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# Managed Aquifer Recharge: Local solutions to the global water crisis


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## *Managed Aquifer Recharge: Local solutions to the global water crisis*

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## Topic 13. MAR AND ECOSYSTEMS

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# Vulnerability of the aquifer system from the Nhartanda Valley (City of Tete, Mozambique)

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**Abstract:** Water is an essential resource and must occur in appropriate quantity and quality. The main objective of this research is the vulnerability assessment of the aquifer system in the Nhartanda Valley (City of Tete, Mozambique). Groundwater is collected from the aquifer for public water supply system of the old city of Tete and a traditional agro-livestock farm, which is irrigated by artesian wells. In situ water determinations and laboratory analysis have been performed to assess water quality in the study area. Groundwater vulnerability was determined through the application of GOD and DRASTIC indexes. The vulnerability indexes of the Nhartanda Valley aquifer vary from moderate-high to very high. During hot and humid seasons, the vulnerability index may reach to extreme levels, being reached relatively quickly by harmful organisms and substances. A specific set of actions and measures are necessary for the protection of Nhartanda Valley aquifer, which necessarily must involve social and environmental awareness of civil society and local population. The better knowledge of the system is essential to support decision makers on sustainable management of the water resources and protection and remediation strategies for the aquifer. The identification of the most vulnerable areas has generated basic information for that.

**Keywords:** Groundwater; Vulnerability; GOD; DRASTIC; Nhartanda Valley; Mozambique.

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## 1. Introduction

Groundwater is one of the most important sources of drinking water due to the reduced chance of surface water pollution and is considered as the only safe water source for domestic, industrial, and agricultural activities [1-3]. However, groundwater quantity and quality are being threatened by increasing demands due to population growth and agricultural/industrial activities, on the one hand, and increased pollution from the discharge of wastewater, on the other hand.

The protection and conservation of groundwater resources is very important, particularly in arid and semi-arid regions where water resources are more limited. The effects of rapid population growth, urbanization and diversification of economic and agricultural activities contribute to the quantitative (scarcity, overexploitation) and qualitative degradation of groundwater (pollution, chemical degradation) [4].

Groundwater management encompasses a broad range of activities including prevention of groundwater contamination. Increasing groundwater contamination around the world has triggered the concept of "aquifer vulnerability", which has been widely used for three or four decades by researchers and policy makers to protect groundwater pollution [5].

Assessment of aquifer vulnerability is an important step in order to implement any management groundwater plans and protecting these water sources [6-8]. However, only a few recent studies have focused on the performance of vulnerability assessment methods [5]. The methods for assessing groundwater vulnerability can be divided in index methods, statistical methods and process methods [9]. Parametric methods such as DRASTIC and GOD were developed to assess groundwater vulnerability [7; 10-16].

The Nhartanda Valley aquifer system, in City of Tete (Mozambique), is exposed to a lack of sewage treatment plants and intensive agricultural activities. In the area, there isn´t any waste management system and wastes are deposited irregularly in the valley and surrounding areas, as well as in its main source of recharge - the Zambezi River. Consequently, there is an increased vulnerability of the aquifer and a deterioration of water quality, which is the main source of human water consumption for the "old" city of Tete.

This study aims to evaluate the vulnerability of groundwater in the Nhartanda Valley aquifer using the GOD and DRASTIC indices. The identification of the most vulnerable areas will generate information to support preventive water use and quality control measures. The management of water resources allows the development of proposals for actions to monitor the quantity and quality of groundwater by local and national policy makers.

## 2. Materials and Methods

### *2.1. Study area – Nhartanda Valley*

The Nhartanda Valley is located in Southern Africa, center of Mozambique, in the southern part of the City of Tete (Figure 1). City of Tete is a large urban area which and hosts ~2.74 million inhabitants. The Nhartanda Valley occupies an area of 6.76 km$^2$, corresponding to 2.2 % of the surface of the City of Tete, which is approximately 314 km$^2$.

