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# THE DEVELOPMENT OF INTEGRATED WATER RESOURCES INFORMATION MANAGEMENT SYSTEM IN ARID REGIONS

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*Water and land use tension is growing with the growing population of the world, especially in arid regions. To develop an efficient, sustainable and integrated water and land use resources management policy, accurate and complex information about available resources and demand centers is required. GIS provides a means of representing the real world through integrated layers of constituent spatial information using overlaying and indexing operations. In Abu Dhabi Water Resources Information System (AWRIS) was developed. AWRIS is a centralized, GIS based, Web enabled integrated information management system that allows storage and management of all water resources information. The system integrates a comprehensive set of tools and applications that facilitate the efficient management of the water resources of the Emirate. All historical water resources information from more than ten existing databases, and ten thousand Excel workbooks have now been compiled, quality controlled, and migrated into the central database. AWRIS is built as an Integrated Information Management System (IIMS) and hence designed to improve productivity by linking all relevant applications for data handling into a centralized data repository and management system. This paper outlines the main features of AWRIS, which provides full support for the Arabic language, is the first of its kind in bringing unrestricted data types into a centralized information management system and providing a wide range of tools for effectively managing information on water resources.*

## INTRODUCTION

Countries in the arid regions face the problem of water resources scarcity. The increased rate of urbanization, rapid population growth, and growth in various development sectors led to increase the water demand and worsening of the environment. This phenomenon places a heavy burden on water planners and managers, who struggle to balance competing increased demand for various development sectors with the available scarce water resources while minimizing environmental degradation. In order to effectively manage the water resources on a sustainable basis, planners and managers increasingly rely on the use of information technologies, numerical modeling techniques (Dragicevic et al., 2000), decision support systems (DSS), and databases which help to save, manage and manipulate the existing water related information (Fedra, 1995 and Sugumaran et al., 2000). These information technologies include combinations of remote sensing, geographical information system (GIS), numerical modeling, multi-criteria evaluation, artificial neural network and internet technology. Several researchers demonstrated the use of GIS for improving decision making (Peterson, 1997; Doyle et al., 1998; Peng 1999; Dawoud, 2005; and Sugumaran et al., 2003). Also, data and information required by hydrogeological studies are complex. Information concerning geology, hydrology, geomorphology, climate, land use, topography, and man-made (anthropogenic) features needs to be analyzed and combined. Data are collected from existing databases and maps as well as through new field measurements. Storing data implies data analysis, conceptual design of data models, and data representation. In hydrogeology, because of a limited number of sample locations, point-attribute data also need to be processed by applying adequate kinds of interpolation or modeling algorithms. The derived data also need to be managed.

In the Emirate of Abu Dhabi since 1995, multiple databases have been developed to act as a comprehensive data management tool for site investigation and drilled water well data. For example as part of an earlier assessment on the water situation in the Eastern Region of Abu Dhabi (ERWDA/Mott Macdonald, 2004a) a GIS Water Database (ERWDA/Mott Macdonald, 2004b) was developed. This database, which also includes an interactive water supply and demand model, was designed using Microsoft SQL Server and according to Environmental Agency – Abu Dhabi (EAD) data management standards. Two other water resources database systems were also developed. The first was by the Deutsche Gesellschaft fûr Technische Zusammenarbeit (GTZ), Dornier Consult and Abu Dhabi National Oil Company (ADNOC) during their work in the Groundwater Assessment Project and the second is an Oracle based database utilized by the National Drilling Company (NDC) and United States Geological Survey (USGS) during their work in the Groundwater Research Program. The application of the databases allow the rapid retrieval of any individual item of data and the preparation of water maps such as groundwater table, salinity distribution, aquifer potential, aquifer layers and extent, as well as other features. Work with hydrogeological data and the study of several commercial hydrogeological database schemes, has led to the intent to design the scheme of a new hydrogeological spatial database. A need exists for an advanced structure to be used for different environmental studies and consulting activities as well as research and modeling. The design has to address: (1) data management, processing, and analysis, as well as hydrogeological map production; (2) numerical modeling, as well as overlay and index techniques used in aquifer vulnerability assessment; and (3) support for water authority decision-making processes.

In March 2005 EAD was mandated to manage the water resources in Abu Dhabi, with an emphasis on exploration, monitoring and management of groundwater resources. Among other tasks, EAD identified the management and maintenance of a water information network including all aspects of water sources and its users, and their impact on the environment as one of key contributors to the success of its activities.

EAD's new responsibilities for managing groundwater meant that existing water information systems no longer adequately met the agency requirements in terms of data storage, management, interpretation, assessment and mapping for water resources management. It was therefore required that the existing database be further developed, enhanced in its complexity and functionality, and configured for additional applications to suit the Agency requirements in the fields of water resources management, regulation, exploration, monitoring, assessment, conservation, and protection.

In February of 2006, EAD started the development of the Abu Dhabi Water Resources Information System (AWRIS) with the aim of developing a centralized water resources database. AWRIS is an integrated and centralized data management system that is based on GIS technology. The system is developed in such a way that relevant data is made accessible through the World Wide Web. This paper summarizes the achievements made through this project.

## BACKGROUND

Abu Dhabi, one of seven Emirates that constitute the United Arab Emirates (UAE) is located in the Arabian Gulf as shown in Figure (1). The Emirate has an arid to semiarid climate with less than 100 mm/yr rainfall, 2000-3000 mm annual evaporation and no permanent, reliable surface water sources. It occupies an area of 67,000 km$^2$, 86% of the total area of UAE and has the second highest per capita water consumption after the USA. Population growth rates are currently about 4%/yr and are forecast to rise to 6%/yr, giving a projected 2010 population for Abu Dhabi of about 2.3 million. Table (1) shows that UAE currently uses nearly seven times its renewable water resource (Khouri, 2002). Consequently, there is an ever increasing reliance on unconventional water

