

A DIGITAL CARTOGRAPHIC SOURCE FOR NUMERICAL MODELS IN HYDROLOGY

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Abstract: A short review of digital data used in hydrological models is presented. There are three basic kinds of digital maps used in hydrology: raster images (scan, orthophotomap), vector maps and digital models (Digital Terrain, Landscape and Elevation Models). Hydrological models are used to analyze natural phenomena: free surface flow, the precipitation-outflow relation and groundwater flow. The choice of cartographic source depends on the problem to be solved. The article includes an analysis of two problems: (i) the solution of flood area due to extreme river flow and (ii) groundwater flow. In both cases, digital cartographic sources are presented.

Keywords: digital cartography, GIS, numerical simulation

1. Introduction

The development of numerical computing has made digital cartographic sources more convenient for solving hydrological problems. In hydrology, numerical modeling is focused on basin surface calculations: identification of inundation zones, free surface flows (*e.g.* flood wave propagation) or groundwater flow modeling including groundwater flow conditions. The main spatial data used are basin geometry and topography and the shape of river valleys or hydrographical networks. Spatial data such as stage and flow in a gauging section, measured and observed meteorological data, watershed management or groundwater level fluctuations may vary in time.

There are many sources of data used in hydrological models. The most common ones are geodetic survey and hydrological measurements. Other sources are master and derived maps, topographic maps or bathymetric charts. Nowadays, orthophotomaps and digital models are used as well. The data collecting for each case is time-consuming and expensive. Nowadays, digital maps containing almost all topographical data are saved as raster maps, vector maps, Digital Terrain Models (DTM) or Digital Elevation Models (DEM). Other digital models are defined as Digital Cartographic Models (DCM) or Digital Landscape Models (DLM) [1]. The type of a digital source depends on the availability of data and the problem to be solved. For example,

DTM and DEM are not so useful in groundwater flow models as maps of aquifer geometry.

2. Digital source examples

Raster graphics images are generally used as digital sources of cartographic data. A picture's definition is a function of the number of pixels in a spatial element. Raster files' saving formats are BMP (BitMaP), JPEG (Joint Photographic Experts Group), DRG (Digital Raster Graphics), CIT (CCITT Group 4, Intergraph scanned image). GeoTIFF and JPEG 2000 have recently become the most important digital formats, enabling preservation of georeferences (spatial relations).

Raster maps are obtained by scanning maps or raw satellite, aerial or ground photographs. In order to obtain a correct raster map, it is necessary to eliminate errors in the digital process so that each pixel has its individual horizontal coordinates (x, y) and there is linear dependence among pixels. DCM and DEM may also be products of the photogrammetric survey process. The main advantage of photogrammetric products is the short time required for data collection.

Examples of raster maps obtained through topographical map scanning are presented in Figure 1. An orthophotomap of the same area is presented in Figure 2.

The main disadvantage of raster maps is the impossibility of inserting additional attribute values in a single pixel; each pixel has its individually defined color only. The dimensions of a pixel can be reduced to allow placement of an additional object, but it reduces the speed of calculations and inflates the file size.

Vector graphics used in the digital employs geometrical elements such as points, lines, curves and polygons. Considering the scale, the accuracy of mapping depends on the number of nodes. Vector objects may be open or closed, respectively describing hydrographical networks or contour lines and basin confines.

Topographical maps of Polish territory are currently available at the Main Centre of Geodetic and Cartographic Documentation (CODGiK). Topographical maps in 1992 coordinates are generalized to print in the 1:10 000 scale. There is no difference between printed raster and vector maps, so Figure 1 may also represent a vector map.

The most popular geoinformation systems based on vector data are ESRI (ArcGIS), Bentley (MicroStation with geospatial products) and INTERGRAPH (GeoMedia) systems. Vector data are also used in engineering graphics (CAD systems); these systems are not easily implemented in spatial models, as they use local coordinates instead of geographical ones.

A digital source based on three-dimensional spatial data very useful in hydrology is the Digital Terrain Model (DTM, see Figure 3). It is mostly created using two-dimensional digital maps or photogrammetric surveys. DTM data consist of square matrices of horizontal coordinates with an elevation attribute for each pixel (the GRID method). This method resembles raster maps, where pixels' color is the equivalent of the DTM elevation attribute. Defining elevation for all grid points is not always easy. Alternatively, a DTM may be based on an irregular triangle network (the TIN method), *i.e.* points of three known coordinates. All digital models may

