GIS Applications in Groundwater Protection /Term Paper

Final Paper

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Introduction

In country like Saudi Arabia where no surface waters, groundwater becomes precious resources. Groundwater is area where we don't see and exposes to various types of contaminations. The challenge would be to create informative animations, maps and images that clearly show us the extent and treatment of groundwater contamination.

Geographic Information System (GIS) is used generally for any computer-based tool for mapping and analyzing processes and events that are related by their location. GIS mapping of geologic strata, groundwater contaminant flow, and aquifer vulnerability are critical aids in establishing procedures for groundwater monitoring, for handling of hazardous substances, and designing remediation plans for the clean up of contaminated sites. GIS technology is utilized to developed maps of the hydrogeology and groundwater flow in several places in the world (Bernhardsen 2002).

The applications of GIS in investigating the groundwater vulnerability and contamination will be explored in this paper. Brief explanations of the groundwater and GIS terms will be provided. The paper will contain a case study of investigating the contamination former refinery site using the GIS maps.

GIS Application in Groundwater Volubility

The concept of groundwater vulnerability is a useful tool in planning and decision making and has been used by many professionals and agencies in evaluating groundwater potential for contamination. The main purpose of a groundwater vulnerability assessment is to identify areas where groundwater contamination is likely to occur from activities at the ground surface, relative to other areas; and, therefore, need more monitoring and protection (Barber et al. 1993). Groundwater vulnerability can be defined as (National Research Council 1993): *"The tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer."*

Different approaches are used for groundwater vulnerability assessment, namely, empirical (e.g. DRASTIC), deterministic, probabilistic and stochastic techniques (Barber et al. 1993). DRASTIC is an acronym representing what is believed to be the most important factors that control groundwater pollution potential: Depth to water (D), net Recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone (I), and hydraulic Conductivity (C). Each factor of DRASTIC is assigned a weight based on its relative significance in affecting pollution potential. The most significant factors are assigned weights of 5 and the least significant have weights of 1.

Geographic Information System (GIS) mapping of groundwater flow to model aquifer vulnerability are important aids in establishing protocols for groundwater monitoring, emergency response, and designing remediation plans for the clean up of contaminants. GIS technology is utilized to developed maps (as shown in figure 1) of the hydrogeology and groundwater flow around the studied area using the spatial data and attributes. These maps are used to model the contamination potential of the upper Aquifer, a regionally extensive and highly productive groundwater resource. The hydrogeology or vulnerability map is based on illustrating of the subsurface geology in three dimensions from land surface to the top of the Aquifer. Soils data are also incorporated into the model to better understand how soil enhance or inhibit recharge of groundwater and affect the movement of contaminants. The geologic map is especially effective in delineating land areas that are most/least sensitive to contaminants.
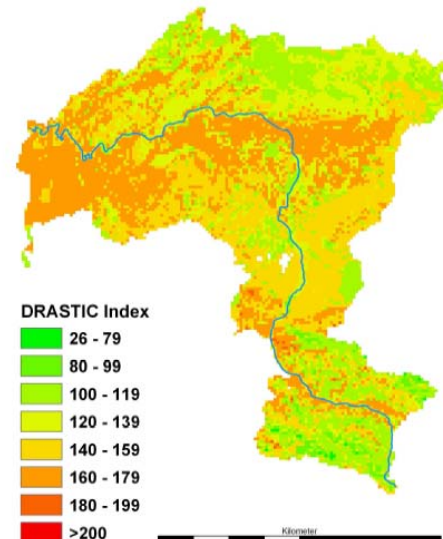

Figure 1: Vulnerability map using GIS

A calibrated 3D groundwater flow model and subsequent detailed flow path and travel time analyses are based on the 3D geologic characterization delineated in the geologic map. The groundwater flow model can be displayed as an ArcView or ArcGIS project. The groundwater travel-time analysis can be used to evaluate the impact of particular land uses on the spread of contaminants introduced at the water table and transported to the upper Aquifer in the dissolved phase (Berkhoff, K., 2006)

GIS tools developed to conduct these analyses and derive the maps have been installed along with the database containing the supporting information.