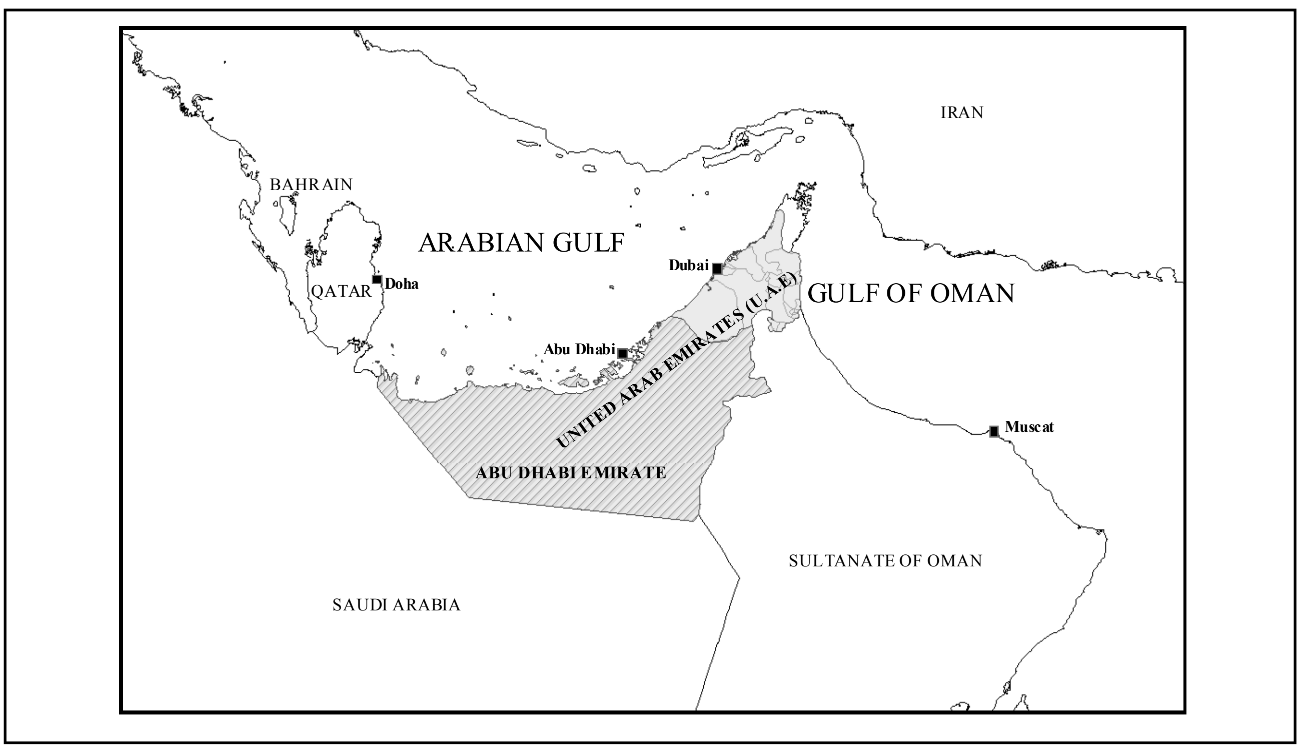


Figure 1. Location of Abu Dhabi Emirate.

Table 1. Water use sustainability in the GCC countries.

| Country | Renewable Water Resource (TR) | Total Demand (TD) | | TD/TR (%) | |
|---|---|---|---|---|---|
| | Year | 2000 | 2025 | 2000 | 2025 |
| U.A.E | 315 | 2180 | 3200 | 692 | 1016 |
| Qatar | 51.4 | 347 | 485 | 670 | 943 |
| Kuwait | 160.1 | 590 | 1400 | 369 | 874 |
| Saudi Arabia | 6080 | 17765 | 24200 | 292 | 398 |
| Bahrain | 100.2 | 282 | 609 | 282 | 608 |
| Oman | 1468 | 1847 | 2430 | 126 | 169 |

resources e.g. UAE is now the second largest user of desalinated water in the Gulf Cooperation Council countries (GCC) after Saudi Arabia.

With the advent of the discovery and subsequent development of oil and gas resources in the 1960's, Abu Dhabi has developed in leaps and bounds. Only 30 years ago, less than 70,000 people relied on traditional water sources from a few hundred shallow dug wells and "aflaj" (gravity fed traditional water canals) and rain harvesting by means of collection in "cisterns". A population growth rate of greater than 4%/yr now gives a present day population of 1.08 million which uses over a billion $m^3$/yr of water. Figure (2) shows that the Emirate's GDP is heavily dependent on revenues from oil and gas exports, but despite lower GDP between 1983-1990, due to depressed international crude oil prices, the per capita consumption of domestic water continued to rise to the present level of nearly 1200 l/c/d (Dawoud, 2009).

Figure (3) shows water sources for the Emirate from 1985 to 2009. Deleterious effects from over-abstraction from groundwater, from the two main aquifer types, alluvial gravels and aeolianite, has meant that the development and use of nontraditional water sources have increased significantly e.g. desalination production has increased from about 100 $Mm^3$/yr in 1985 to >400 $Mm^3$/yr in 2000. Within the UAE and Abu Dhabi there are now only 30 and 10 aflaj respectively, the latter being almost now totally supported by pumping from groundwater. Nevertheless groundwater still accounts for > 60% of all water used, with desalination and recycled water comprising the balance. About 85% of all water sources in the Emirate are used for agriculture (Joudeh, 2001). There are now over 20,000 farms and 1.7 million date palms, 13.8 million other productive trees and 19.6 million nonproductive trees (257,000 ha forestry) and over 300 ha under greenhouse cultivation.