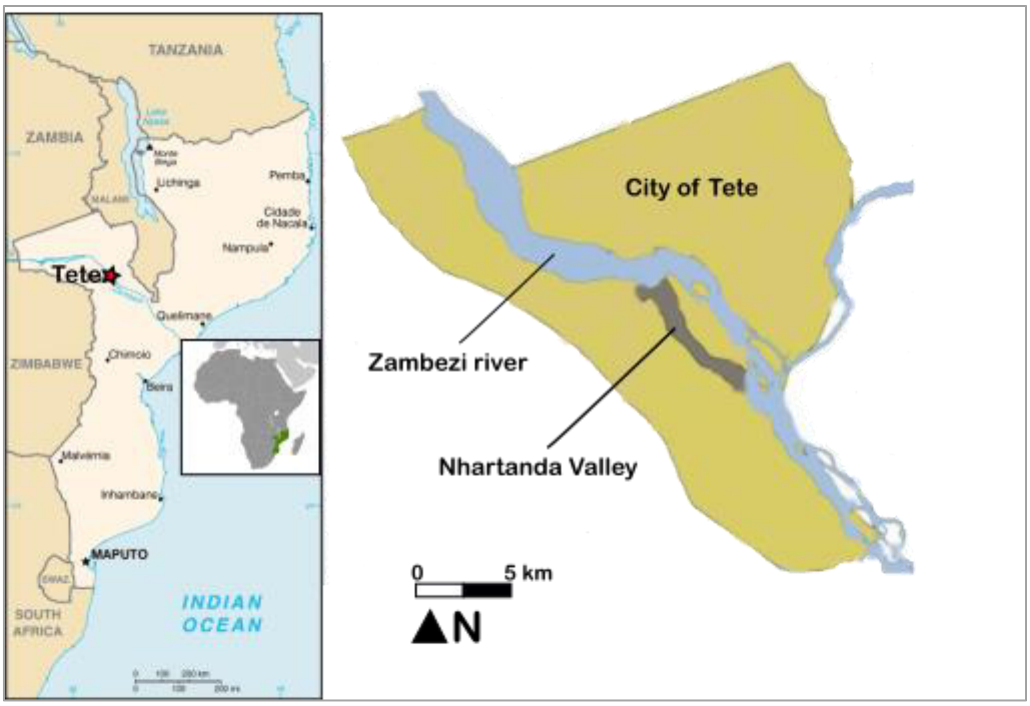


**Figure 1.** Geographic setting of the Nhartanda Valley (City of Tete, Mozambique) and Zambezi River.

City of Tete faces a set of serious structural issues of access to water such as a precarious public water supply system - large losses, pressure drawdown, and lack of investment in the network management, water rationing and a poor sewerage system [17]. Historically, the public water supply in the area relies mainly on surface water reservoirs and groundwater. Nevertheless, repeated droughts have caused groundwater abstraction increase in the last few decades, and it was identified as a risk for the groundwater quality and quantity.

The region is included in the northern Mozambique climatic region, dominated by a typical tropical dry climate [18] and constitutes a typical climatic hotspot facing demographic and groundwater over-abstraction pressures in southern hemisphere countries [19]. The relative air humidity reaches the lowest values at the end of the dry season and its maximum in January/February, where the annual average value does not exceed 65 %. Average annual temperatures are generally high, on the order of 28° C, and annual maximum rainfall rarely reaches or exceeds 800 mm [20]. Frequent climatic extreme events generate urban drainage issues which associated to urbanization implies that large water volumes are not available to recharge local aquifers. The combination of high temperature and low rainfall characterizes this part of Mozambique's zone as one of the most arid in the country. The extreme dryness of this climate results from the weak oceanic influence, coupled with the high average annual temperatures, where the altitude effect is not enough to make the climate wetter [18]. Additionally, the increase of impervious surface due to urbanization causes drainage issues, when frequent climatic extreme events take place, and reduces the recharge of local aquifers.

The study area occurs in the watershed of the Zambezi River. The Zambezi river rises in the mountains of Kalene Hill, northwestern Zambia, at an altitude of 1 450 m. It traverses a total of 2700 km, orientated W-E, and flows into the Indian Ocean in the Zambezian Province (Mozambique). The Nhartanda Valley is a fluvial plain of Zambezi river, orientated NW/SE. The topography of the valley shows a slight slope converging towards the central region.

