An Integrated Approach for Estimating the Impact of River Hydropower Generation on Groundwater Dynamics: A Case Study from the Saale River in Thuringia, Germany.

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Abstract In the Saale River, near the town of Jena in the state of Thuringia, Germany, a power generation plant is planned which is expected to feed into the communal electricity supply of the town of Jena. To evaluate the impact of the backstorage of river water to the groundwater dynamic in the valley floor an integrated approach was applied. The methodology consists of the following components: (i) deriving a digital elevation model (DEM) of the valley floor using photogrammetric aerial photography interpretation by means of a ZEISS Planicomp P33; (ii) applying the MODFLOW physically-based groundwater flow model to describe the present groundwater dynamic; (iii) predicting the groundwater dynamic after construction of the power plant and river storage of about 2 m height; (iv) prognosticating the regeneration of wetlands on the valley floor by combining the DEM and average groundwater levels calculated by MODFLOW. First results of the study are very much encouraging: (i) a high resolution DEM of the valley floor was derived from the aerial photography; (ii) groundwater time series have been analysed and used for a steady-state model. Based on these results a dynamic groundwater flow and groundwater recharge model will be established. It will be used to predict and to analyse the changing groundwater dynamic after the construction of the power station on the Saale River and the local distribution of regenerated wetlands on the valley floor.

1. INTRODUCTION

Generation of hydropower from rivers is quite common [Cassidy 1995, Burt & Watts 1996] but was restricted to larger river systems. However, due to the technical progress in designing such power stations even smaller rivers are becoming economically attractive and especially relevant for smaller communities in the countryside. Despite of the environmentally clean nature of hydropower there are, some restrictions to the use of rivers for power generation such as: (i) the backstorage of river water to generate the necessary head of about 2 to 3 m changes the hydrological flow regime [Ubell 1987, Giebel & Hommes 1994]; (ii) groundwater in the flat valley floor will rise if a hydraulic link with the river water level exists [Vekerdy & Meijerink 1998] and (iii) as a result of (ii) wetlands are expected to regenerate on the valley floor which will hamper agriculture and endanger the foundations of buildings on the flood plain.

Environmental impact assessment studies as part of a legal prefeasibility study, at present, are using available groundwater observations to predict the changing groundwater dynamic. However, such predictions are depending on the quality of available groundwater time series which frequently are lacking. They do not account for (i) the dynamic interaction between groundwater and river flow [Swain 1994] and (ii) the microscale topography of the valley floor. Both is of importance if the regeneration of wetlands has to be prognosticated.

Using adequate methods of aerial photography, GIS techniques and groundwater modelling components [Fuchs et al. 1995, Michl 1996] the analysis and impacts of such power stations can be examined with a high accuracy and in a limited amount of time. For the modelling exercise MODFLOW [McDonald & Harbaugh 1988], a three dimensional, modularly structured open system groundwater flow model was applied.

2. OBJECTIVES

The objectives of this paper combine the practical aspects of environmental impact assessment studies with the integrated technologies of aerial photography, GI systems and groundwater modelling tools. In this contexts the following approach was selected: (i) design of an integrated system using the ZEISS Planicomp P33, the GI system

ArcInfo/Arcview and the MODFLOW groundwater model; (ii) the derivation of a highly accurate digital elevation model with a 5 m horizontal resolution using the ZEISS Planicomp P33; (iii) constructing a detailed conceptual groundwater flow model using borehole data of 178 points in VISUAL MODFLOW and (iv) calculating a steady-state model using MODFLOW as general basis to predict and to analyse the changing groundwater dynamic after the construction of the power station and the local distribution of regenerated wetlands on the valley floor.

3. STUDY AREA

The study area is part of the Saale valley, Thuringia, Germany. Its location is shown in Figure 1. It is situated in the flood plain in the northern part of the city of Jena (inhabitants approximately 100,000) and covers an area of 2.56 km². Along the river stretch the study area is about 4.7 km long and up to one kilometer wide. The highest parts of the flood plain are found in the southwest with an altitude of 144 m AMSL whereas the lowest elevation was measured in the northeast with an altitude of 137 m AMSL.