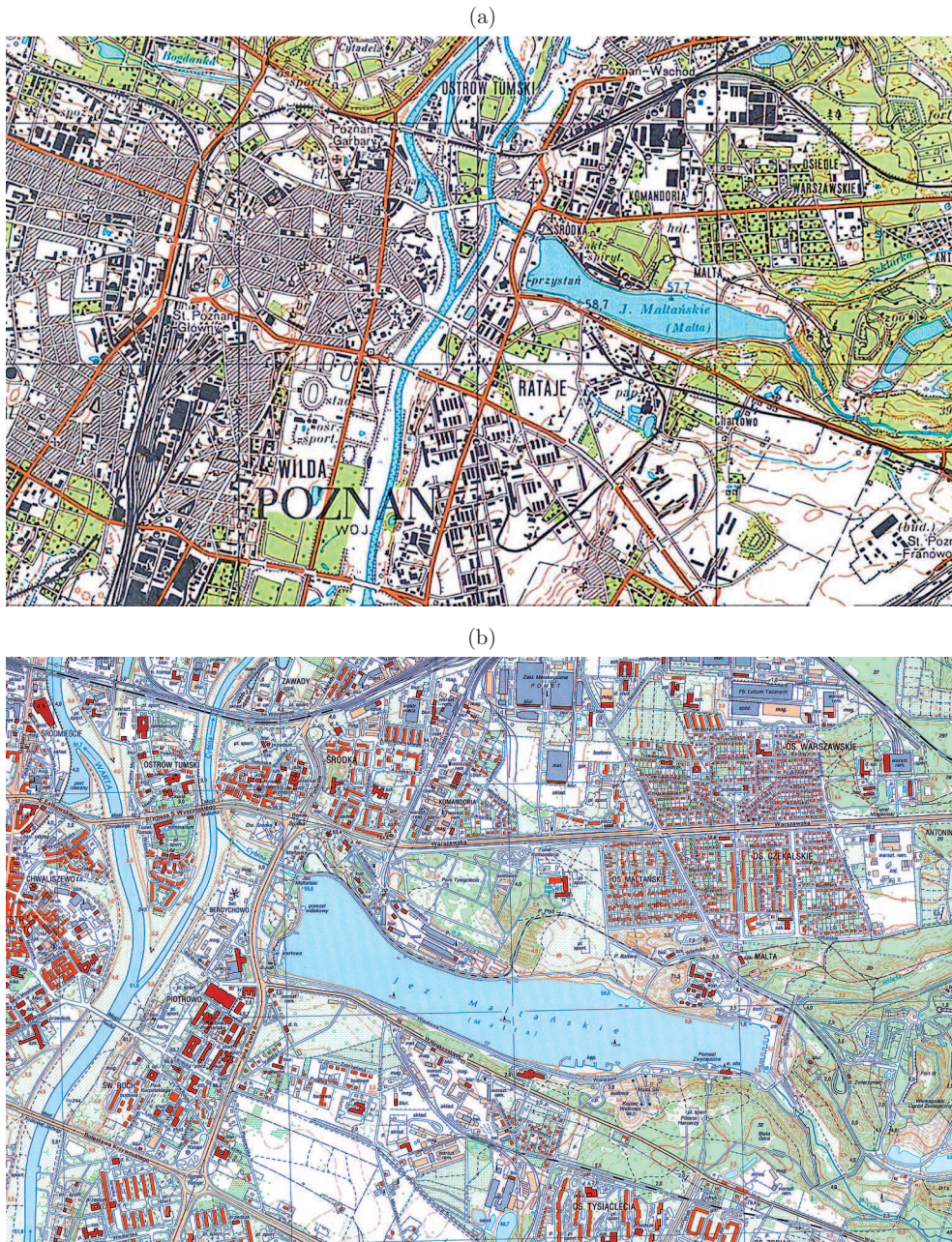


Figure 1. (a) A raster (analog topographic) map: scale 1:50 000, PUWG 1965 arrangement of geodetic co-ordinates [2];
 (b) a raster (digital topographic) map: scale 1:10 000, PUWG 1992 [2]

contain additional surface elements, natural (lakes, slopes, gorges) or artificial (roads, reinforcements, embankments).

In some cases, it is preferable to know the elevation of an existing object instead of the ground level. This information is saved in a Digital Elevation Model



Figure 2. An orthophotomap: scale 1:5000, PUWG 1992 [2]

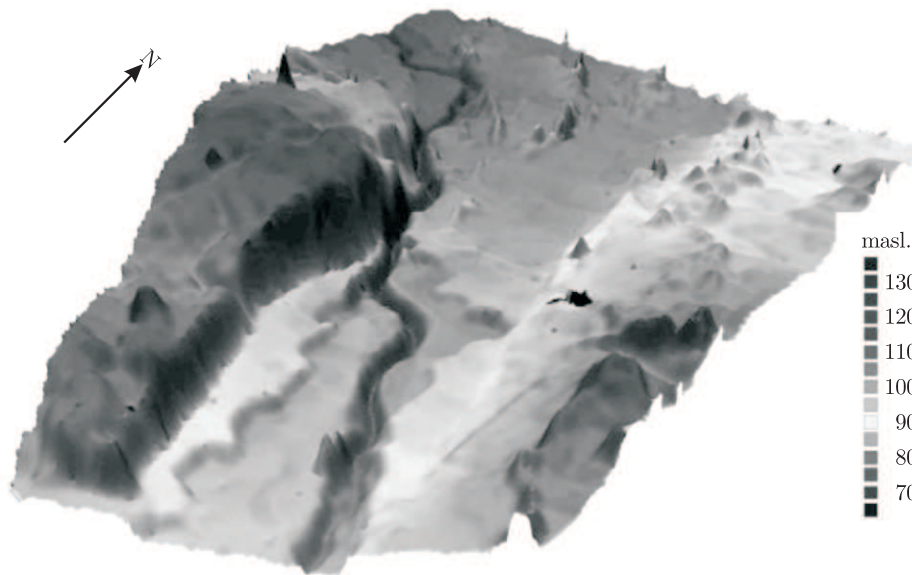


Figure 3. A Digital Terrain Model (DTM) of the Vistula valley in the Warsaw region [3]

(DEM), which is useful in analyzing flood wave propagation in urban areas. In this model, forests and other large surface objects can be defined with their average elevation.