GIS Application in Groundwater Monitoring and Contamination

The application of GIS in tracing the groundwater contaminant produces endpoints of visualization, sample optimization, and cost-benefit analysis. Visualization uses the software to organize and display site and contamination data. It is good approach to understand current conditions, problems, potential solutions, and eventual cleanup choices. Sample optimization is achieved by selecting the minimum number of samples needed to define a contaminated area within a programmed statistical confidence. Cost-benefit analysis can be applied by either assessing the size of the zone to be remediated according to cleanup goals, or estimating human health risks due to the contaminants. These can be related to costs of cleanup.

GIS provides environmental decision support through its integration of data from multiple sources (i.e., spreadsheet, drawing, and database files) into a platform that

supports query operations, data manipulation and visualization. GIS can generate two-dimensional maps of data and surface features. The 3D Analyst extension provides the capability to layer two-dimensional maps to provide a quasi–three-dimensional representation of site features (e.g., geologic layers, contamination). GIS allows analysts to manage and share their site data using a project file that integrates the different data and visualization files (McDonald, and Harbaugh, 1988). GIS demonstrate the capability of integrating large quantities of data into a visual framework for assistance in understanding a site's contamination problem. The following maps the use of GIS in groundwater contaminations:
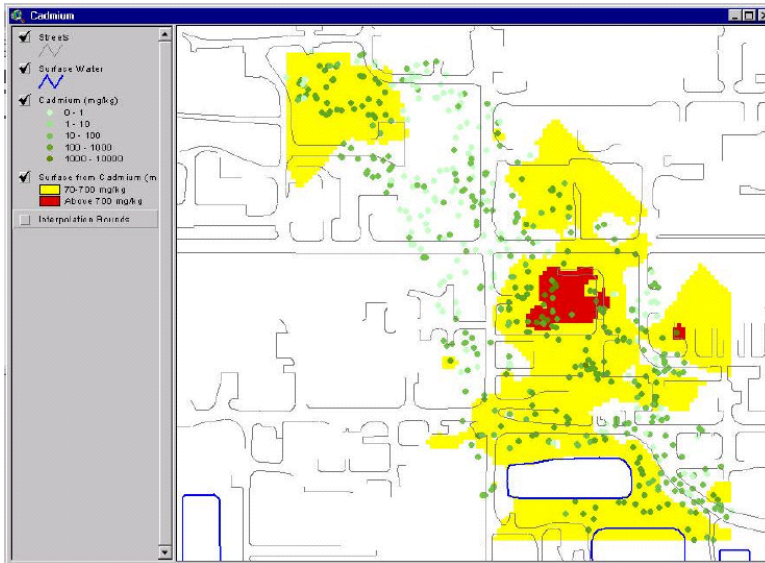

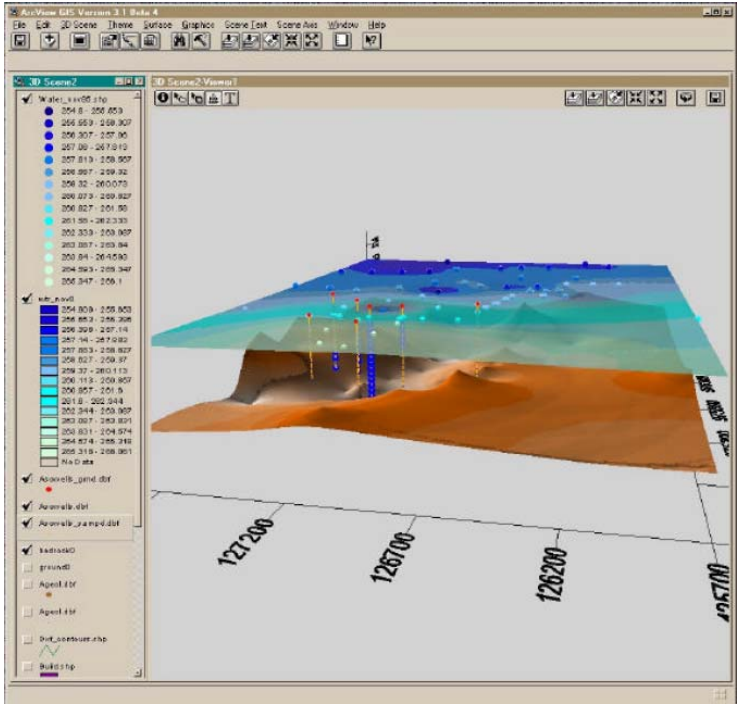Figure 2: ArcView with Spatial Analyst contamination map