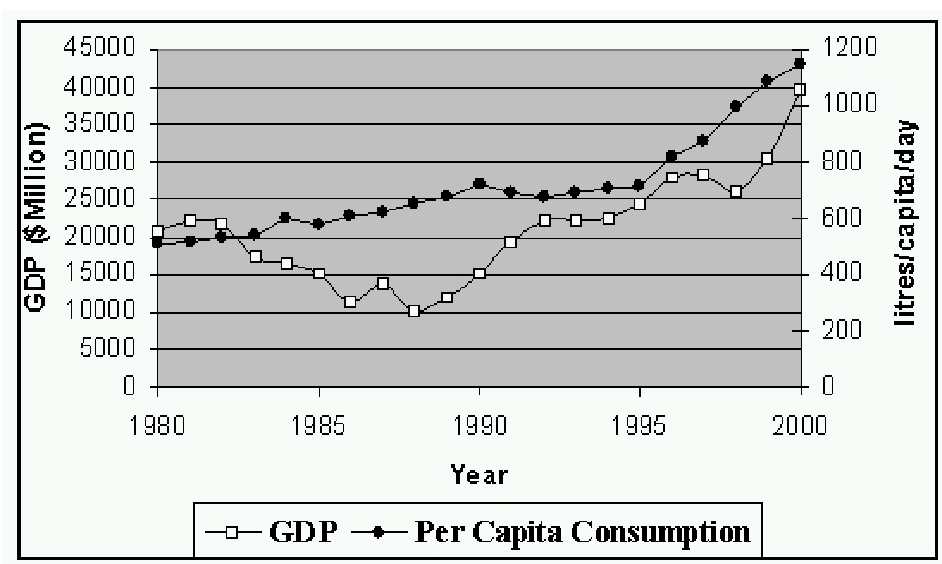


Figure 2. GDP versus per capita domestic water use in Abu Dhabi.

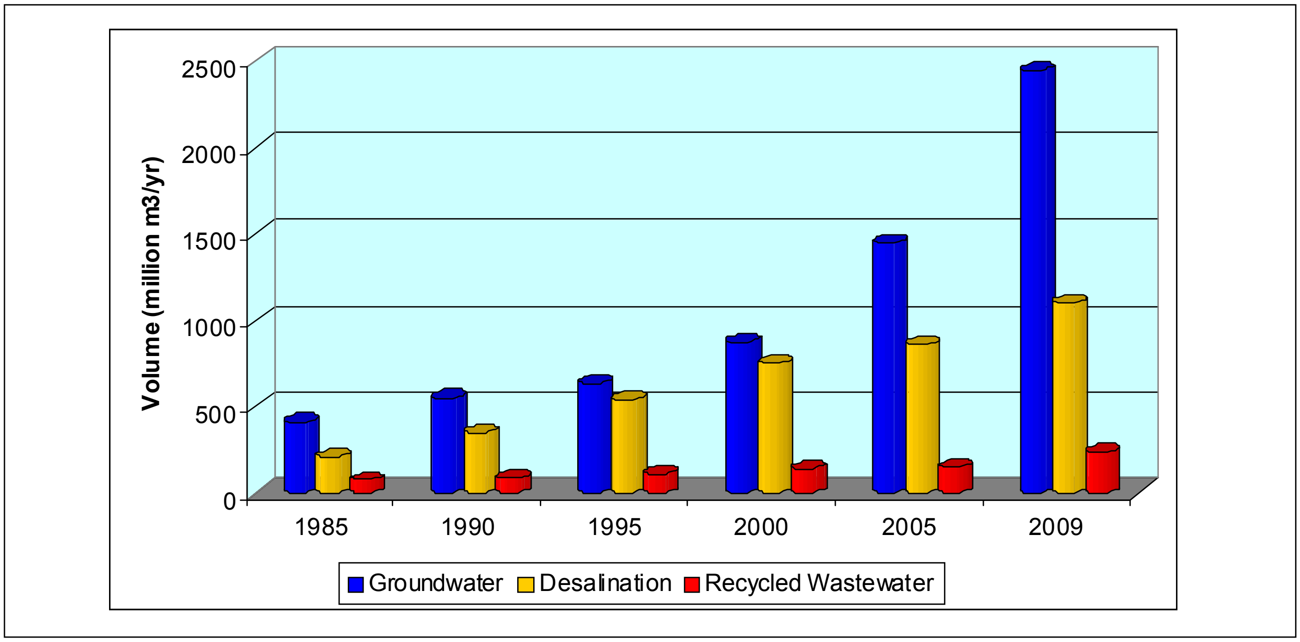


Figure 3. Abu Dhabi Emirate water sources.

Over the last 20 years, the total number or irrigation wells has increased from 5667 to 59124, but the percentage of unproductive wells has also increased from about 10% to now over 25% of the total, reflecting the depletion of aquifer reserves (Dawoud, 2009).

## THE STRUCTURE OF AWRIS

The main goal of data collection is to attain a reasonable understanding of the system that users are interested in. In water resources studies, such activities are undertaken in order to assist in tasks such as resources exploration, exploitation, monitoring, and protection. Figure (4) depicts a typical data workflow in the area of water resources in general and groundwater resources management in particular.

The data workflow depicted in the figure accounts for the complete workflow from data acquisition to reporting. A comprehensive integrated data management should integrate the complete workflow by providing tools and mechanisms for activities ranging from data discovery to delivery. AWRIS, whose architecture is depicted in Figure (5), is designed to cover this workflow by providing the tools from automated data acquisition to automated and dynamic reporting. The system has at its core a central, GIS based, Web enabled database built on the widely used Microsoft SQL Server platform. The database is designed to provide extreme flexibility allowing storage and management of wide range of environmental data types including surface water, groundwater, meteorology, geology, water, soil and air quality, to mention just few.

In addition to integrating various types of data types, the system also brings together a number of tools that can be used to analyze, interpret, and visualize the information. AWRIS features the following main tools:

o Data acquisition (e.g. universal data transfer system, automated data acquisition from data loggers, etc.);

o Analysis tools (e.g. time series analysis, water quality analysis, statistical analysis, spatial analysis, pumping test analysis, etc.);

