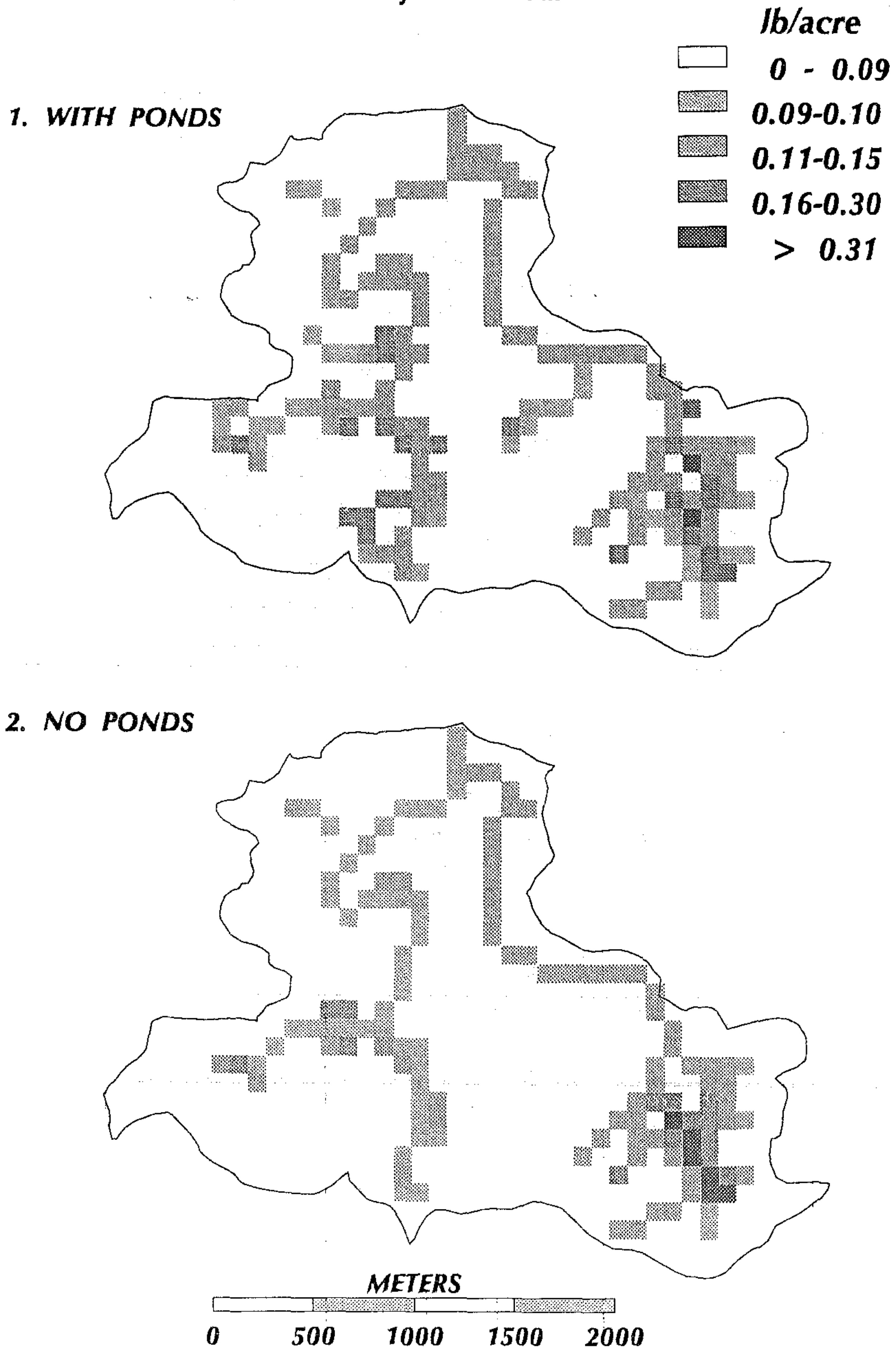


Figure 19. Concentration of soluble nitrogen within cells at Finlander Bay watershed.