Figure 3: A view of bedrock, groundwater levels, and measured
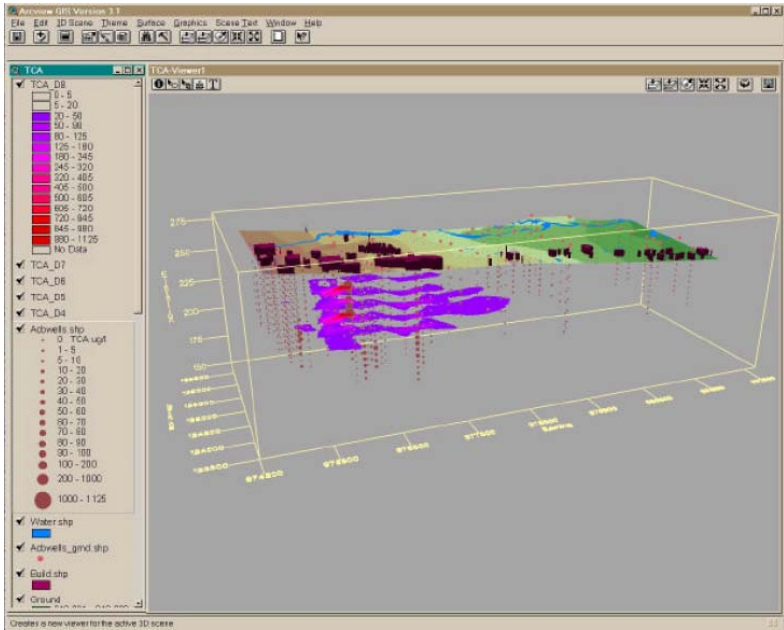contaminant concentrations on ArcView.

Figure 4: ArcView and 3D Analyst side view of the regions with
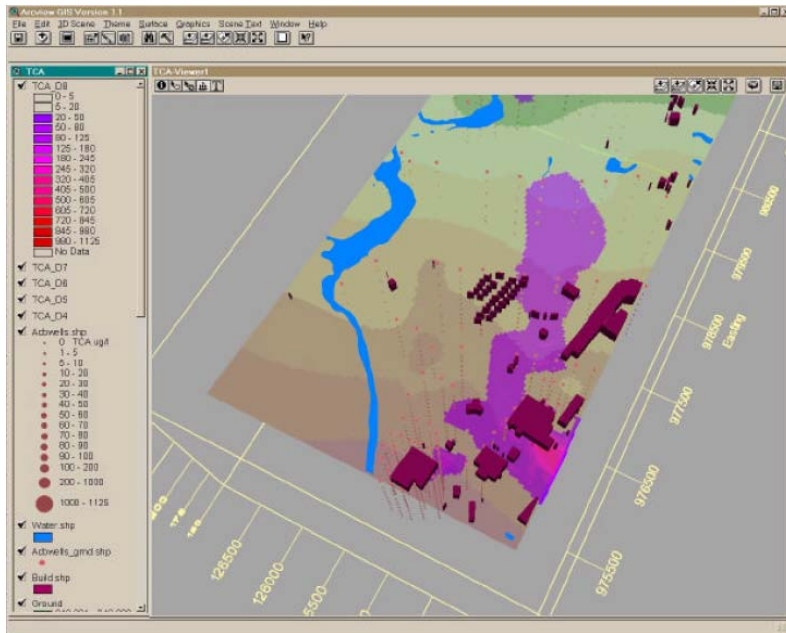groundwater contamination

