A GIS APPLICATION FOR REMOTE SURVEILLANCE OF GROUNDWATER CONTAMINATION

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ABSTRACT

Current advances in wireless technology supported by the development of customized GIS applications, can significantly enhance field data collection, processing and visualization in environmental research. A distributed wireless sensor network was designed to collect and remotely transmit data in real-time to an in-house geodatabase, to monitor the long-term natural attenuation of groundwater contamination. The integrated software application includes automated control of water quality sensors with built-in mobile agents, for scheduling data collection and testing sensor integrity. Sensor-derived parameters can then be used to generate a predictive model using GIS to characterize the wells and determine potential impact on the surrounding environment.

INTRODUCTION

According to the United States Environmental Protection Agency (U.S. EPA), natural attenuation is defined as "the naturally occurring processes in soil and groundwater that act without human intervention to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in those media". These processes include biodegradation, dispersion, dilution, sorption, precipitation, volatilization, and chemical or biological stabilization, transformation, or destruction of contaminants.

The efficiency of natural attenuation in organic contaminants mainly depends on the biodegradation process. Biodegradation of chlorinated solvents brings about measurable changes in the chemistry of groundwater in the affected area and by measuring these changes, it is possible to evaluate and document efficiency of biodegradation. Some of the monitored analytical parameters include: chlorinated solvents and their daughter products, dissolved oxygen, nitrate, manganese, sulfate, iron, methane, chloride, oxidation-reduction potential and alkalinity. Measurement of the electron acceptors available in an aquifer is critical in identifying the predominant microbial and geochemical processes that are occurring or have occurred at the time of sample collection.

A major portion of the costs incurred during the remediation of a contaminated site are during site characterization and monitoring and very often, inadequate or inappropriate monitoring techniques result in a high level of uncertainty in the efficiency of clean-up at sites. It is for this reason that better monitoring tools and instrumentation be developed. Currently, staff and students of the Hemispheric Center for Environmental Technology at Florida International University are investigating the development of innovative multiparameter probes, which are designed to collect and remotely transmit real-time measurements of some of the major parameters of interest during remediation. Conventional sampling and monitoring methods tend to disturb the target environment, however, the concept of wireless sensor networks was developed with the intention of addressing this problem by providing in-situ, undisturbed, real-time data. These units are meant to be deployed within the monitoring wells and include automated controls for scheduling data collection and testing of sensor integrity. Sensor derived parameters can then be used to generate a predictive model using Geographic Information Systems (GIS) integrated with mathematical models such as MODFLOW and MT3DMS in order to assess the feasibility of natural attenuation as a remedial option. These sensor parameters can also be used to validate and update the model.

WIRELESS SENSOR NETWORKS

Distributed Wireless Sensor Networks are basically data-gathering networks which are designed specifically to facilitate end users who require a high-level description of the target environment. Data collected by these networks is highly correlated and thus enables reliable water quality monitoring. They are also easy to deploy, have a long system lifetime and low-latency transfers. This is a very different paradigm to traditional wireless networks that require point-to-point connectivity, have uncorrelated data and often rely on a fixed infrastructure. The purpose of designing wireless sensor nodes is to enable monitoring of remote areas, as in many cases contaminant plumes tend to be spread over a large geographical area, making it extremely difficult to deploy a wired network of sensors under such conditions to monitor groundwater contaminant levels.

Sensor Nodes and Clusters

A sensor network is comprised of a series of node clusters. Each cluster is made up of sensors deployed individually within a series of adjacent monitoring wells which are located within a specified distance of each other (Fig.1). Sensors are powered by a built-in battery and consist of transmitting units that communicate with the base station. The base station is the essential communication unit for the entire sensor network, which controls the reception and transmission of data back and forth. A clustering infrastructure allows data from the nodes within a cluster to be processed locally, and a distributed algorithm randomly selects a cluster-head that aggregates the data from each sensor node within that cluster, sending a single transmission to the geodatabase representing a dataset for that cluster of wells (Fig. 2). Data aggregation techniques such as this facilitate the combination of several correlated data signals into smaller datasets (effective data) of the original signals, so less actual data needs to be transmitted from the cluster to the base station which results in considerable energy savings.