The occupation of the Nhartanda valley is dominated by agro-livestock activities, residential areas, services and handmade ceramic factories. All the valley area is exposed to diffuse and local pollution sources related to the lack of wastewater treatment plants in the city and adjacent areas of the Nhartanda Valley, which influence the water quality.

Mozambique presents two major geological units: (i) Precambrian, subdivided into inferior or archaic - *Rhodesian Craton* - with 200 Ma, consisting of metamorphic rocks from magmatic and sedimentary protoliths, and Superior - *Mozambique Belt* - with 500 Ma, and (ii) Phanerozoic represented mainly by sedimentary rocks, with 300-700 Ma, and subdivided into: Karroo, Jurassic, Cretaceous, Tertiary and Quaternary [18]. The Nhartanda Valley is composed of Phanerozoic sedimentary formations belonging to the Quaternary [17].

In the valley area, there is a several number of deep drilled wells with very large pumping rates and many shallow wells, most of them illegal, which also presents large pumping rates. This scenario led to dramatic piezometric drawdowns which make evident an unsustainable management of aquifer resources. Otherwise, anthropogenic activities developed along the Nhartanda Valley and adjacent areas may be or become a threat to the groundwater quality and constitute a hazard to the population consuming it directly or indirectly.

### *2.2. Vulnerability Methods*

The GOD vulnerability method determines the intrinsic vulnerability. Hence, it does not consider the type of pollutant. It is based on the designation of indices between 0 and 1 to the following variables: *groundwater occurrence including recharge* (G), *overlaying aquifer lithology* (O) and *depth to groundwater* (D). The index is calculated according to the equation: $V_{index} = G_r * O_r * D_r$ [21-25]. This is an easy and quick assessment method to map the groundwater vulnerability for contamination as the classical models assume some generic contaminants. This model has relatively lesser parameters in comparison to pragmatic models such as DRASTIC.

The DRASTIC method was developed by the US Environmental Protection Agency to evaluate the groundwater pollution potential for the entire USA [26]. It considers the hydrogeological pattern, which depends on the major geological and hydrological factors that affect and control the groundwater flow [27-28]. DRASTIC is the acronym of seven hydrological parameters: *Depth to water* (D), *net Recharge* (R), *Aquifer media* (A), *Soil media* (S), *Topography* (T), *Impact of the vadose zone* (I) and *hydraulic Conductivity* (C). The depth of groundwater is very important because it determines the vertical and/or perpendicular distance which a pollutant must run to reach the aquifer. The vulnerability decreases with the increase of the distance between of surface and groundwater, because deeper water levels imply longer times for contaminants to reach the aquifer. Net groundwater recharge can affect the vertical transport of pollutants to the aquifer and their dilution and dispersion once in the aquifer. It depends on precipitation, topographic slope and soil permeability [29]. Soil texture properties affect the amount of water infiltrated from surface to groundwater levels [30]. Topography also influence groundwater infiltration processes. The decrease of topographic slope reduces runoff, promotes water retention and infiltration and, consequently, increases potential contamination. The potential pollution attenuation of vadose zone depends on its permeability and sediment characteristics. The attenuation processes which may take place within the vadose zone are biodegradation, neutralization, mechanical filtration, chemical reaction, volatilization and dispersion. Those processes tend to decrease with depth. Aquifer hydraulic conductivity determines the velocity of pollutant migration and dispersion once it goes in the aquifer.

The index can be calculated using the following equation:

$$DRASTIC_{index} = D_rD_w * R_rR_w * A_rA_w * S_rSw * T_rT_w * I_rI_w * C_rD_w$$

The rating score (r) varies from 1 to 10, based on their relative effect on aquifer vulnerability, and the weight (w) varies from 1 to 5, reflecting the relative importance of each parameter. It is an index that indicates the potential pollution of groundwater resources. The higher value, the greater pollution risk is (Table 1).

**Table 1.** Evaluation of degrees of vulnerability DRASTIC [31].

| DRASTIC index | vulnerability |
|---|---|
| 1-100 | low |
| 101-140 | moderate |
| 141-200 | high |
| > 200 | very high |

## 3. Results

The GOD index and DRASTIC index have been calculated for wells and boreholes of the Nhartanda Valley area, respectively.

