The Use of a GIS in the Processing of Morphohydrogeometric Analysis for the Determination of Privileged Groundwater Flow Pathways

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Abstract

A specific GIS application will be presented to a pilot project dealing with morphohydrogeometric analysis for the determination of privileged groundwater flow pathways. Analysis is based on the basic assumption that the relief is a form of the expression of geological content. Another assumption is that the relief consists of two basic forms – concave and convex, i.e. depressions and elevations. The system of interconnected depressions represents privileged groundwater flow pathways. The plasticity of relief can also be used to define the boundaries between different geological units. GEOtest, a.s. as the author of the methodology for the identification of these pathways updates the way of obtaining this data. The original method works with large-scale printed topographic maps and requires trained staff. Now, thanks to the GIS, we are able to work with a digital terrain model obtained from laser scanning. The identification is much more easier and allows more further processings. On the basis of the results obtained, protection zones of groundwater resources are designed and the directions of the spread of pollutants are predicted. It is also possible to estimate the location of suitable sites for abstraction wells for drinking water.

Keywords: GIS, morphohydrogeometric analysis, groundwater flow pathway, spread of pollutants

1. Introduction

This paper is concerned with the methodology of digital processing of morphohydrogeometric analysis in a GIS environment. It identifies inhomogeneities of the rock mass with preferred water movement, as well as privileged groundwater flow pathways (PGFPs). The conventional methods of location are compared with those in a GIS environment. The method has been tested on a model area around the Vir Dam Reservoir, which is located in the Bohemian-Moravian Highland in Zdar nad Sazavou District. The project implementation is supported by a subsidy within cluster CREA Hydro&Energy, o.s. (in which is GEOtest, a.s a member) and the Operational Programme Enterprise and Innovation (OPPI). The project has a number 5.1 SPK01/004. Provider of subsidy is the Ministry of Industry and Trade (Ministerstvo průmyslu a obchodu).

In the hydrosphere, precipitation is transformed into groundwater within the water cycle. It, in turn, changes into surface water by being drained into streams. Surface runoff as the outflow of water in a stream is only a partial indication in the entire hydrological cycle. It is situated into places of natural groundwater accumulation. There is a hydraulic continuity between a surface stream and groundwater flow. In a landscape, it is possible to define sub-segments – river basins that are closed areas in terms of hydrological balance (Fig. I).
It can be assumed that the orographic basin, which is delineated by the highest elevations around its periphery, matches the hydrogeological basin. Atmospheric precipitation enters the basin (by infiltration); the output is formed by evaporation, transpiration of water by vegetation, by surface runoff and subterranean runoff. Infiltrated water recharges groundwater and also forms hypodermic runoff. Hypodermic runoff is the outflow of water through the rock environment and/or soil that has not reached down to the groundwater table. The most significant component of surface runoff from a basin is formed by the outflow of water through water streams. These are situated into places of natural groundwater accumulation. In precipitation-free periods, the outflow in surface streams constitutes the outflow of groundwater.

Groundwater flow depends on hydrogeological conditions – for example on the composition of rocks, their fracturing, and the slope of the impermeable basement. Water in the rock environment generally migrates by up to several orders of magnitude slower than on the surface. Groundwater always flows in the environment with the lowest hydraulic resistance, usually in the direction of the gravitational force. It accumulates in cavities of various dimensions – in rock pores, tectonic fractures and zones of fracturing, and in karst caverns. The basic hydraulic parameters of these parts of the rock mass – permeability and transmissivity – are higher than in the surrounding environment which represents places of impaired groundwater movement. Places with the highest velocity of groundwater flow and, at the same time, with its largest shifted volume are designated as privileged flow pathways (PGFPs).

The height of the groundwater table in places of privileged pathways (PGFPs) corresponds with the height of the groundwater table in its vicinity. In these places, water has only a lithologically or tectonically governed possibility to move more rapidly and thus in a larger volume. These places form the most significant component of the subterranean runoff of water from a basin. They are found in interconnected depressions, from which they preferentially carry water away from their vicinity. This particularly concerns places of descents (subsidence), cuts, inclines, pits or valleys. The first visible signs of geofiltration flows on the surface are springs. Channels of water streams in their natural positions or their relict overlapped positions can also be considered as signs of geofiltration flows.