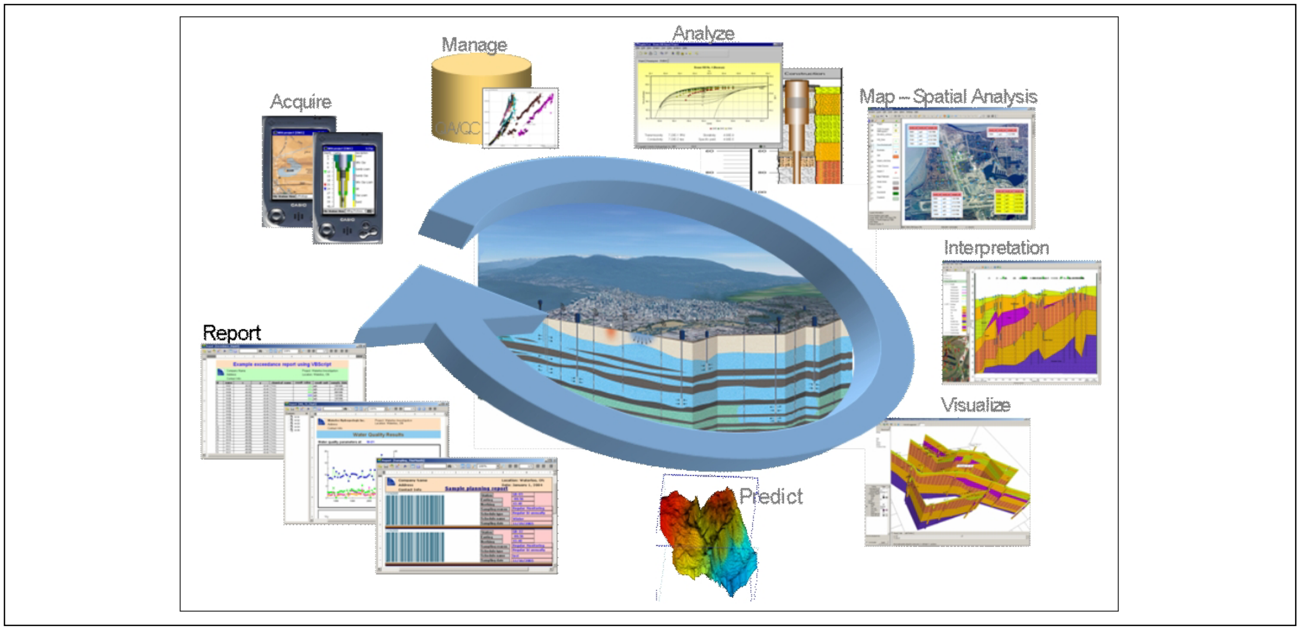


Figure 4. Typical data workflow.

o Interpretations (e.g. cross-sectional interpretation, spatial interpretation, water quality interpretation and modeling, etc.);

o Visualizations (e.g. charting, GIS mapping, borehole logging, 3D fence diagrams, 3D plume display and animation, etc.);

o Conceptual model building environments (Pre-Processor for Visual MODFLOW, FEFLOW and other simulation environments; and

o Comprehensive and Dynamic Reporting.

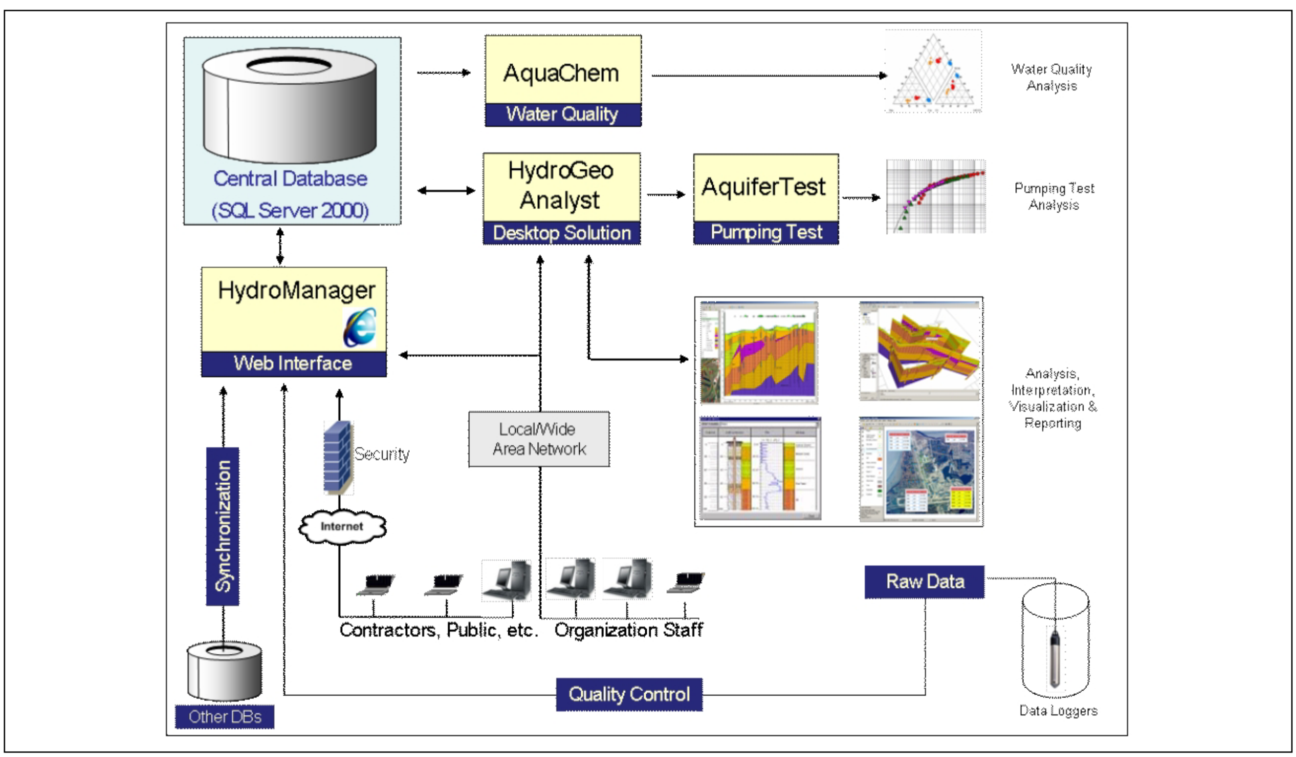


Figure 5. Architecture of data management system for water resources.

## BENEFITS OF THE AWRIS

### Business strategy

There are three main key requirements for managing water resources, namely:

- o A comprehensive water resources monitoring network,
- o Water regulations, and
- o A centralized water information network.