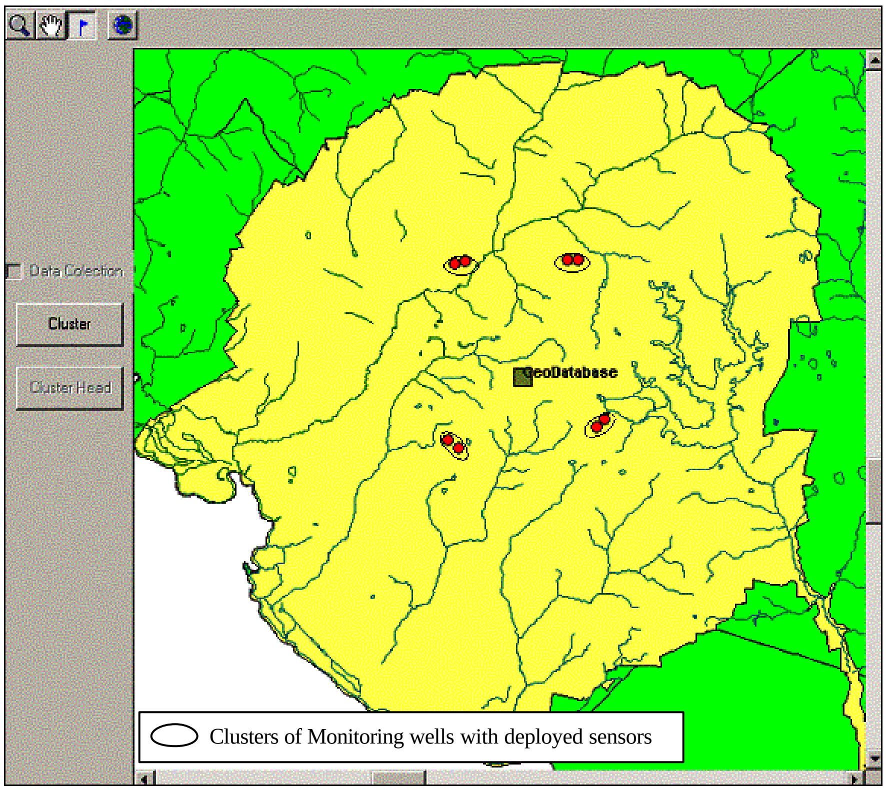

Figure 1: Contaminated site showing Sensor Network Clusters

The distributed algorithm enables the sensor nodes to be able to detect others within the distance specified and hence are able to make the autonomous decision to form clusters without any centralized control. This generates a fixed cluster formation. The advantages of this approach are that no long-distance communication with the base station is required and distributed cluster formation can be achieved without knowing the exact location of any of the nodes in the network. As the clusters are fixed, there is no continuous set-up overhead which would be required if clusters had to be formed and reformed. There is great energy efficiency in this approach as the only variable is in the cluster-head position that randomly rotates, which is also controlled by the same algorithm based on simulated annealing done by the base station. Cluster-head nodes are more energy intensive than non-cluster-head nodes, hence cluster-head rotation is significantly important. In a scenario where the nodes are energy-limited, if the cluster-heads were chosen a priori and fixed throughout the system's lifetime, the cluster-head sensor nodes would quickly use up their limited energy. In this case, if the cluster-head runs out of energy and is no longer operational, then all the nodes that belong to that cluster lose communication ability. Random rotation of the cluster-head among the different nodes therefore helps to avoid draining of individual node batteries. In this way, the energy load in being a cluster-head is more evenly distributed among the nodes. In addition to this, the cluster-head node knows all the cluster members so it can create a TDMA (Time Division Multiple Access) schedule that tells each node exactly when to transmit its data. This allows the nodes to remain in the sleep state with internal modules powered down as long as possible to conserve energy. Using a TDMA schedule for data transfer also prevents intra-cluster collisions.