The method of location of privileged groundwater pathways is currently used in interpreting the patterns of contours on conventional printed base maps (Fig. 2). The task was to digitize and automate the procedure. The necessary prerequisite for
processing is a high-quality digital terrain model. The project involved working with a model obtained from the company GEODIS BRNO, spol. s r.o. with an accuracy higher than one metre. The model resulted from the stereophotogrammetric evaluation of measuring aerial photographs. Data were processed in the ArcGIS program environment in the ArcMap application. In it, by using the tools of geographic information systems (GIS), privileged pathways of surface runoff formed by liquid and solid precipitation and recharged by surface water and groundwater from the immediate vicinity are located. Based on the definition of surface water pathways, we are able to locate groundwater pathways. Groundwater accumulates in places of depressed areas or local depressions. Its runoff is governed by gravity, taking the line of least resistance.

2. The Methodology of Processing

The input layer was formed by the digitized pattern of a conventionally manually defined PGFP. The second, not less important input was a digital terrain model (DTM), each sub-element (pixel) of which gives the most accurate possible altitude located to this point. This raster (Fig.2) enters into many subsequent processings, during which the position of privileged pathways is further specified. The purpose of the processing was to find a method which can automatically help locate the pattern of conventionally manually defined PGFPs in the GIS environment.

For the purposes of processing an accurate hydrological model, it was first necessary to eliminate local depressions from the DTM. Local depressions are both natural and artificial areas of water, such as swamps, lakes, reservoirs and ponds. We consider such places as already filled by water. We can thus eliminate them – level them with the surroundings. For this purpose, the tool Fill from the environment Arc Toolbox (Spatial Analyst Tools – Hydrology – Fill) was used.

Subsequently, above the adjusted raster, it is possible to simulate a simplified model of runoff where falling precipitation flows away in the direction of the greatest gradient of the slope. The velocity of water movement depends on the size of the gradient of the slope. The direction and size of the gradient can be derived from the DTM raster. The calculation of the raster giving the direction of runoff from each sub-pixel is obtained by using the tool Flow Direction from the environment Arc Toolbox (Spatial Analyst Tools – Hydrology – Flow Direction). The result of the application is shown in an annex (Fig.3).

Now it is possible to calculate the raster of water accumulation from the obtained layers using the tool Flow Accumulation from the environment Arc Toolbox (Spatial Analyst Tools – Hydrology – Flow Accumulation). The output of analysis is the amount of water flowing into the individual cells of the raster (Fig.4). The values of the cells flowing into the analysed cell are added to the value of the analysed cell. It is suitable to further adjust the resulting raster by individually set thresholds, the purpose of which is to find the raster of water streams and separate it from its surroundings. By thresholding we can highlight only significant accumulations, determine their directions, origins, etc. The tool Reclassify from the environment Arc Toolbox (3D Analyst Tools – Raster Reclass - Reclassify) is used for this operation.
The cells, into which no water flows, represent a ridge of terrain. For further understanding of spatial relationships of the studied area, the tool Stream Link from the environment Arc Toolbox (Spatial Analyst Tools – Hydrology – Stream Link) was used. The raster of accumulation of water streams obtained by the preceding method and the raster giving the direction of runoff enter into this analysis. The result is a layer representing mutually separated sub-sections of streams up to the place of conflux (Fig. 5). Sub-basins of the studied area are obtained using the tool Watershed from the environment Arc Toolbox (Spatial Analyst Tools – Hydrology – Watershed). The result of the application is shown in an annex (Fig. 5).

2. Interpretation of Discovered Facts

For the accurate location of privileged pathways of surface water, the highlighted output of the function Flow Accumulation was used by thresholding (Fig. 3). It was possible to find both places of the current position of water streams and water areas, and places flown through by water only during heavy precipitation or thaw. Water flows down into the highlighted areas from the wide vicinity and the patterns of privileged groundwater pathways can be situated there.