### *3.1. GOD Index*

The vulnerability to water pollution of Nhartanda Valley, through the application of the GOD methodology, varies from medium to high, with a predominance of the highest vulnerability class. In order to allow a more detailed evaluation, these classes were subdivided into subclasses: (i) moderate-medium, (ii) moderate-high and (iii) medium-high. It is observed that 9.1 % of the Nhartanda Valley is considered as an area of medium vulnerability, while 90.9 % is of high vulnerability. Of the latter, 80 % of the area has a moderately high vulnerability.

The areas with a moderate-to-medium vulnerability occur concentrated in the northwest of Nhartanda Valley. That is an area of low population density, which promotes a reduced number of contamination sources. The zones of high vulnerability coincide with recharge areas and central Nhartanda Valley.

### *3.2. DRASTIC Index*

The intrinsic vulnerability to pollution of the Nhartanda Valley aquifer system has been determined by calculating the DRASTIC index value following previously presented methodology. The values for each parameter have been defined according to data of boreholes of the water supply system of the City of Tete. The groundwater depth was obtained from available data of piezometric head of the boreholes just after drilling. Predominant soil texture in the study area are alluvial soils, with a sand-loamy and clay texture, resulted from Zambezi river flood materials. The clay properties contribute to pollutant natural attenuation, increasing the retention capacity of the unsaturated zone and, consequently, decreasing the vertical pollutant movement. The topographic slope in the valley is neglectable. However, the valley is lower than adjacent areas and, thus, contaminants from east and west adjacent areas converge to the valley increasing the groundwater potential pollution. The unsaturated zone of the study area contains altered soil with predominant fine sand, clay and locally silts, and with the depth increase a fine to medium sand material [17].

## 4. Discussion

Evolution of groundwater vulnerability assessment methods over the past 35-40 years reveals that the two index-based qualitative methods - DRASTIC and GOD - that evolved during late-1980s, are the pioneering qualitative methods for groundwater vulnerability assessment [5]. The GOD and DRASTIC methods are very efficient in estimating the vulnerability to groundwater contamination. However, these methods are restricted by qualitative and subjectivity aspects. Nevertheless, they are important tools to be used, especially by decision makers and public administration, in order to decide the activities to be implemented or restricted in an area.

According to the uniformity of study area characteristics, the GOD and DRASTIC vulnerability maps are practically homogeneous. The GOD map is very homogeneous with most of the area with a vulnerability index of 0.63, showing a general high vulnerability. DRASTIC method vulnerability resulted in a qualitative map showing a high and very high vulnerability in the Nhartanda Valley. The vulnerability indices determined by the two methods - GOD and DRASTIC - clearly demonstrate that the aquifer is characterized by a high to very high vulnerability and sometimes can reach extreme levels.

Comparing both vulnerability methods, GOD index considers three parameters in its evaluation, while DRASTIC evaluates seven parameters. DRASTIC methodology is the most detailed analysis, since the knowledge of the studied area will promote a prediction of the subsoil behavior against possible sources of pollution. However, the two methodologies showed a similar vulnerability response to area of the aquifer system of the Nhartanda Valley.

The presence of potential contaminant activities along the valley and adjacent areas associated with Zambezi river pollution contribute to the degradation of water quality. The high vulnerability indexes indicate that water is easily affected by bacteria and viruses and other substances that will contaminate the water, according to defined parametric values for drinking water and agriculture.

## 5. Conclusions

A global risk assessment methodology has been used to determine groundwater vulnerability to contamination from anthropogenic activities in the Nhartanda Valley area. A deep study of hydrological, hydrogeological and land uses of the study area has been carried out. The GOD index and DRASTIC index have been calculated for wells and boreholes of the Nhartanda Valley.

The vulnerability to water pollution of Nhartanda Valley, through the application of the GOD methodology, varies from medium to high. The 9.1 % of the study area is considered of medium vulnerability, while 90.9 % is of high vulnerability. Of the latter, 80 % of the area has a moderately high vulnerability. The vulnerability of the aquifer, through the application of the DRASTIC methodology, varies from high to very high, corresponding to 40 % and 60 % of the area, respectively. The two methodologies have shown a similar vulnerability response in the aquifer of the Nhartanda Valley and have demonstrated that the aquifer is characterized by a high to very high vulnerability.