Figure 5: ArcView and 3D Analyst top view of the regions with groundwater contamination

Integration with other Groundwater Modeling Software

One of the strongest features of GIS is that it integrates with groundwater model software such as MODFLOW and MT3DMS. The generated spatial data such as boreholes, well points and aquifers along with their associated attribute information including aquifer field properties, aquifer base elevation, infiltration data, layered extraction and injection well data, diffusion dispersion data and any other hydrogeologic and geochemical data required for multilayer aquifer analysis, can be entered as fields in feature table of the database. Shapefiles or coverages can then be easily generated from the database and the resulting files directly imported into the groundwater modeling software GMS, in order to run models such as MODFLOW and MT3DMS (Van der, et al. 1997).

A MODFLOW simulation in GMS can be built through either a grid approach or a conceptual model approach. The grid approach involves working directly with a three-dimensional (3- D) grid, applying sources/ sinks and other model parameters on a cell- by- cell basis. The conceptual model approach on the other hand, involves using integrated GIS tools within the map module to develop a conceptual model of the target site. The conceptual model approach in this case, is selected over the grid approach to overcome cell- by- cell editing which is required in the latter (McDonald, and Harbaugh, 1988). The location of sources/ sinks, layer parameters such as hydraulic conductivity, model boundaries and all other data necessary for simulation, can then be defined at the conceptual level. The models are then run for the required cleanup- time to estimate the contaminant concentrations at potential receptors. As the geodatabase is easily updated facilitating simple shapefile/ coverage generation, data is always readily available for

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spatial and temporal analysis required in the model calibration and application phases of groundwater flow and contaminant fate and transport modeling. Geographical output of the numerical results as well as related geospatial features can then be generated and displayed as a result of integration of GIS Spatial Analyst tools into the groundwater modeling. The most significant advantage of integrating GIS with a numerical model such as MODFLOW, however, is the fact that any derived simulation results are already geo- referenced and can therefore be directly displayed. This facilitates visualization of the topological relationships between derived results and other related spatial features, which enhances the analytical process and the ability to make more informed decisions. it is now also possible to publish modeling results and newly generated surfaces via a Web- based client viewer where users can display and query the well data.

In addition, GIS integrates with Surfer to make groundwater contouring through EQuIS. EQuIS for ArcGIS is an extension for the ArcView, ArcEditor, and ArcInfo 8.x desktop applications, allows users to query, report, and map the information found in the EQuIS databases. EQuIS for ArcGIS is ideal for displaying and effectively communicating environmental data integrated with spatial features such as facilities, roads, rivers, etc. Built upon the ESRI ArcGIS 8.x platform, EQuIS for ArcGIS allows for overlay of various map features of both vector and raster data types, including AutoCAD DWG and DXF formats and USGS quad image maps (DRGs - Digital Raster Graphics) (Van der, et al. 1997).