There are geographic and thematic maps in the digital cartographic data resources. Geographic maps are divided into the following groups of topographical maps according to their scale: large-scale (scales 1:5000 and 1:10 000), middle-scale (scales 1:25 000, 1:50 000 and 1:100 000) and small-scale (scales from 1:200 000 to 1:500 000). Large-scale topographical maps are sources of cartographic elaboration based on geodetic survey results. Middle-scale and small-scale topographical maps

are products of cartographic elaboration based on large-scale topographical maps prepared by reproduction and editorial work [4].

Thematic map edition highlights aspects of a geographical map or natural and social-economic phenomena. The thematic maps' division is based on technical instruction K-3 (see Figure 4) [5].

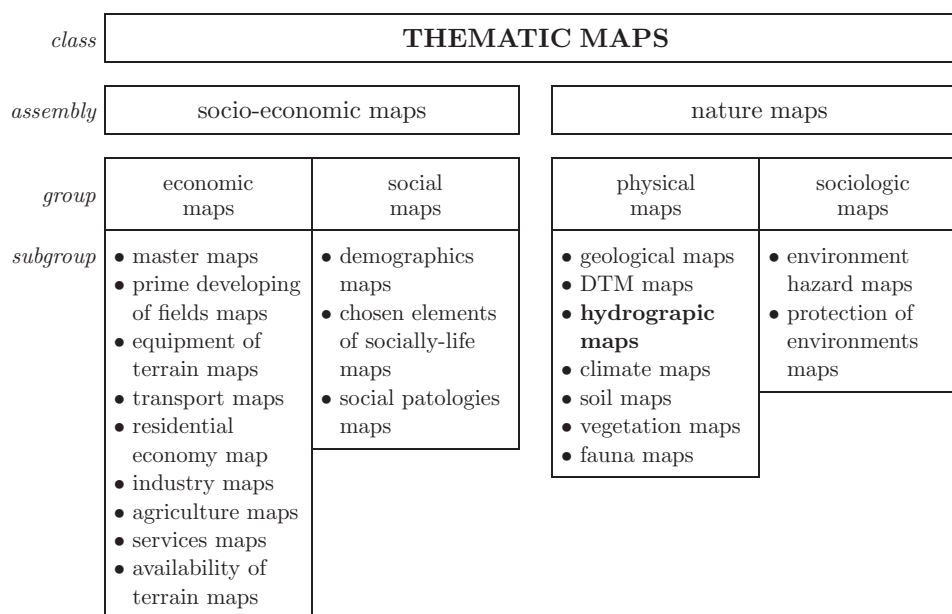


Figure 4. Specification of thematic maps

The maps of the natural environment may be divided into seven thematic groups, including geology, soils, geomorphology, climatology, fauna and hydrography. The hydrographic map, currently covering about 40% of the Polish territory, is used in hydrological problems. It presents the surface and groundwater flow conditions in the shallowest aquifer. The hydrographic maps also include information about water management objects and phenomena and, moreover, they conform to environmental protection rules of the European Union (see Figure 5).

The oldest known Polish hydrographic map which contains rich information is a Hydrographic Map of the Polish Kingdom dating from 1850. There are also a few hydrographical cartographic drawings from earlier centuries, such as the cartographic prints from King Stanislaus August's collection, dating from the 18th century and prepared by Charles de Perthees.

The hydrographic maps are currently available as vector maps in 1992 coordinates. They are edited to be printed in the 1:50000 scale as a part of national cartographic documentation (TBD – Topographic Data Base Vmap Level 2).

3. Digital sources in hydrology

In hydrology, most of numerical models are described by systems with decomposed parameters. They consist of partial differential equations, a first-order time