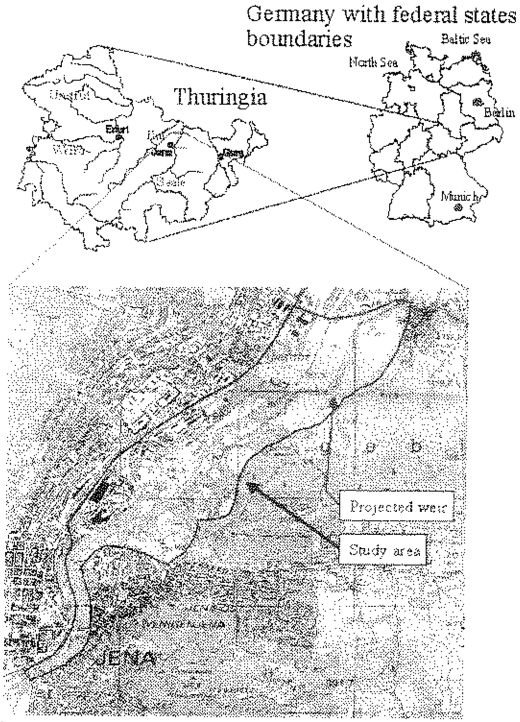

Figure 1: Location of the study area within Germany and the state of Thuringia.

The projected weir (see Figure 1) will have a capacity of 450 KW and a height of 2 m. It will be constructed along a river stretch where already a former weir existed that was torn off in 1978.

The climate is very much affected by the position of the valley. The average annual rainfall adds up to 590 mm and the wind speed reduces rapidly in comparison to the adjacent highlands. The annual mean temperature is 9.4 degree centigrade.

Concerning the hydrological flow regime of the Saale River within the study area the following characteristics can be given:

- Stream lenght is about 5,2 km,
- Slope averages to 0,1 %,
- Mean annual flow of 31 m³/s,
- Mean flood flow is with 133 m³/s,
- Mean low flow is 10.9 m³/s.

4. ANALYSIS OF THE AERIAL PHOTOGRAPHY AND DERIVATION OF THE DIGITAL ELEVATION MODEL

To account for the environmental impacts of the weir construction in terms of the regeneration of wetlands a highly accurate digital elevation model is essential to evaluate changes in the groundwater regime. For this study a threshold value of 10 cm

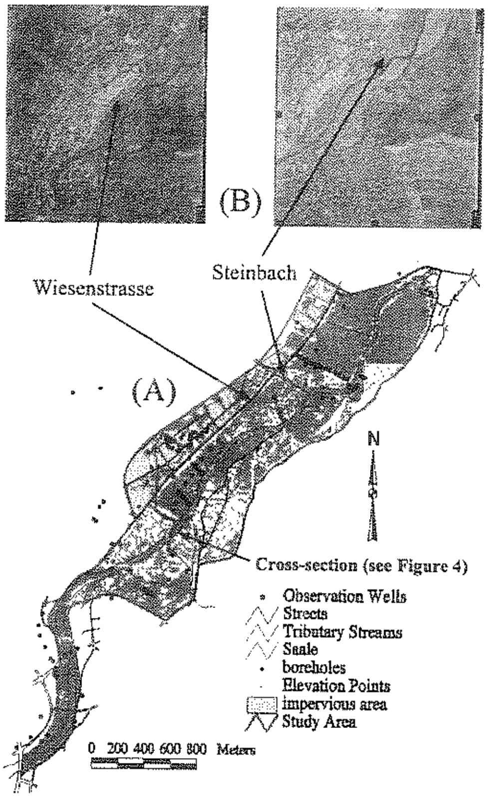

Figure 2: (A) Point density of the measured 8181 elevation points, the boreholes and the observation wells. (B) One of the stereoscopically analysed pairs of the aerial photographs is shown.

in the vertical direction was defined. This accuracy could not be achieved by any existing DEM. Using ZEISS technology to derive elevation information from aerial photography and GIS algorithms this vertical and horizontal accuracy could be matched. Furthermore, this methodology is much more efficient than ground measurements for the desired scale.

The used elevation points are shown in figure 2. Their distribution account for the relief energy (high point density) and the coverage of the valley floor by trees and buildings (lower point density). All together, three pairs of aerial photographs (date of acquisition: 04/23/1995, scale: 1:12,500) were stereoscopically analysed with the Planicomp P33. They were oriented using the software PCAP. Additionally, 16 control points per pair were measured in the field using standard surveying equipment to obtain a high resolution along the x-,y- and z-axis (see table 1).

Table 1: Horizontal and vertical accuracy calculated between field control points and the equivalent points in the oriented stereoscopic photographs.

	accuracy along x- and y- axis	accuracy along z- axis
pair 1	14.2 cm	6.8 cm
pair 2	8.5 cm	5.2 cm
pair 3	7.6 cm	10.4 cm

The digitalization of the elevation points was done using the software AutoCad 12. Every 15 m one elevation point was set if the ground was not covered. Zones with a varying relief like slopes, river banks and abandoned river courses were measured with a higher horizontal resolution. In total 8181 elevation points were used for the DEM generation. Furthermore the impervious areas, like streets and buildings, and relevant geomorphologic features like the river stretch of the Saale and other tributaries were digitized.