Case Study

Former Petroleum Refinery

A case study illustrates the applicability of GIS, with GIS Spatial Analyst extension, to determine the spatial distribution of potential hydrocarbon migration of Non-Aqueous Phase Liquid (NAPL) at a former petroleum refinery and processing facility where known leaks had produced five separate oil plumes. Site characterization activities at the facility involved the installation of more than 50 soil borings and 35 groundwater wells as shown in Figure 6. Data from these locations indicated that several NAPLs were present at the site, and the plumes varied in composition from fuel oil to diesel fuel. Measured oil thicknesses ranged from less than 0.25 feet to more than 8 feet. In addition, the soils across the site varied from clay to medium sand. To further complicate the situation, the water table at the site varied daily due to tidal fluctuations in an adjacent inlet.
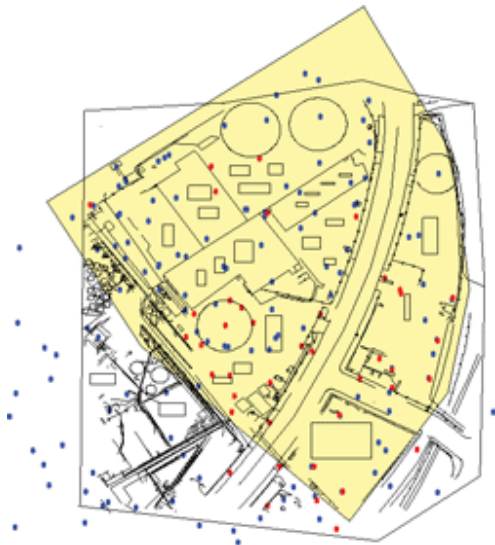
Figure 6: The project site shown with the focus area highlighted in yellow. Red dots represent wells where NAPL was detected, and blue dots represent the wells where NAPL was not detected.

To define the spatially varying complex site conditions, thematic data layers were developed in ArcGIS to define the soil properties as shown in Figure 7 and viscosity distributions as shown in Figure 8. Data layers for product density distributions, free oil saturation distributions, temporally variable water tables, derived gradients from water tables, basemaps, and well locations with relevant attribute data were also developed.
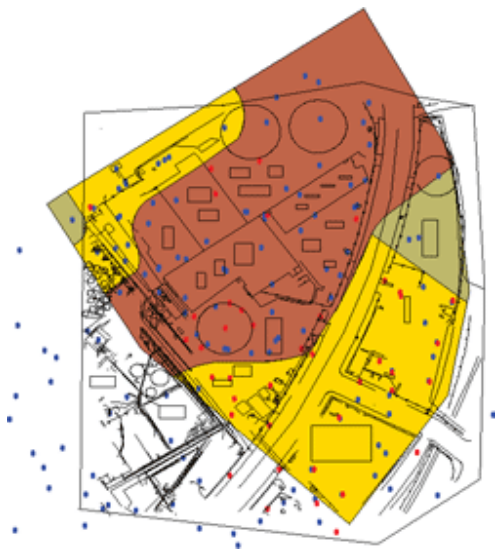

Figure 7: Delineation of soils across the site

Using these data layers, spatial analyses were performed to determine the inherent NAPL mobility and stability across the site. A grid composed of 699,000, one-square-foot cells was defined across the site. For each cell, the inherent NAPL mobility and stability were calculated using various parameters as defined in the thematic layers. This analysis included surface/raster generations, slope and aspect derivations, reclassification,

projection conversions, feature-to-raster conversions, clipping, spatial joins between various thematic datasets, and map and data calculations.
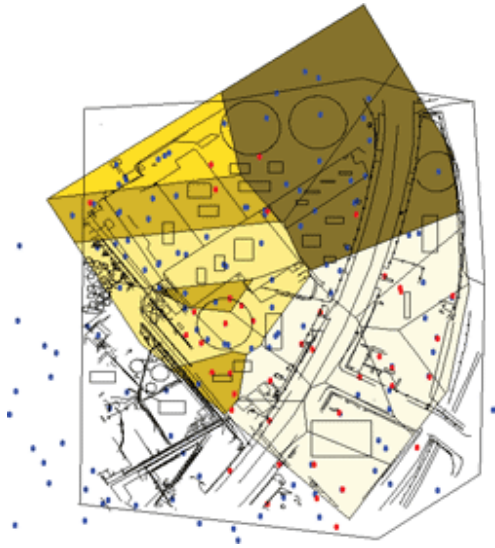