The presence of potential contaminant activities along the valley and adjacent areas, associated with Zambezi river pollution, contribute to the degradation of water quality. The high vulnerability indexes that water is easily and relatively quickly affected by bacteria and viruses and other substances that contaminate the water, according to defined parametric values for drinking water and agriculture.

A specific set of actions and measures are necessary and urgent for the protection of Nhartanda Valley aquifer; which main function is to provide drinking water to City of Tete population. Those actions must also involve social and environmental awareness of civil society and local population.

The better knowledge of the hydrological and hydrogeological system is essential to support decision makers on sustainable management of the water resources and protection and remediation strategies for the aquifer. The identification of the most vulnerable areas has generated basic information to water use planning, quality control monitoring and designing of measures for aquifer protection and remediation.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Brikić, Z.; Urumović, K.; Briški, M. Post audit analysis of a groundwater level prediction model in a developed semiconfined aquifer system. *Wat Resour Mang* 2013, 27, 3349-3363.
2. Oke, S.A.; Fourie, F. Guidelines to groundwater vulnerability mapping for Sub-Saharan Africa. *Ground Sustain Develop* 2017, 5, 168-177, doi: 10.1016/j.gsd.2017.06
3. Misi, A.; Gumindoga, W.; Hoko, Z. An assessment of groundwater potential and vulnerability in the Upper Manyame Sub-Catchment of Zimbabwe. *Phys Chem Earth*, 2018, Parts A/B/C, 105, 72-83.
4. Allouche, N.; Maanan, M.; Gontara, M.; Rollo, N.; Jmal, I.; Bouri, S. A global risk approach to assessing groundwater vulnerability. *Environ Model Softw* 2017, 88, 168-182.
5. Machiwal, D.; Jha, M.K.; Singh, V.P.; Mohan, C. Assessment and mapping of groundwater vulnerability to pollution: Current status and challenges. *Earth Sci Rev* 2018, 185, 901-927.
6. Hashimoto, T.; Stedinger, J.R.; Loucks, D.P. Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resourc Res* 1982, 18, 14-20.
7. Shrestha, S.; Kafle, R.; Pandey, V.P. Evaluation of index-overlay methods for groundwater vulnerability and risk assessment in Kathmandu Valley, Nepal. *Sci Total Env* 2017, 575, 779-790.
8. Salman, A.; Salman, M.; Arauzo, A.; Elnazer, A. Groundwater quality and vulnerability assessment in west Luxor Governorate, Egypt. *Ground Sustain Develop* 2019, 8, 271-280.
9. Ribeiro, L.; Pindo, J.C.; Dominguez-Granda, L. Assessment of groundwater vulnerability in the Daule aquifer, Ecuador, using the susceptibility index method. *Sci Total Env* 2017, 574, 1674-1683.
10. Kim, Y.J.; Hamm, S.Y. Assessment of the potential for groundwater contamination using DRASTIC/EGIS technique, Cheongju area, South Korea. *Hydrogeol J* 1999, 7, 227-235.