The measured elevation points were integrated into the GIS ArcInfo/ArcView and interpolated by the inverse distance weighted interpolator (IDW). The derived DEM of a 5x5 m horizontal grid resolution is shown in figure 3. To adapt the elevation information efficiently to the groundwater model MODFLOW with differing grid cells in the x- and y- dimension from 5 to 20 m (minimizing the amount of inactive cells) the grid was rotated by 30 degrees.

On the basis of the derived elevation information and the digitized stream channel the resolution of the used model grid for the groundwater calculations within MODFLOW was defined. Due to the high accuracy of the elevation data the regeneration potential of wetlands can be prognosticated if the groundwater levels are known.

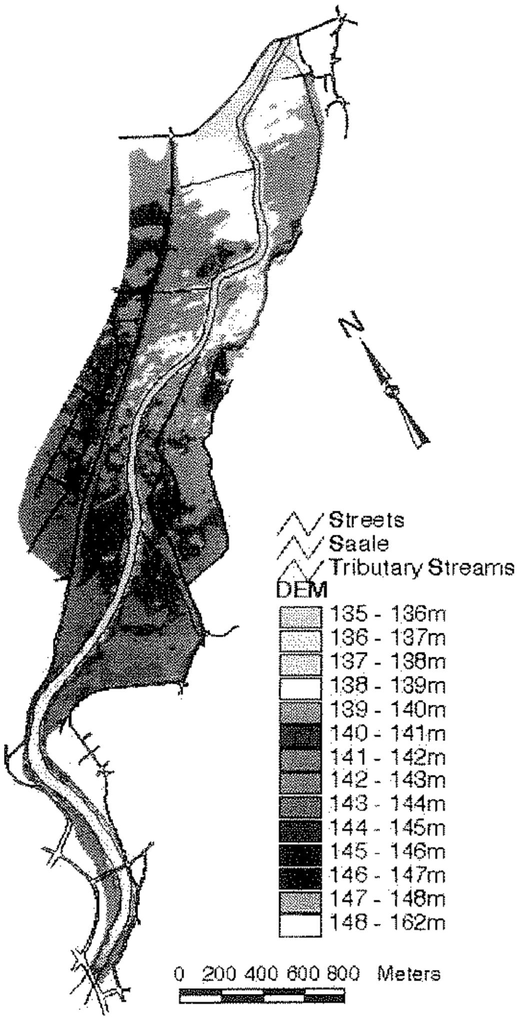

Figure 3: Digital elevation model calculated on the basis of 8181 elevation points using an inverse distance weighted interpolator.

5. CREATING THE CONCEPTUAL MODEL WITHIN MODFLOW

The functionality of the GIS and the pre- and postprocessor VISUAL MODFLOW was used to derive the model input and to construct the conceptual model within MODFLOW.

5.1 Deriving the model layers from borehole data

Using the available data of 178 boreholes several MODFLOW input grids were generated in the GIS and imported as ASCII file into the processor

VISUAL MODFLOW. Basically this includes the thickness grids of four stratigrafically different model layers (see 5.2) and the model parameter grids of the hydraulic conductivities and leakances.

The thickness grids were calculated using the layer top and bottom heights which were derived like the elevation grid using the inverse distance weighted interpolator. The necessary transmissivity grids for every layer were generated by multiplying the thickness grids with the horizontal hydraulic conductivities.

The processor VISUAL MODFLOW was additionally used to modify and to validate the input data (see 5.3) and finally for the construction of the MODFLOW input files. The described input data pathway was operated in the reverse direction once the groundwater heads were calculated to integrate them in the GIS based spatial data base.

5.2 Hydrogeology and boundary conditions

A representative profile of the different model layers based on the stratigrafic information of 17 boreholes is shown in Figure 4. Generally the following four hydrogeological layers where distinguished:

- Deposits overlying the heterogenous gravel sediments (including made ground, meadow loam and sandy materials),
- Heterogenous gravel sediments,
- Impervious claystone overlying the Upper Bunter and
- Upper Bunter Formation.

Spatially these hydrogeological units can be found throughout the whole study area, with a clearly variable thickness.

The Upper Bunter Formation reaches a vertical thickness of over 200 m and acts as a confined groundwater aquifer. Although this formation has no account in respect of the formulated objectives of this study, it was integrated in the regional groundwater model of the city of Jena, where this case study is part of.