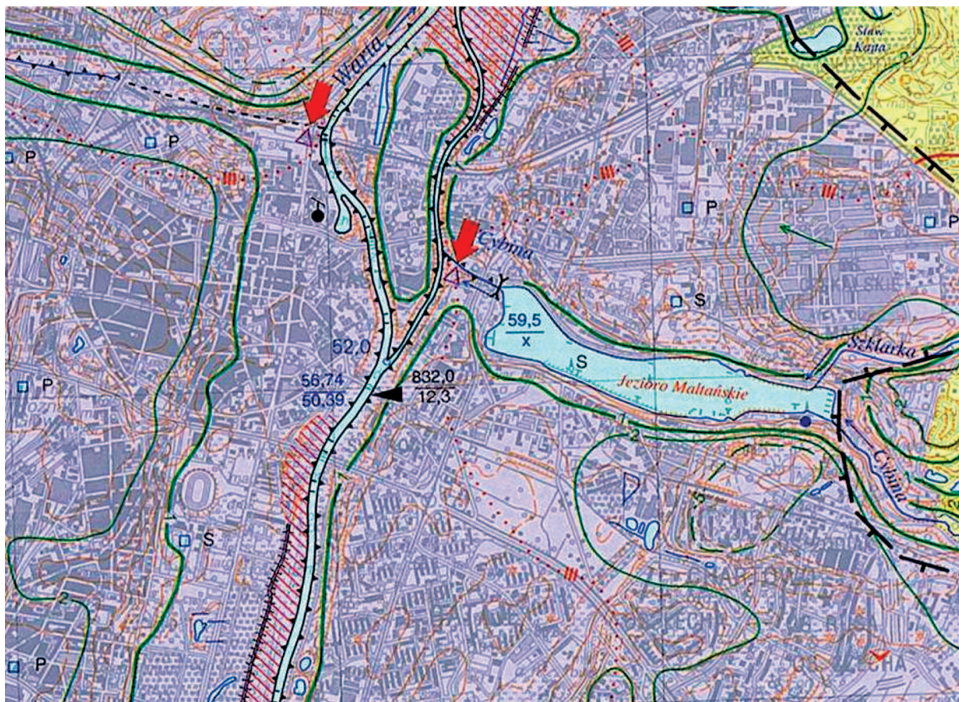


Figure 5. A digital hydrographic map, PUWG 1992 [2]

derivative and first- or second-order spatial derivatives. Their numerical solutions are mostly based on the finite difference, finite element or finite volume methods.

In its general form, the mathematical model should be calculated for the three variables of spatial dimensions (x, y, z) and in transient conditions. Several simplifications are used to solve partial differential equations. Prior to numerical calculation, the discretization process has to be prepared. An individual cell must be oriented in space and have its spatial and time parameters defined. As a result of the discretization process, huge amounts of entry data must be defined. Digital sources are very useful to reduce the time required for data collection. In the lack of complete data, an interpolation method is used. Depending on the problem, some kinds of digital data are more useful than others. Two hydrological problems are presented below, the solution of each requiring different spatial entry data.

3.1. Area flooded by catastrophic flow

Identification of a flooded area is a problem for all streams of a hydrographical network. Current regulations require identification and preparation of potential flooded areas for extreme flows in river systems. The defined flow's probability is a criterion of identification of the endangered surface. In the majority of cases, the criterion of catastrophic flow probability is $Q_{1\%}$, corresponding to an event occurring once during a period of 100 years. Flow probabilities $Q_{2\%}$ or $Q_{10\%}$ are sometimes indicated, corresponding to an event occurring on average once every 50 or 10 years. If a Digital Terrain Model is available, three-dimensional models may be used. A better source of digital data for urban regions is a Digital Elevation Model. The solution,

representing water depth in the flooded area, is a new layer of the vector map (see Figure 6). The accuracy of analysis depends on the quality of the DTM or DEM, especially in river valleys. Digital data for local flow networks are often less accurate in some parts of the model than expected and require additional geodetic surveys, especially in river valley cross-sections.

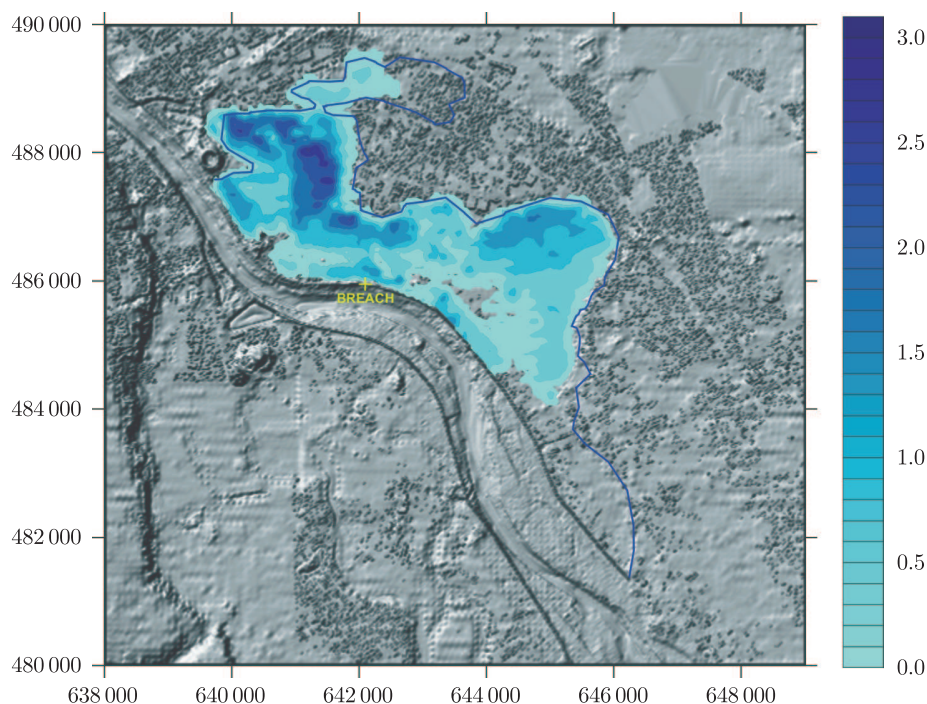


Figure 6. Example of flooded area: a result of numerical investigation based on DEM [6]

When only raster maps are available, the analysis is simplified by using one-dimensional data in the numerical calculations. Hydrological and geodetic data must be collected in the characteristic river valley cross-section where the mean values of flow must be calculated. Flow parameters between two neighboring cross-sections are interpolated. Flow quantity in the lower cross-section consists of the flow value of the upper cross-section and the lateral recharge rate between the two cross-sections.