Through this project (AWRIS), EAD aimed at developing a centralized water resources database that will:

- o House all data that is currently available scattered in a number of databases and spreadsheets
- o Store all water resources information that will be collected in the future and hence enhance monitoring and reporting efficiency
- o Build the system to support future activities such well permitting applications and approval processes among others

### Benefits of the system

The system brings numerous advantages to EAD in its effort to efficiently manage the Water Resources of the Emirate. In addition to addressing current issues facing the agency, the proper planning and use of the system opens various opportunities in the future that will enhance productivity.

The efficient use of the system provides EAD with the tools and mechanisms to monitor, control and enforce regulations set to protect the environmental resources. Through AWRIS, the agency now has the provisions to standardize various components of its activities and dealings with all stakeholders. For instance, it is now possible to standardize information exchange formats between drilling firms and consultants and the agency and hence enforce proper reporting of activities that have direct or indirect impact on the water resources of the Emirate.

## DATA MANAGEMENT

### Data Acquisition

Environmental data are collected in various ways depending on the type, frequency, and use. For instance for water quality monitoring at contaminated sites, sampling locations and intervals are designed based on site conditions and the nature of contamination. Samples are then collected from the site often with quality control measures (e.g. duplicate sample collection) taken into consideration. The samples will then be sent to a laboratory for analyses from where results will be sent to the originator.

EAD has established an extensive monitoring network for regular data collection on its water resources and the environment. The network includes groundwater, surface water and meteorological monitoring points most of which are equipped with data loggers. Data from some of these loggers are remotely downloaded through telemetry while regular site visits and manual downloading are required for others. Data gathered from all monitoring locations are imported into the central database through mechanisms provided in AWRIS which support automated and unattended data quality control and importing, as well as traditional ways of manually importing data through rigorous quality control steps.

### Data Storage

AWRIS currently manages information gathered from more than 30,000 monitoring locations. EAD is currently undertaking a well inventory survey which is expected to bring in about 100,000 additional monitoring locations into the central database. The flexibility of AWRIS allows adopting the database structure to any future requirements while continuing to allow all provided tools to function properly even with newly added data types. As the system is implemented in the MS SQL Server platform, database size is only limited by the amount of storage available on the machine where the database is installed.

**Data Analysis**

Analysis tools provide the mechanism to extract essential information from the raw data and in so doing provide insight into the system under study. The type of analysis the HydroGeo Analyst/HydroManager system provides include: statistical analysis, spatial analysis, water quality analysis, pumping test analysis, and time series analysis. All tools are designed to work with data stored in the central database and do not require exporting or formatting of the data. Data can be accessed directly and/or through queries and hence allow various levels of intermediate data processing prior to data analysis. For instance if spatial analysis of statistically aggregated data (e.g. average water level over a specified time and specified area) is desired, data can be aggregated through the statistical analysis tools provided and passed to the spatial analysis tools all within the same system.

If spatial analysis of statistically aggregated data (e.g. average water level over a specified time and specified area) is desired, data can be aggregated through the statistical analysis tools provided and passed to the spatial analysis tool all within the same system. As these tools are working with live data stored in the central database and not with a copy, all updates to the database are reflected on all analysis tools in an automated manner hence a significant amount of time is saved. The HydroGeo Analyst/HydroManager system is integrated with the world renowned water quality analysis and modeling system, AquaChem. Similarly the pumping test analysis system, AquiferTest Pro, is used for pumping and slug test analyses. Both these tools are seamlessly integrated with the system as shown in Figure 6.

**Data Interpretation**

Most of the interpretation tools provided in the system are focused on groundwater resources. These tools include the borehole log plotter and cross-section interpretation component. Both tools provide environments whereby subsurface data including geophysical investigation results,

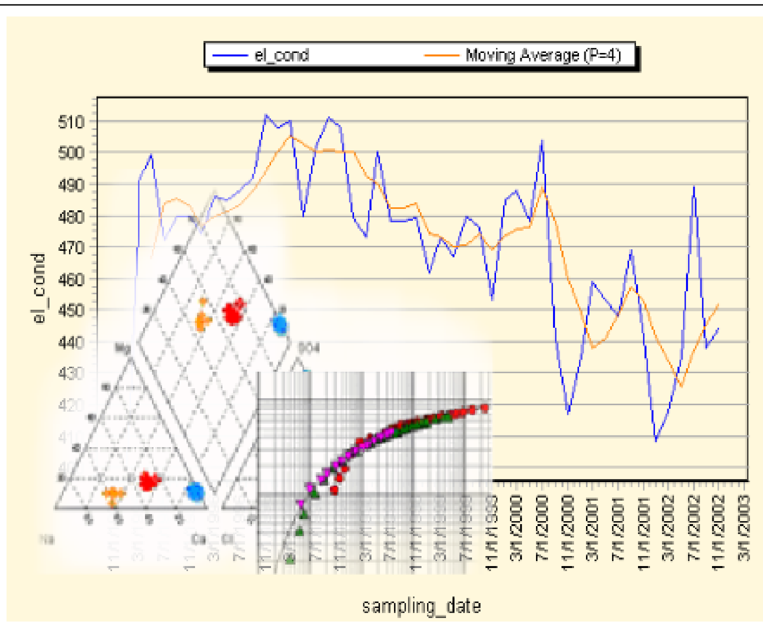


Figure 6. Example of analysis results

water quality profiles, geology, water levels, etc. can be displayed and interpreted by hydrogeologists. Users have the ability to make cross-sectional interpretations based on lithology, hydrogeology and model layers. As such the system is also referred to as a conceptual model building environment.

## Interpolation method for borehole logs

Geological and geotechnical data with borehole logs are irregularly distributed in horizontal and vertical directions. Therefore, the automatic contouring method is required to reveal the diverse subsurface structures. Many contouring methods have been proposed so far, which regarding their principles can be classified into two categories. The first method is a global fit algorithm (Kane et al., 1982) termed approximation. The usual global algorithm is trend surface analysis, which reveals a regional trend in samples (or measured) data through the weighted least squares method. The regional trend is expressed by a polynomial or a double Fourier series (Davis, 1973). In this method, weighting coefficients are assigned to each data point according to the statistical property of sample data. The second method is a local fit algorithm termed interpolation, which constructs a curved surface passing through or very near to every sample value.