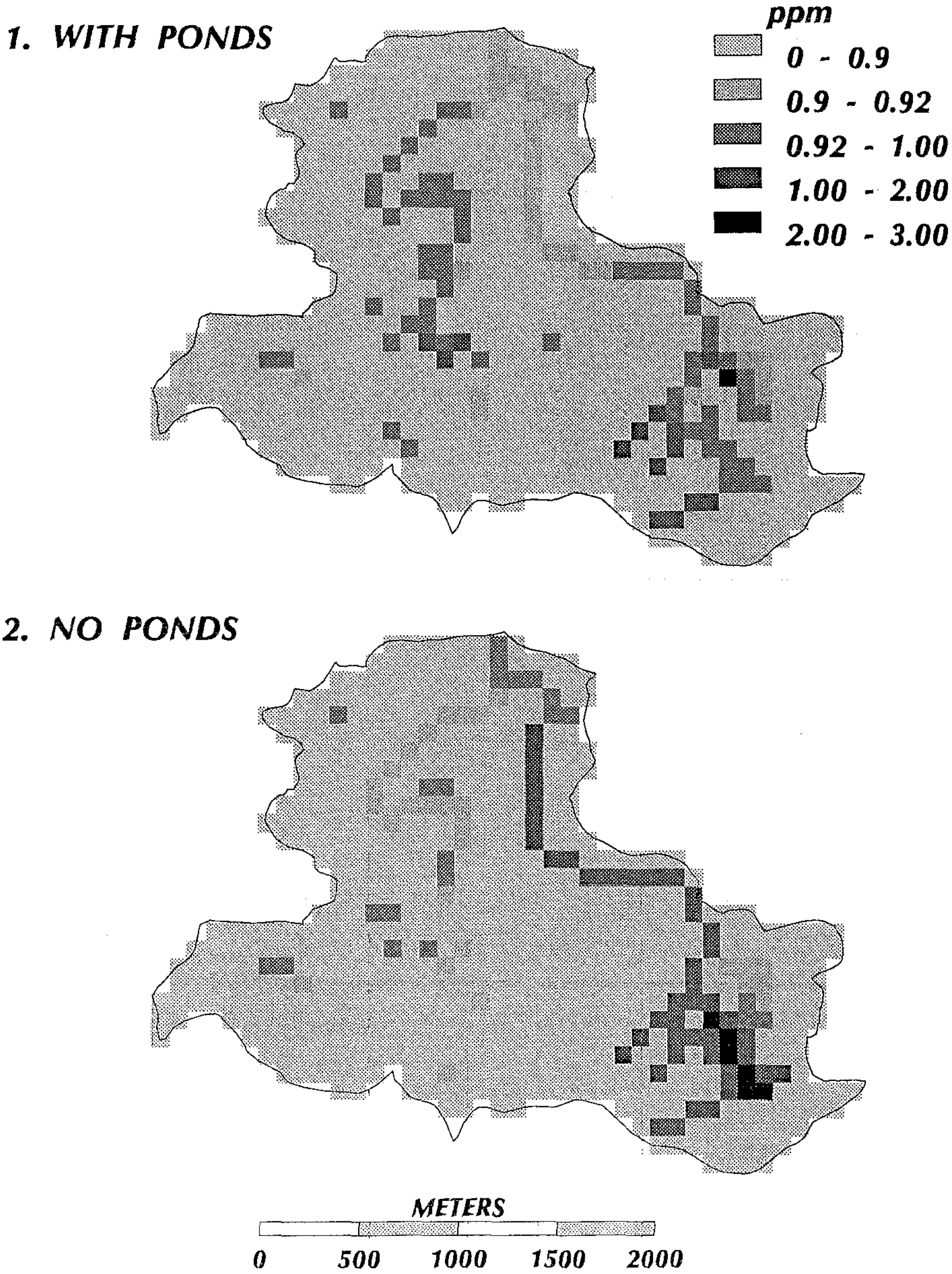