Finally, water levels at cross-sections are calculated and the flood area is determined on the basis of interpolation of calculated points (see Figure 7). There is no possibility to present the depth of flood, as was the case with DTM and DEM data.

3.2. Groundwater flow

A branch of hydrology which describes underground water flow is sometimes referred to as hydrogeology. Hydrogeological models deal with local or regional water flow analysis. Their boundaries depends mostly on the hydrographic network and aquifer range.

A groundwater flow system is composed of several aquifers, which may be in hydraulic contact. Spatial data should contain information about the aquifers boundaries, their bed and roof elevation, the elevation of water stage in the surface

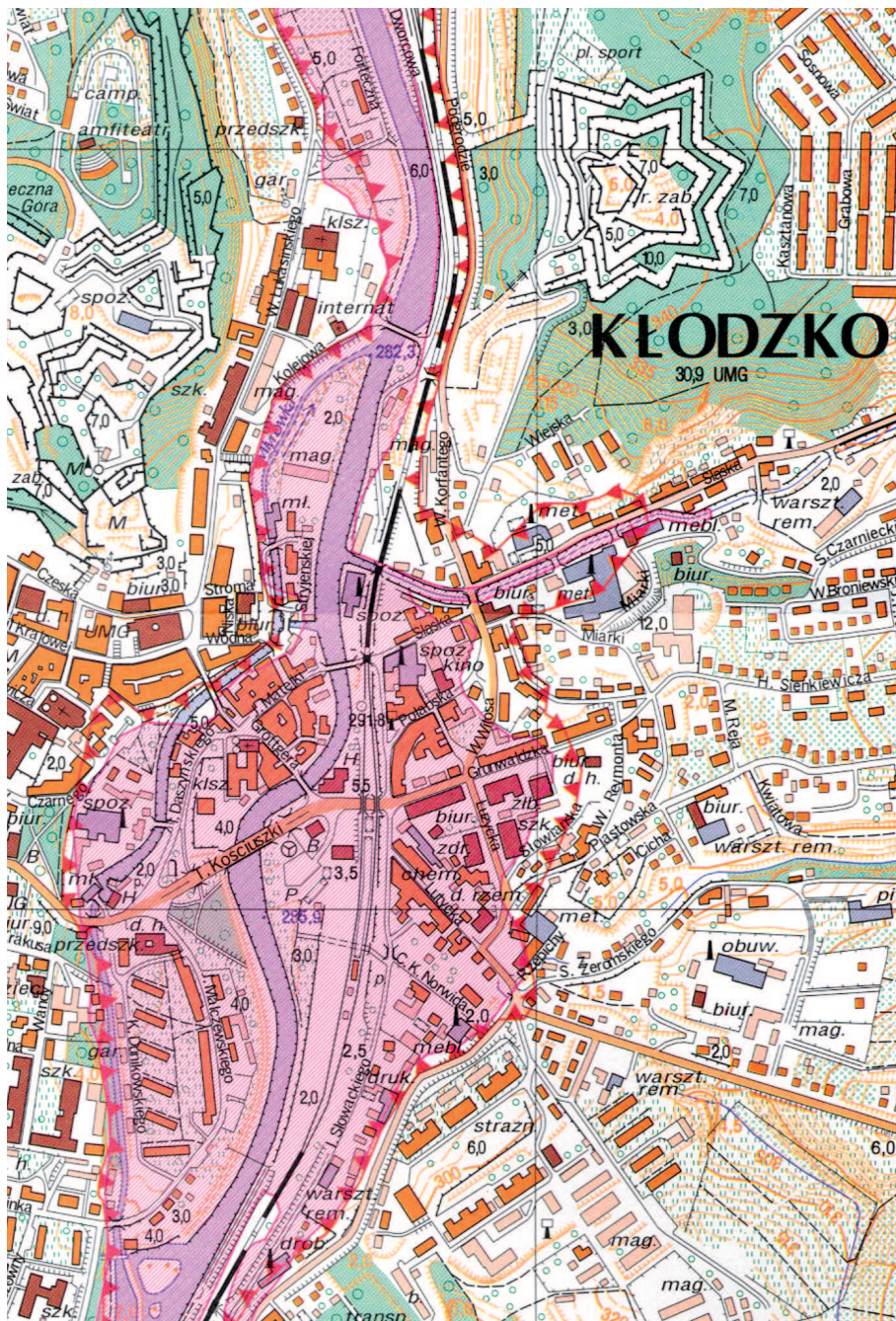


Figure 7. A flood area on the Nysa Kłodzka near Kłodzko using raster data: map generalization 1:10 000, the actual flood range of 1997 shown as the red asymmetric line [7]

water network, the positions of wells and the spatial distribution of the filtration parameters in aquifers and aquitards. The necessary data are often obtained from additional analysis of flow conditions in the groundwater system. The main digital data source is a raster or vector map. The flow parameters are prepared as a digital