Figure 8: Viscosity distributions across the site

Results of the analysis indicate that the NAPL mobility varies spatially across the site. NAPL saturations in the aquifer range from less than 5 percent to approximately 90 percent, as shown in Figure 9. Four of the five NAPL plumes were determined to have low mobility (i.e., less than one foot per day) and were essentially stable with low migration potential. One plume, which consists primarily of diesel fuel and is located in the sandy portion of the aquifer, was determined to have mobility of 20 to 50 feet per day. Because GIS analysis was conducted on a refined grid, mobile plumes could be characterized into different mobility zones.
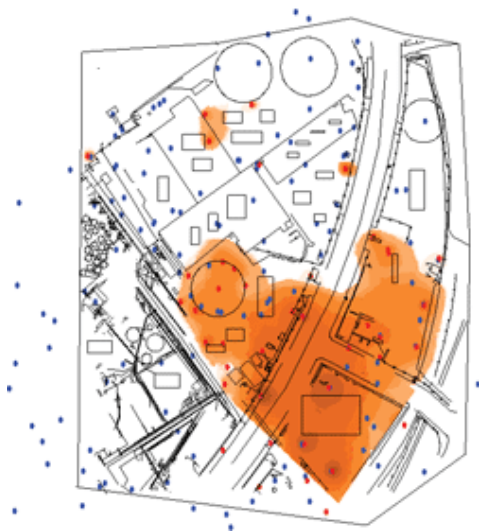
Figure 9: NAPL saturations across the site

By evaluating NAPL mobility, stability, and recoverability spatially using GIS, it was possible to determine the migration potential for each NAPL plume. Spatial analysis enabled an assessment of the potential risk derived from the mobility of the NAPL plume and the potential of NAPL to be recovered from the aquifer. These results enabled more efficient and effective use of resources and considerable savings in addressing the contamination at the facility, because of focused remediation efforts rather than sitewide remediation efforts.

Figure 10: This final map shows mobility across the site. The light brown plume is the only mobile plume among the five plumes.

Advantages of using GIS in groundwater Field

GIS integrates common database operations, such as query and statistical analysis, with the visualization and geographic analysis benefits offered by maps. GIS provides environmental decision support through its integration of data from multiple sources (i.e., spreadsheet, drawing, and database files) into a platform that supports query operations, data manipulation and visualization. GIS can also generate two-dimensional maps of data and surface features. The 3D Analyst extension provides the capability to layer two-dimensional maps to provide a quasi–three-dimensional representation of site features (e.g., geologic layers, contamination). In addition, GIS allows analysts to manage and share their site data using a project file that integrates the different data and visualization files. In addition, the integration of GIS with a numerical model such as MODFLOW

will result in the fact that any derived simulation results are already geo- referenced and can therefore be directly displayed. The more the groundwater systems at installations are understood, the more effectively (and less costly) regulatory compliance can be maintained.

By delineating areas of high aquifer vulnerability, an installation is better equipped to prevent accidental or intentional contamination of that aquifer. Placing of results of the MODFLOW groundwater flow path analyses within an ArcView or ArcGIS platform makes the results much more accessible to environmental professionals.

Conclusion

Efficient management of groundwater resources relies on a comprehensive database that represents the characteristics of the natural groundwater system and modeling tools to describe the impacts of decision alternatives. The integration of GIS and numerical groundwater models will result in the development of decision support tools for groundwater management which has several advantages. GIS provide a considerable number of components that support efficient groundwater modeling and the application of the results. In fact, a numerical groundwater model can be seen as a specialized GIS function (Fedra, and Reitsma 1990).

Accurate mapping of aquifer vulnerability is dependent upon both the proper mapping of geologic sensitivity and the formulation of a realistic groundwater model. The groundwater flow model is the basis for groundwater pathline analyses that predict the major advected trajectory of a dissolved phase contaminant plume.

GIS is an excellent tool to be used in groundwater protection field. Although the many literatures talk about the applications of GIS in groundwater world wide, there is limited utilization of this technology in this field Saudi Arabia. As of Saudi Aramco, there is ongoing project to reflect the groundwater measurement data on GIS.

References

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