Interpolation methods using the principle of minimum curvature (Briggs, 1974), the spline function (Casanova and Alvarez, 1985), and kriging (Journel and Huijbregts, 1989) are included in the second group. For the present analysis, the optimization principle method proposed by Shiono and others (1987) is examined, because the method is applicable to construct a complicated model from sample data with obscure spatial correlation. The optimization principle is based on the criterion of constructing the smoothest surface, and is analogous to the minimization problem of mechanical potential energy. We extend the method for data with coordinates in three-dimensional space as follows.

Initially, a cubic mesh of constant spacing is superimposed over the volume containing the sample data as shown in Figure 7. For the simplification of expression, let the dimension of mesh to be unit. Suppose the coordinate of sample data is $(X_r, y_r, Z_r, d_r: r = 1 \ldots\ldots n,$ where $n$ is the number of data, and $dr$ represents data value), the interpolated value at each grid point is $f_{ijk}$ $(i = 1 \ldots\ldots n_x;$ $j = 1 \ldots\ldots n_y;$ $k = 1 \ldots\ldots n_z;$ $n_x, n_y, n=$ are number of grid points along the x, y, z axes, respectively) and the function $f$ is the desired model. The extended objective function $Q(f; m_r, m_2, co)$ is defined to obtain the function $f$. $Q(f; m_1, m_2, w)$ is expressed by a linear combination of the functional $Q(f, m_1, m_2, w)$ which evaluates the smoothness of the $f$, and the penalty function which is the squared summation of residuals between the sample value and the estimated value. Figure 8 shows the resulting groundwater borehole from the system.

$$Q(f, m_1, m_2, w) = m_1 \iiint \left\{ \left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2 + \left(\frac{\partial f}{\partial z}\right)^2 \right\} dxdydz + m_2 \iiint \left\{ \left(\frac{\partial^2 f}{\partial x^2}\right)^2 + \left(\frac{\partial^2 f}{\partial y^2}\right)^2 + \left(\frac{\partial^2 f}{\partial z^2}\right)^2 + 2\left[ \left(\frac{\partial^2 f}{\partial xdy}\right)^2 + \left(\frac{\partial^2 f}{\partial ydz}\right)^2 + \left(\frac{\partial^2 f}{\partial zdx}\right)^2 \right] \right\}$$

$$+ \omega \sum_{r=1}^{n} \left\{ s(x_r, y_r, z_r) - d_r \right\}^2$$

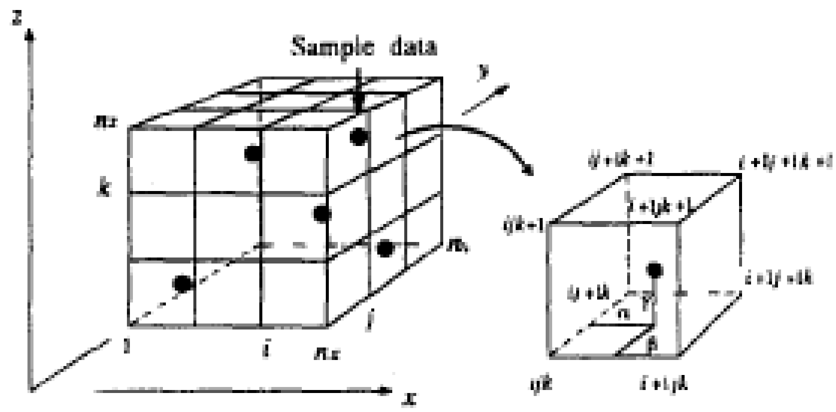


Figure 7. Setting of cubic mesh of constant spacing over the volume containing the sample data.

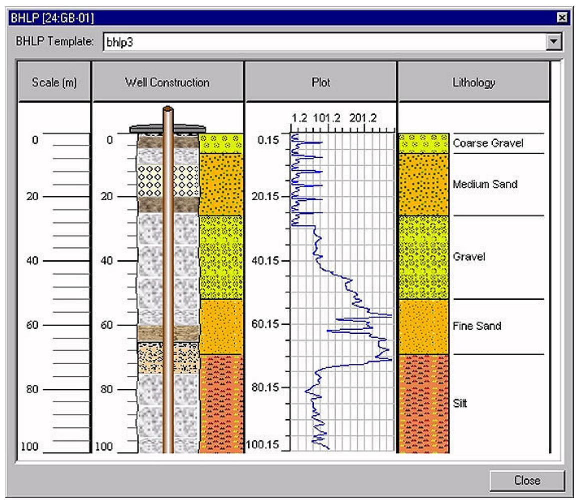


Figure 8. Example of borehole logs.

## MAPPING AND REPORTING

### GIS Mapping

Environmental data is inherently spatial and as such the use of GIS for handling of such data is of paramount importance. However, most GIS environments in existence do not provide the ability to connect all environmental data to the GIS in an integrated manner. The AWRIS provides GIS that is integrated with the central database. The system allows displaying, analyzing and interpreting all relevant data right from the central database with all resulting information stored back in the same system while provisions are made for exporting such information to other systems and/or locations.

The GIS in AWRIS provides a comprehensive set of functionalities most of which are not found in most GIS environments. For instance any data can be queried and displayed on the GIS map in tables for each desired station. The tables are connected with their corresponding stations through a customizable callout box. Data in these tables can be compared to either fixed value or values in other columns and exceedances can be highlighted in a desired color. Figure 9 depicts a typical view of a GIS map showing summary tabular data along with time series plots. As the GIS system is integrated with the database, all such displays are optionally dynamically updated as updates to data are obtained. Also contour maps can be created for any spatial distributed parameters such as groundwater levels, salinity, topography, etc. as shown in Figure 10.