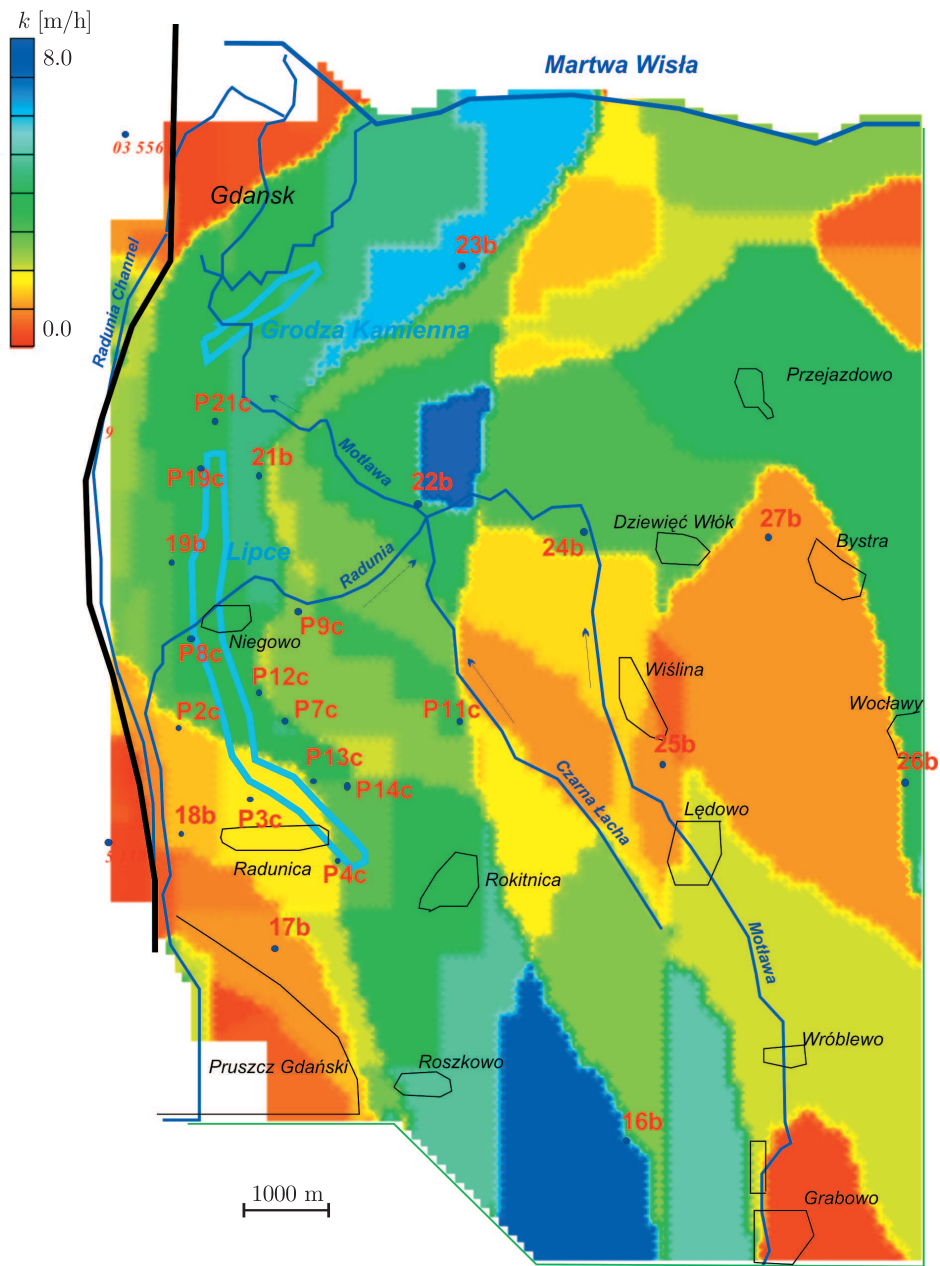


Figure 8. Analysis of hydraulic conductivity distribution in the western part of the Vistula Delta Plain principal aquifer using the GMS program [8]

model (values of filtration parameters are defined for all discrete elements, see Figure 8). The geometrical surfaces of aquifers and values of filtration parameters may also be interpolated from punctual borehole observations.