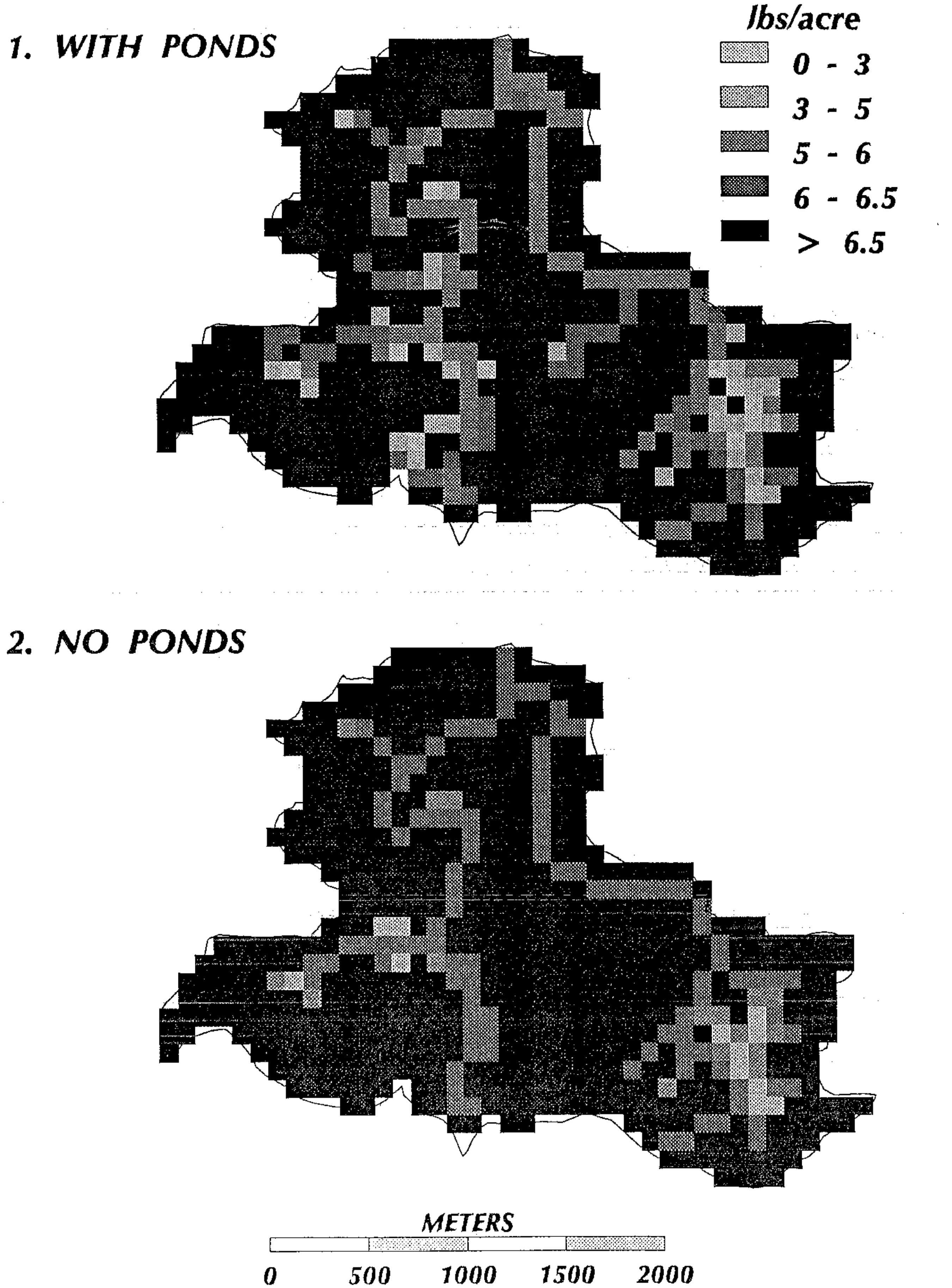