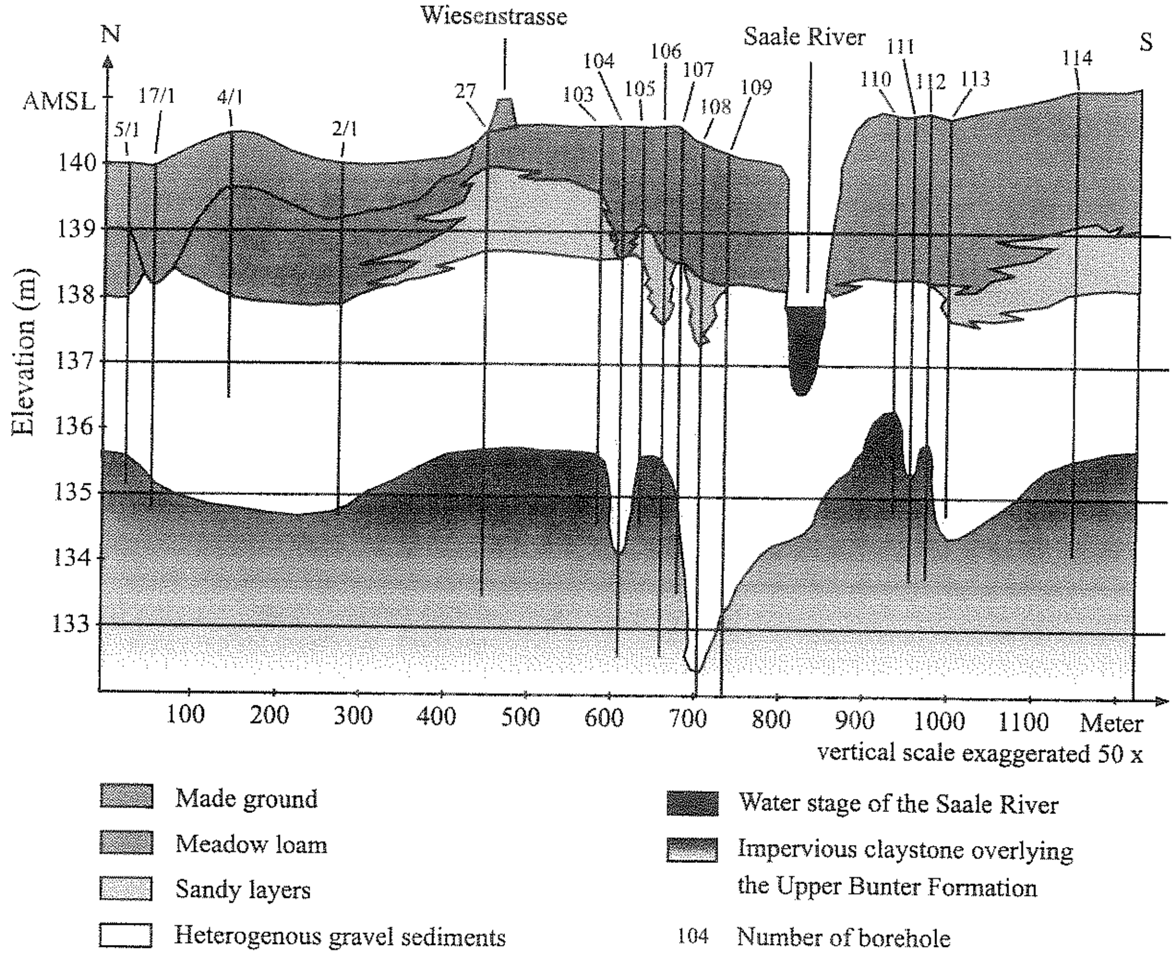

Figure 4: Representative profile perpendicular to the Saale River showing the relevant hydrogeological units. (Location of the cross-section is shown in Figure 2.)

The pre Quaternary geological set-up is formed by calcareous clayey residuals of the Upper Bunter which have a thickness between 1.5 and 15 m. These sediments are almost impervious and separate the confined aquifer of the Lower Bunter Formation from the upper aquifer of the gravel sediments.

The Quarternary gravels are the main aquifer in the study area. They are composed of gravel sediments varying in size. The average depth lies in the range of 2.5 to 3.5 m, whereas a thickness of up to 5 m can occur. The aquifer is sporadically overtopped by a silty and sandy quiescent-area facies, which is lying adjacent to the meadow loam of a similar granulometric composition. Both formations reach a thickness of up to 3 m. In parts they are intermittent by made ground resulting from the construction of buildings along the valley floor.