A free water table and a confined groundwater surface obtained from groundwater flow calculations are basic data for further analysis (*e.g.* water balance, contaminant migration analysis). The most popular groundwater flow software is based on

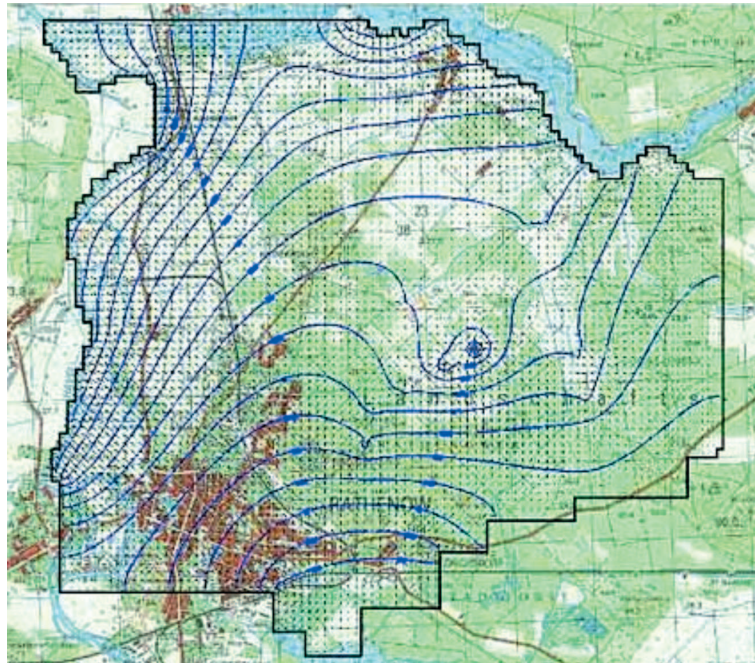


Figure 9. An example of confined groundwater surface on a scanned topographical map (raster map) using Modflow [9]

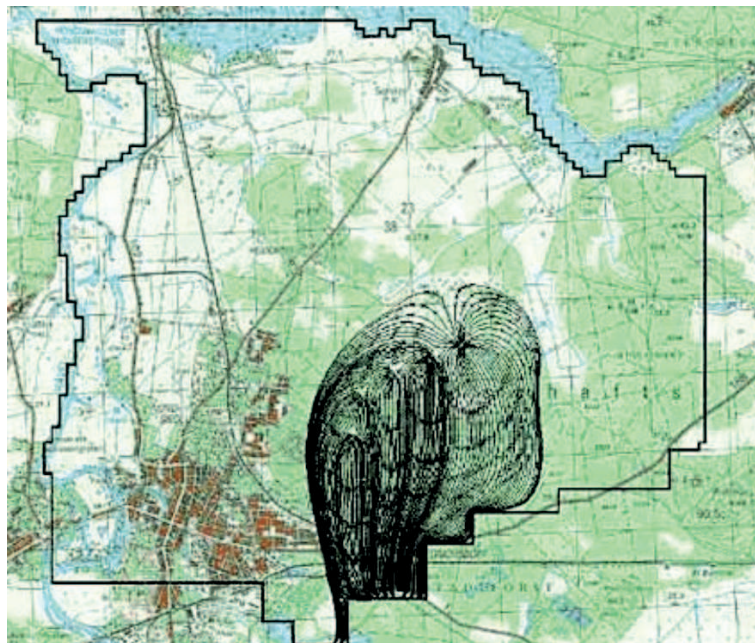


Figure 10. A particle tracking solution using Modflow and Modpath [9]

the Modflow code (see Figure 9). A particle tracking solution may be obtained using the Modflow and Modpath codes (Figure 10). The solution of contaminant transport requires the Modflow and MT3D codes (see Figure 11).

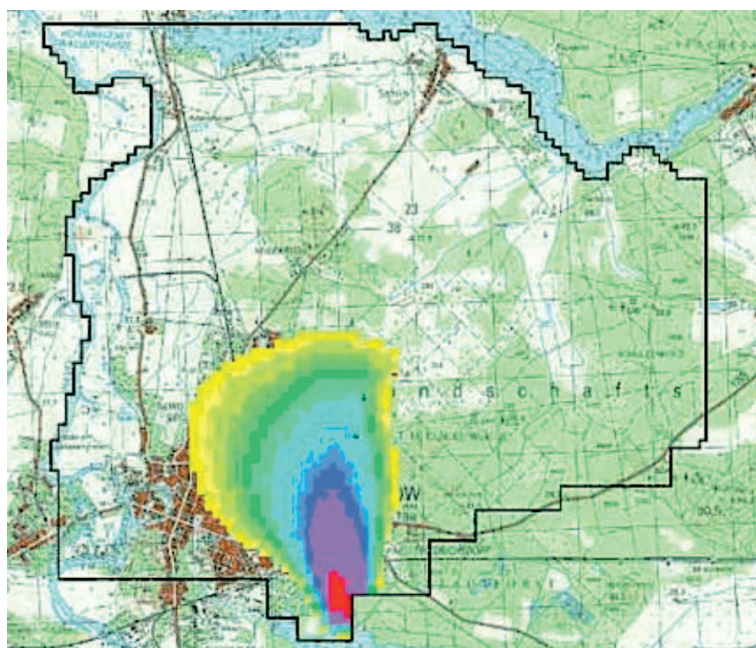


Figure 11. A contaminant transport solution using Modflow and MT3D [9]

One of the most important groundwater analyses is identification of groundwater intake inflow (see Figure 12), the results of which are saved in a hybrid map consisting of several layers, called a calibrated raster map [10]. Its other layers consist of vector data: calculation results constitute additional map layers.