Figure 20. COD distribution within cells at Finlander Bay watershed.



caused a 10% increase in runoff at the lowest rainfall intensity, but only a 1% difference during the 100 yr storm. The runoff contribution of individual cells changed relatively little between the two scenarios, but there were easily discernable differences in accumulated runoff per cell with distance downstream.

Sediment deposition in the beaver ponds also had an effect that accumulated downstream, so that the "with ponds" scenario yielded 7 to 12% less sediment than the "no ponds" scenario, an effect that increased with storm intensity. The model predicted a 4% decrease in watershed nitrogen output with ponds for a 1 yr storm, but there was no effect for storms with a 10 to 50 yr frequency, and a net increase for a 100 yr storm. This implies that while beaver ponds may retain N during low-intensity storms, there may be a flushing of that retained N during high-intensity storms. This pattern is visible on GIS maps for "with ponds" scenario with low intensity storm: higher nitrogen concentrations were observed at the locations, where no ponds were situated, and nitrogen content in runoff had remarkable alterations in cells adjacent to ponds. Chemical oxygen demand (COD) showed the largest effect of any of the parameters predicted: the presence of beaver ponds was associated with a 10 to 17% reduction of COD, depending on the storm intensity. This is because a forest has a lot more primary productivity than a pond, and therefore contributes more organic matter (and therefore COD) to the system.

10. CONCLUSION

This model-based approach provided insight into the landscape scale influence of beaver ponds that could not have been derived using conventional field techniques. The modeling was done at a spatial level of detail that would have been impractical using manual data entry to AGNPS. Automating the derivation and interchange of variables with a GIS made this research possible. The advantages of integrating ARC/INFO and AGNPS for this modeling study were:

- automated derivation of input variables from standard databases (e.g., DEMs)
- ability to explore existing and hypothetical scenarios over large areas
- ARC/INFO analysis and display capabilities greatly supplemented those in AGNPS
- GIS analysis and display of preliminary results aided error checking and verification of input variable and model assumptions
- ability to relate output findings to other databases

However, integrating ARC/INFO with AGNPS was more difficult than expected, due to:

different platforms (ARC/INFO GRID on workstations only, AGNPS on PCs only)

data exported from INFO were comma delimited, whereas the AGNPS format combined certained columns of data, requiring data parsing in Excel

format requirements for AGNPS input data were poorly documented

AGNPS couldn't generate output in GIS-compatible format; output files had to be reformated with Excel

bugs in GRID and AGNPS required fixes or work-arounds

Numerous other applications of GIS to the input - output data analysis in environmental simulation exist. They stay beyond the scope of the current case study and could be explored during further stages of research. The standard GIS procedures, like overlay, buffering, network and grid analysis, provide a wide variety of tools for many specific tasks, emerging in the input data acquisition, input - output data manipulations, simulation analysis and decision making process. Any opportunity for these GIS techniques could be further explored with regard to the specific problems of decision making, regional ecosystem properties and availability of data and resources in particular studies.

The graphical presentation by means of GIS of scenario based output results of AGNPS simulation modeling, provides both the particular answers for the ecosystem behavior studies at this watershed, and the general methodological outlines for the further investigations, aimed at linking GIS with environmental models.

GIS presents a perfect analytical tool for processing and modification of basic input data, stored in the parameter library, with regard to the specific individual requirements of simulation models. After implementation of GIS supported interchanges of input data, the comparative studies of performance of various models, stored in the model library, could be conducted with the same data inputs. The higher reliability of simulation output results, obtained from independent simulation studies, contribute to the more efficient decision making process, which is significantly enhanced due to the possibility to apply and compare various model results. The comparative studies of performance of different simulation models is essential for the better understanding and description of the complicated natural processes which is quite a common case in environmental studies.

The outlined methodology and case study results could be considered as the intermediate framework for next studies, when the approach will be refined and further developed.

11. LITERATURE.

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