Groundwater recharge is dominated by springlets marking the border between the Quaternary geological set-up and the adjacent Muschelkalk Series. Recharge by precipitation is of minor importance. Goetze [1985] published groundwater recharge rates along the Muschelkalk Series varying from 1.5 to 2.8 L/s per 100 m border lenght based on groundwater resources calculations. Additionally Goetze [1985] specified the infiltrating water from two important ditches entering the aquifer within the study area with an average flow rate of 5 L/s. In MODFLOW these boundaries were handled as constant flow conditions (Neumann-type) using the General Head package.

5.3 Interaction between the river system and the upper aquifer

The intensive hydrogeological studies by Goetze [1985] seize a relatively small hydraulic conductance of the Saale riverbed. However, exact measurements of the river bed conductance were not taken, groundwater observations during flood flow show a high gradient between the river stage and adjacent groundwater heads almost reaching 1m. These observations can be confirmed by pumping test data pointing out a low discharge capacity of the aquifer along the river bed and having a very low groundwater increase after the pumping stopped. Reasons for the low river bed conductance values are certainly a high silting-up during the former times of the existing weir from 1913 to 1978 and man made changes of the natural river bed.

In MODFLOW the stream stage of the Saale River is characterized by constant head values (Dirichlet-type) and was integrated into the groundwater model using the River packages. This package allows the quantification of the interaction between the river stage and the shallow aquifer. As input it requires the model layer, row and column number, the elevation of the river stage, the river bed hydraulic conductance and the elevation of the base of the river bed for each designated river cell [Swain 1994, Brodi 1997].

The river bed elevation was measured along several profiles and linear interpolated to match the derived model grid. The river stage was known from a gauging station upstream. River bed thickness and the hydraulic conductivity building the river bed conductance were assigned during model calibration using the optimization routines of Model Independent Parameter Estimation Module (PEST) [Watermark 1994].

6. STEADY-STATE MODEL

The calibrated steady-state model based on the described conceptualization is mapped in Figure 5. The groundwater heads shown in Figure 5 correspond to the mean flow conditions as they were

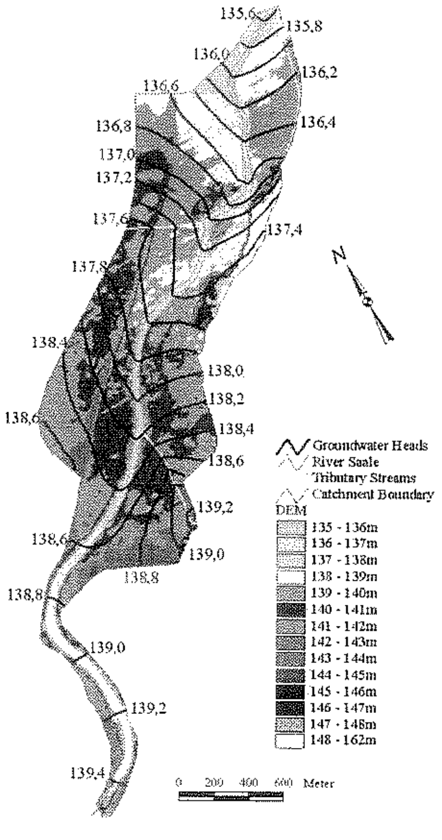

Figure 5: Steady-state groundwater model building the basis for a dynamic groundwater flow and recharge model.

observed in the study area (absolute error of 6.2 cm and an RMS-error of 7.6 cm). Regarding to the low error values it has to be mentioned that all four observation wells (see Figure 2) are positioned along the western half of the flood plain. Considering also, the much lesser density of the borehole data in the eastern flood plain, any prediction in that area must be associated with a much higher uncertainty.

Nevertheless, with respect to the environmental impacts of the planned weir (mainly the regeneration of the wetlands) the western part of the flood plain is the most interesting. A relevant groundwater rise can be expected along the Steinbach ditch and will effect a landfill adjacent to the weir construction.

7. CONCLUSION

The combination of the interpretation of aerial photography with ZEISS technology, GIS and groundwater modelling tools (pre- and postprocessor VISUAL MODFLOW and several MODFLOW packages) could efficiently be integrated to develop a tool set for environmental impact assessment studies. Regarding a low error of about 10 cm in the DEM generation as well as in the modelled groundwater heads the results are very promising for a detailed analysis of groundwater changes and the regeneration of wetlands. Potentially endangered areas regarding a rise of the watertable are restricted to the western part of the flood plain were a high accuracy was achieved.

Further model evaluations will include a dynamic groundwater model.

8. ACKNOWLEDGEMENTS

The results presented in this paper are subject to a project supported by the local government of the city of Jena, Germany.

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