When searching PGFPs, it was necessary to determine such a threshold value from which the conflux of surface water from surrounding pixels was considered as the origin of the privileged groundwater pathway. The setting of threshold values differs in relationship to the morphometric type of relief, in which we search PGFPs. The relative vertical ruggedness appears as the key factor. The optimum value of conflux in excess of 400 pixels was chosen for the territory of the Vir Dam Reservoir. An envelope zone of 25 m was created around the defined PGFPs by the tool Buffer (Analysis Tools – Proximity – Buffer). It was thus possible to eliminate both positional inaccuracies between the digital terrain model and The Basic Map of the CR at a 1:10 000 scale, and the inaccuracies related to the human factor in the analog interpretation of the position of PGFPs. The results of the thresholding performed are shown in Tab. 1 and also graphically in Fig. 6. When setting the threshold of conflux at the level of 400 pixels, the length of the analog route identical with the digital route has been achieved (105%), as well as agreement in the position of the digital route at 71% of the length of the analog route.

<table>
<thead>
<tr>
<th>Set threshold of conflux [pixel]</th>
<th>Length of analog PGFPs [m]</th>
<th>Length of digital PGFPs [m]</th>
<th>Length of concurrence of both PGFPs [m]</th>
<th>[%] of digital PGFPs out of analog PGFPs</th>
<th>Success rate of position of digital PGFPs [%]</th>
</tr>
</thead>
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<tr>
<td>200</td>
<td>69 518</td>
<td>107 945</td>
<td>55 221</td>
<td>155</td>
<td>79</td>
</tr>
<tr>
<td>300</td>
<td>69 518</td>
<td>85 933</td>
<td>52 175</td>
<td>124</td>
<td>75</td>
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<td>69 518</td>
<td>72 863</td>
<td>49 211</td>
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<td>71</td>
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<td>500</td>
<td>69 518</td>
<td>65 372</td>
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<td>94</td>
<td>67</td>
</tr>
<tr>
<td>600</td>
<td>69 518</td>
<td>60 353</td>
<td>44 095</td>
<td>87</td>
<td>63</td>
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<tr>
<td>800</td>
<td>69 518</td>
<td>53 413</td>
<td>41 344</td>
<td>77</td>
<td>59</td>
</tr>
<tr>
<td>1 000</td>
<td>69 518</td>
<td>49 295</td>
<td>38 856</td>
<td>71</td>
<td>56</td>
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</table>
3. Improvement Based on the Location of Concave Forms

By using the application of the function Curvature (Spatial Analyst Tool – Surface – Curvature), we are able to distinguish convex forms from concave forms above the digital terrain model. A raster distinguishing between concave and convex forms was created above the digital terrain model with a 10m grid by the application of this function. Concave forms with the parameter of incline less than –0.1 were selected using the function Reclassify (progressively also < -0.2, -0.3, -0.4, -0.5). The resulting layer created the first input layer for further processing.

The second layer was formed by an intermediate product obtained and described above. It was formed by a raster of accumulated runoff. A raster more accurate by one class, defining privileged groundwater pathways longer than the original manually interpreted groundwater pathways, was intentionally selected for illustrating the problem to be resolved. For the territory of the Vir Dam Reservoir, a raster of accumulation was thus chosen with the threshold of conflux in excess of 300 pixels, which indicated the total length by 124% greater as compared to the result of analog interpretation.

By using Raster Calculator (Spatial Analyst Tool – Map Algebra – Curvature), pixels were queried, which lie on the intersection of both rasters – the raster of accumulated runoff above 300 pixels and the raster created by the function Curvature. The procedure was repeated for another setting of the parameter of the definition of the concave form and depicted numerically and graphically (Tab.2, Fig.7).