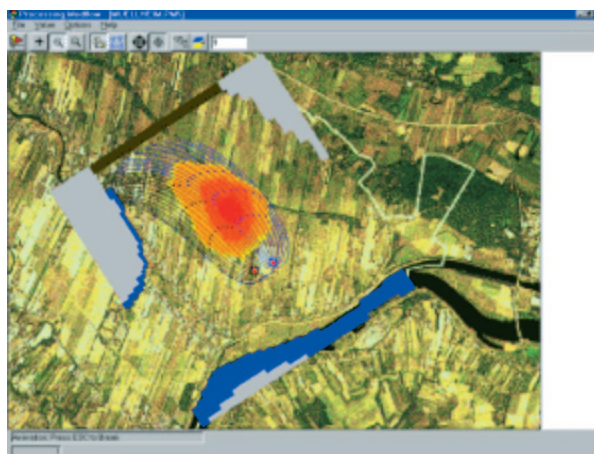


Figure 12. Groundwater intake inflow and flow directions on an aerial ortophotomap [11]

As vector data can be prepared from a topographic map, only necessary information is presented (see Figure 13). Directions and quantity of flow in the aquifer are marked with plotted arrows. Only the hydrographical network is extracted from raster maps to vector data and included in final solutions as a topographic map would obliterate flow directions.

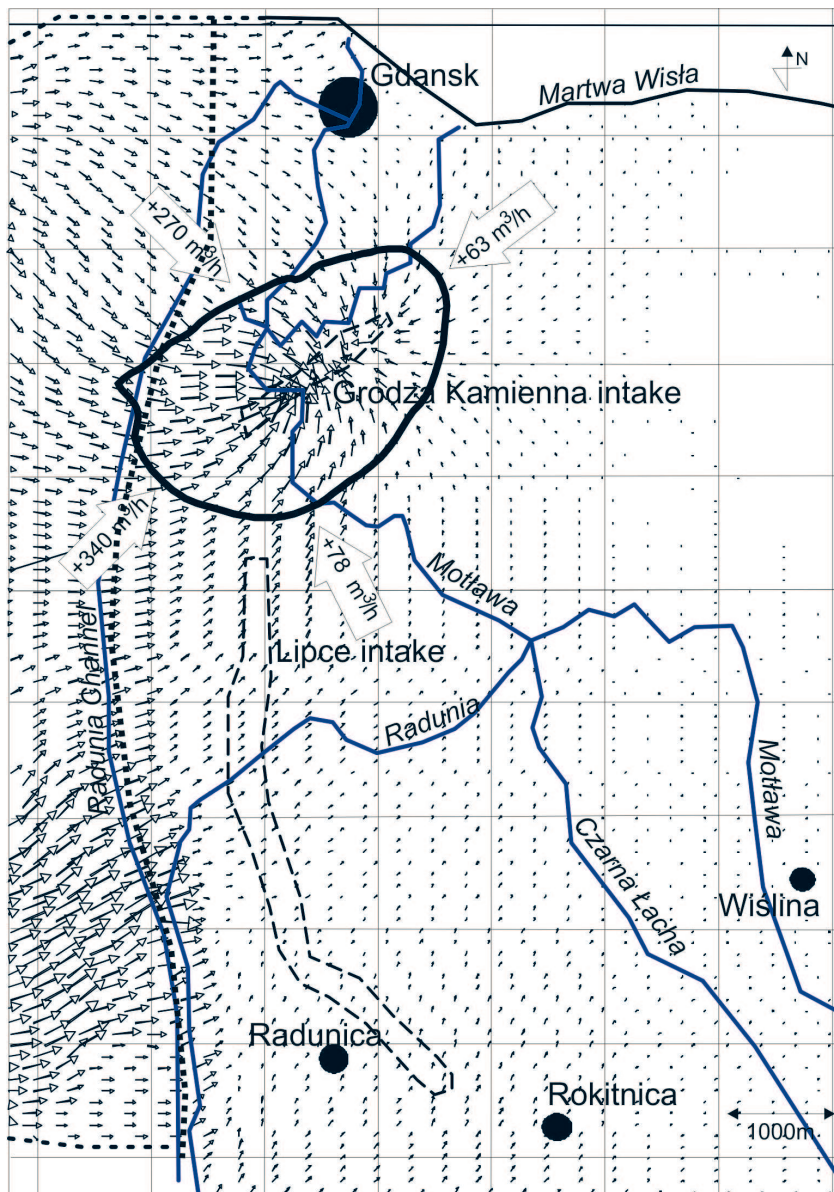


Figure 13. Groundwater flow in the Vistula Delta Plain quaternary aquifer.
 Bolded line marks 10 years' flow to Grodza Kamienna intake wells [12]

4. Conclusions

Numerical solutions of hydrologic problems are currently obtained on the basis of digital environmental data consisting of topographic and equation parameters (e.g. the groundwater flow filtration parameter, the surface flow basin and the river valley floor). Topographic maps are most commonly used, printed or saved as raster or vector files. Their usefulness is limited by the lengthy preparation process of the model input data. Digital Terrain and Elevation Models are the most popular digital

sources, applicable to hydrologic models in very short time. Additionally, DTM and DEM data offer better possibilities of visualization. Unfortunately, digital models are not the main source of entry data in groundwater flow models, where supplementary analyses of model geometry and flow parameters are necessary.

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