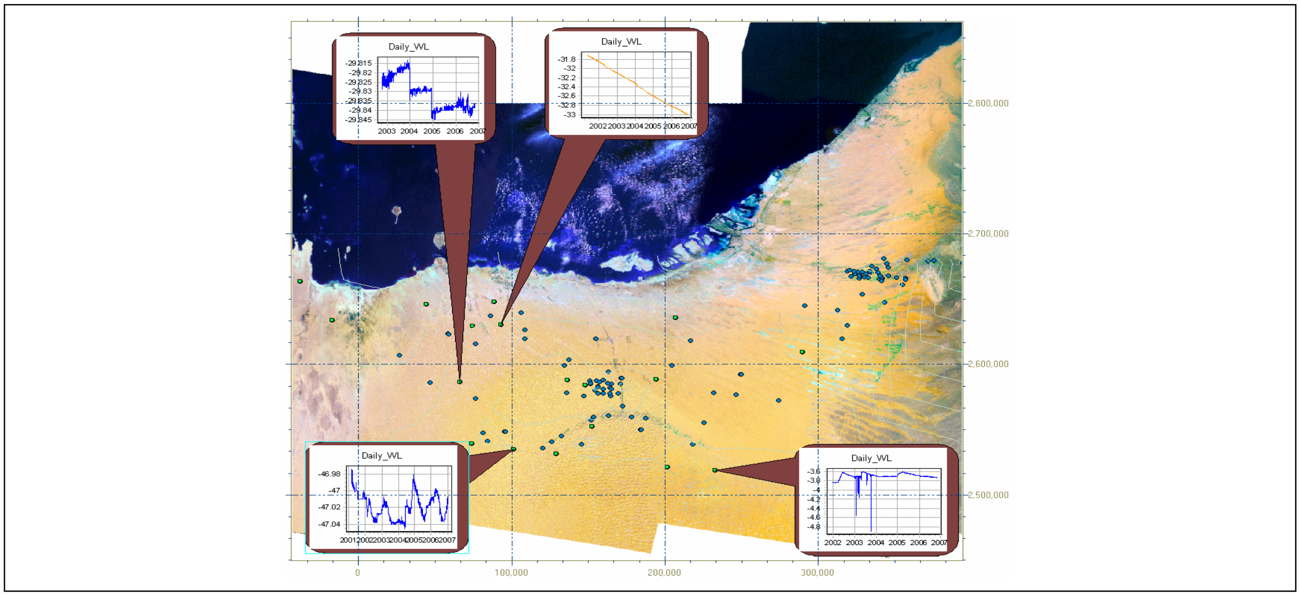


Figure 9. Tabular and time series data display in AWRIS.

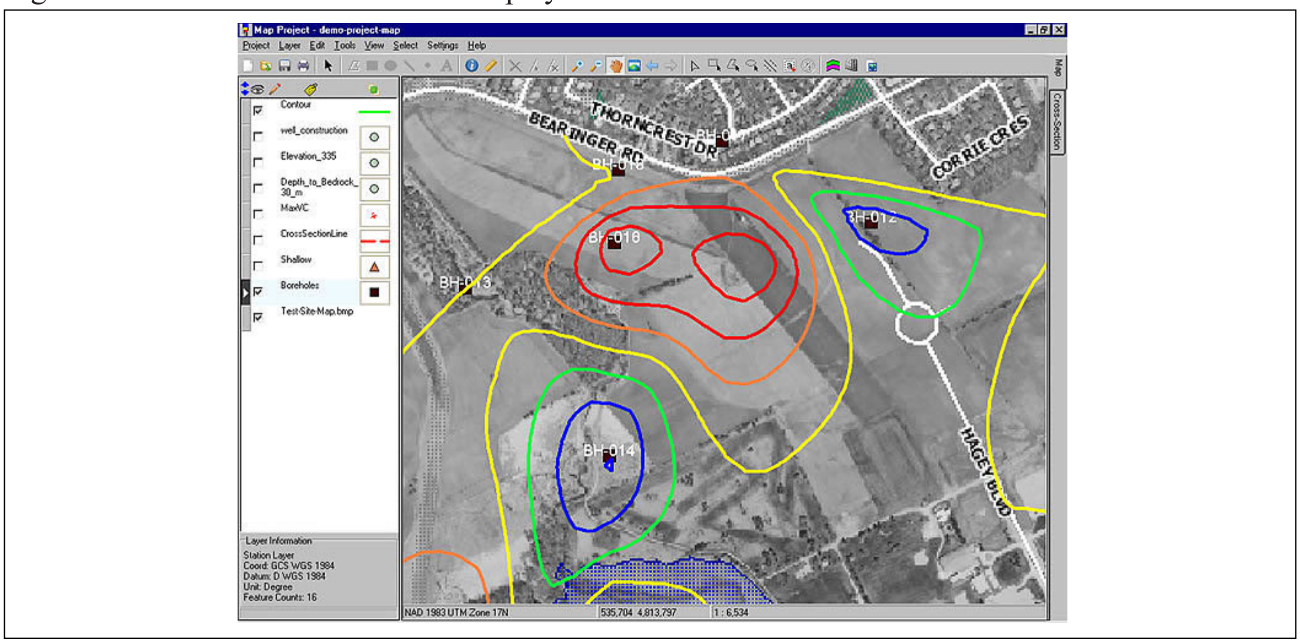


Figure 10. GIS contour maps.

## 3D Visualization

HydroGeo Analyst comes with a powerful 3D visualization system. The system allows for displaying fence diagrams, surfaces (e.g. topography, water level, etc.), time series of plumes, and wells. Transient plumes can be created for any chemical that has historical data. The system allows for recording of 3D plume animation into a standard video format that can be displayed at various media outlets including power point presentations. Figure 11 depicts a typical two dimensional cross-section showing various types of information.

Plumes can be projected on any plane allowing visualization of water quality data across selected boundaries. For instance when dealing with contaminated sites, the system allows tracing the historical progression of the chemical(s) of concern. Plume projection can also be made along any cross-section line that is digitized on the map and displayed as a fence diagram as shown in Figure 12.