Tab. 2: Results of the output from the interconnection of concave forms with the raster of accumulation

<table>
<thead>
<tr>
<th>Set threshold for concave forms</th>
<th>Length of analog PGFPs [m]</th>
<th>Length of digital PGFPs [m]</th>
<th>Length of concurrence of both PGFPs [m]</th>
<th>[%] of digital PGFPs out of analog PGFPs</th>
<th>Success rate of digital position of PGFPs [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; - 0.1</td>
<td>69 518</td>
<td>80 973</td>
<td>51 512</td>
<td>116</td>
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<td>50 372</td>
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<td>&lt; - 0.3</td>
<td>69 518</td>
<td>75 599</td>
<td>48 645</td>
<td>109</td>
<td>70</td>
</tr>
<tr>
<td>&lt; - 0.4</td>
<td>69 518</td>
<td>73 456</td>
<td>46 699</td>
<td>106</td>
<td>67</td>
</tr>
<tr>
<td>&lt; - 0.5</td>
<td>69 518</td>
<td>69 939</td>
<td>44 095</td>
<td>101</td>
<td>63</td>
</tr>
</tbody>
</table>

The most accurate results in this morphometric type of relief were achieved by using the setting of thresholds in the function Curvature for concave forms less than – 0.3. The total length of analog-identified PGFPs in the studied area of the Vir Dam Reservoir was 69 518 m. The length of PGFPs identified from the digital terrain model was by about 9% greater, i.e. 75 599 m in total. When setting the threshold in the function Curvature to values less than –0.3, agreement in the position of the digital route was achieved at 70% of the length of the analog route.

If we compare the results of improvement of both methods (Tab.1, Tab.2), we find out that these results are very close by the mathematical expression of accuracy. However, when comparing the results visually, we can see differences (Fig.8).
Based on the location of concave forms, the mapped pattern of PGFPs is more accurately situated into places of accumulation. It better describes the places of conflux thanks to the interconnection of local depression forms with the direction of runoff. This is also evidenced by the fact that the accumulated raster of conflux with the threshold set above 300 pixels enters into the improvement given in this chapter. Thanks to the connection of this layer with the layer of concave forms, we are able to filter out indistinctive accumulations and reach the level of accuracy of the accumulated raster of conflux with the threshold above 400 pixels.

4. Conclusion

When setting the thresholds to the optimum value of conflux, the success rates of the comparison of the accuracy of the location used by the analog method with that used by the digital method vary around 75%. The differences relate to the technology of the method of processing and to the different input data. In the case of manual, analog processing from the topographic base map, the end product results from the professional erudition of the interpreter showing the knowledge of geomorphology, geology, hydrography and hydrogeology. However, the result can be loaded with an error of the human factor in interpretation. Small disagreements between both methods are outweighed by the speed with which digital PGFPs can be obtained. At the present time, we are working on other options of improvement on the basis of landscape cover and dealing with research comprising the time component for determining flow velocities in different rock environments.

Interpreted privileged groundwater flow pathways are used for various purposes. They can be used wherever it is necessary to define the degree of vulnerability of the rock environment in relation to groundwater or to search for the part of the rock environment with maximum transmissivity. Basic areas of the use of privileged flow pathways are as follows:

- Determination of protection zones of drinking-water resources;
- Background information required for land-use planning;
- Location of a suitable place for siting hydrogeological wells as sources of drinking water (Fig.9);
- Identification of vulnerable ground surfaces with respect to groundwater contamination;
- Optimization of flood-control measures;
- Identification of parts of a landscape extremely threatened by contamination due to traffic (Fig.9);
- Prediction of impacts of anthropogenic interventions in the rock environment (e.g. construction of tunnels) on hydrogeological conditions – changes in the water regime in a landscape;
- Determination of the direction and velocity of migration of contaminants through groundwater in crisis management, e.g. after accidents (Fig.9).
5. References


6. Annexes

Fig.1: The Basic Map of the CR at a 1:10 000 scale (24-11-20) with privileged groundwater flow pathways plotted by an analog method.
Fig. 3: Raster elevation model
Fig. 4: Determination of the direction of surface conflux
Fig. 5: Water accumulation – privileged groundwater flow pathways
Fig. 6: Sub-basin and delineation of PGFP according to the places of conflux
Fig. 7: Groundwater accumulation identified on the basis of a raster of accumulation with a 400-pixel threshold

Fig. 8: Comparison of the results obtained by the method of plain accumulation with those obtained by the method of location on the basis of concave forms

Fig. 9: The application of PGFPs to the design of constructions

Fig. 10: The application of PGFPs above a map of risks and map of the suitability of sites