11. Panagopoulos, G.; Antonakos, A.; Lambrakis, N. Optimization of the DRASTIC method for groundwater vulnerability assessment via the use of simple statistical methods and GIS. *Hydrogeol J* 2006, 14, 894-911.
12. Rahman, A. A GIS based DRASTIC model for assessing groundwater vulnerability in shallow aquifer in Aligarh, India. *Appl Geogr* 2008, 28, 32-53.
13. Beaujean, J.; Lemieux, J.M.; Dassargues, A.; Therrien, R.; Brouyère, S. Physically based groundwater vulnerability assessment using sensitivity analysis methods, *Groundw*, 2013, 1-11.
14. Fijani, E.; Nadiri, A.A.; Tsai, F.T.C.; Dixon, B. Optimization of DRASTIC method by supervised committee machine artificial intelligence to assess groundwater vulnerability for Maragheh-Bonab plain aquifer, Iran. *J Hydrol* 2013, 503, 86-100.
15. Sadeghfam, S.; Hassanzadeh, Y.; Nadiri, A.A.; Zarghami, M. Location of groundwater vulnerability assessment using catastrophe theory. *Water Resour Manag* 2016, 30, 4585-4602.
16. Thapa, R.; Srimanta, G.; Shirshendu, G.; Harjeet, K. Sensitivity analysis and mapping the potential groundwater vulnerability zones in Birbhum district, India: A comparative approach between vulnerability models. *Wat Sci* 2018, 32, 44–66.
17. Bande A.D.J.P. Vulnerabilidade em sistemas aquíferos no Vale de Nhartanda, Cidade de Tete, Moçambique. Ms Thesis, Geociências – Valorização dos Recursos Geológicos, Universidade do Minho, Braga, Portugal. 2018.
18. Muchangos, A. Moçambique, Paisagens e Regiões Naturais, Maputo, Moçambique, 1999, 159 pp.
19. Coelho, V.H.R.; Guillaume, F.B.; Montenegro, S.M.G.L.; Paiva, A.L.R.; Almeida, C.N.; Galvão, C.O.; Barbosa, L.R.; Batista, L.F.D.R.; Ferreira, E.L.G.A. Piezometric level and electrical conductivity spatiotemporal monitoring as an instrument to design further managed aquifer recharge strategies in a complex estuarial system under anthropogenic pressure. *J Env Managm* 2018, 209, 426-439.
20. INAM – Tete. Resumo das medias mensais do ano de 2016, 2016, Tete, Moçambique.
21. Foster, S. Fundamental concept in aquifer vulnerability pollution risk and protection strategy. Proc. Intl. Conf. Vulnerability of soil and groundwater to pollution Nordwijk, The Nether-lands, 1987.
22. Robins, N.; Adams, B.; et al. Groundwater vulnerability mapping: the British perspective. *Hydrogeol* 1994, 3, 35-42
23. Gogu, R.C.; Dassargues, A. Current trends and future challenges in groundwater vulnerability assessment using overlay index methods. *Environ Geol* 2000, 39(6), 549-559.
24. Foster, S.; Hirata, R.; Gomes, D.; D´Elia, M.; Paris, M. Protecção da qualidade da água subterrânea: um guia para empresas de abastecimento de água. Órgão Municipais e Agencias Ambientais, S. Paulo, 2016, 114 pp.
25. Shirazi, S.M.; Imran, H.M. et al. GIS-based DRASTIC method for groundwater vulnerability assessment: a review. *J Risk Res* 2012, 8, 991-1011.
26. Aller., L.; Bennett, T.; Lehr, J.A.; Petty, R.; Hackett, G. DRASTIC: A standardized system for evaluating groundwater pollution potential using hydrogeological setting. 1987. U.S. Environmental Protection Agency, Washington DC. 643.
27. Babiker, I.S.; Mohammed, M.A.A.; Hiyama, T.; Kato, K. A GIS-based DRASTIC model assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, Japan. *Sci Total Env* 2005, 345, 127-140.
28. Saidi, S.; Bouri, S.; Dhia, H.B. Groundwater management based on GIS techniques, chemical indicators and vulnerability to seawater intrusion modelling: application to the Mahdia-Ksour Essaf aquifer, Tunisia. *Enviornm Earth Sci* 2013, 70(4), 1551-1568.
29. Ouedraogo, I.; Defourny, P.; Vanclooster, M. Mapping the groundwater vulnerability for pollution at the pan African scale. *Sci Total Env* 2016, 544, 939-953.
30. Khosravi, K.; Sartaj, M.; Tsai, F.T.C.; Singh, V.P.; Kazakis, N.; Melesse, A.M.; Prakash, I.; Bui, D.T.; Pham, B.T. A comparison study of DRASTIC methods with various objective methods for groundwater vulnerability assessment. *Sci Total Env* 2018, 642, 1032–1049.
31. Engel, B.A.; Navulur, K.C.S.; Cooper, B.S.; Hahn, L. Estimating groundwater vulnerability to non-point source pollution from nitrates and pesticides on a regional scale. In: Kovar, K.; Nachtnabel, H.P. (Eds), HydroGIS 96: Applications of Geographical Information Systems in Hydrology and Water Resources Management. Proceedings of the Vienna Conference, International Association of Hydrological Sciences Publications 1996, 235, 521-526.