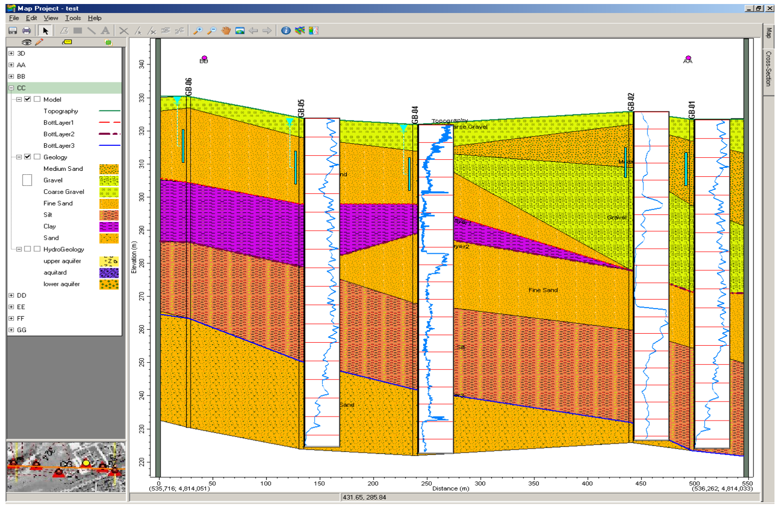


Figure 11. Typical cross-section interpretation in HydroGeo Analyst.

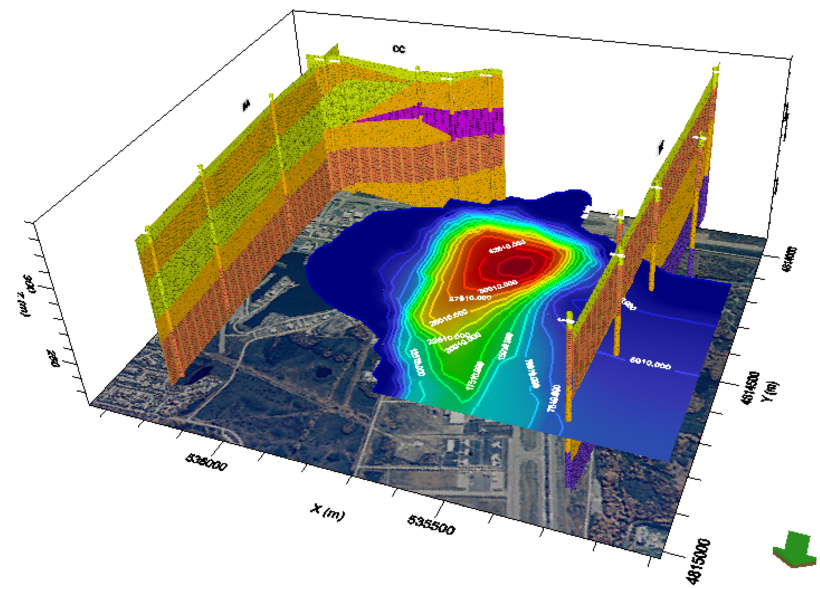


Figure 12. Typical 3D depiction of a fence diagram and projected plume.

## REPORTING

HydroGeo Analyst offers a dynamic reporting system that is used for reporting all raw as well as processed data. The report works on the principle of “design once” and “use often”. Tabular reports displaying data as well as water quality standards can be generated and displayed. The system provides advanced features that allow for comparison of data to standards. Optionally all data in violation of specified standard(s) can be highlighted in various ways. Most data displayed on the report module can be updated dynamically again allowing for automated updating of reports. The report module may be used to generate multiple pages of report reporting data from multiple stations at once.

The report design can be stored and used whenever necessary while the generated reports can be exported to various formats for storage. The formats that are supported by HydroGeo Analyst include: rich text format (RTF), portable document format (PDF), hypertext markup language format (HTML) among many others. Figure 13 depicts sample reports that are generated through HydroGeo Analyst.

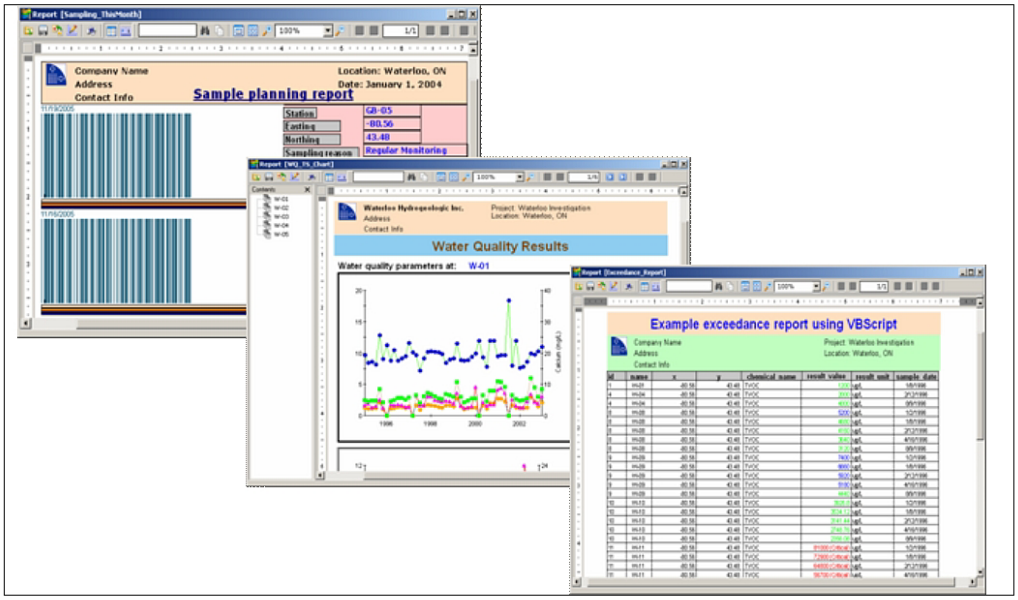


Figure 13. Sample reports.

## DATA ACCESSIBILITY OVER THE INTERNET

All raw data as well as analysis, interpretation, and visualization results are made available over the Internet through the web interface provided in AWRIS. The web interface is built upon a flexible and yet user friendly web based data management system. It allows for navigation of results produced through all the other modules provide in AWRIS as well creation of ad-hoc queries and reports over the Internet.

AWRIS provides a customizable user interface including provision of choice of a desired language(s) for all user interfaces as well as data components. It comes with modules such as document management, project management, automated data acquisition through telemetry, alarms and notifications, to mention a few.

## CONCLUSIONS

The AWRIS provides an unparalleled environment for integrated water resources information management. The system integrates:

1. All types of environmental and water resources data; and
2. A wide range of tools for analysis, interpretation and visualization of the data.

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