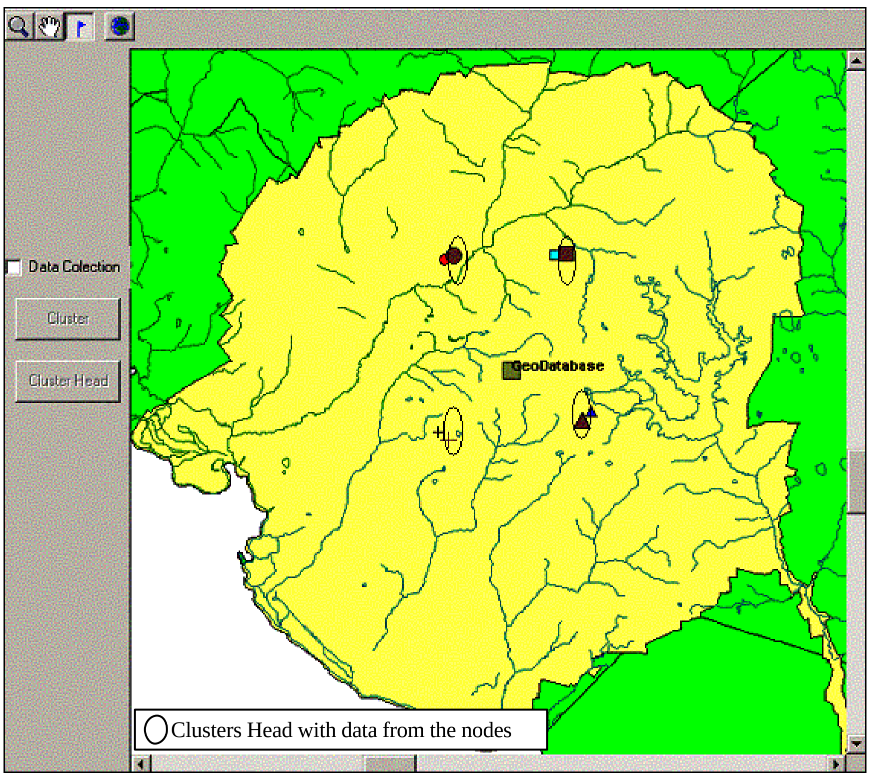

Figure 2: Diagram showing randomly selected cluster-heads

Testing Sensor Integrity

The most important design feature of networks such as this is a mechanism to monitor the existence and health of the sensors involved. The base station is primarily responsible for controlling this by analyzing such information and responding appropriately. There are two types of faults that may be detected, the first related to the network health status and the second related to the events the network has been designed to monitor. These faults may be determined via either explicit or implicit detection. Explicit detection occurs when a sensor is able to detect an event that can affect its physical integrity. If this occurs, the sensor is able to send out an alarm that is, by default, directed to the base station via the cluster-head. Implicit detection is inferred by a lack of communication from a particular sensor suggesting that the sensor is faulty and disconnected from the network for some reason. As the system has been designed such that the sensors continuously send messages of their existence to the base station via the cluster-head, the base station should always be able to actively monitor network integrity.

While there are advantages of using the fixed distributed cluster formation algorithm, there are inherent problems to be considered as far as problem detection is concerned. This infrastructure is unable to detect the lowering battery life of the nodes in the cluster and hence cannot determine when a battery needs to be replaced until implicit detection, where there is no longer any communication from the sensor. Although the system has not employed the use of any such device, it would certainly be an advantage to develop a mechanism by which an alarm is triggered once the energy level of a battery falls below a certain level, to ensure replacement in a timely manner and avoid any break in transmission. The fixed nature of this type of cluster formation also does not facilitate the addition of new nodes in the event that other wells are added.

Simulation of Data Collection by the Sensors

A simulation was created using the front-end graphical user interface (GUI) of Visual Basic with MapObjects control to demonstrate these concepts. ESRI has described MapObjects as a tool to add dynamic mapping and GIS capabilities to existing Windows applications or build custom mapping and GIS solutions. With the aid of MapObjects, when the designed application is initiated, a shapefile representative of the target site appears and points representing the associated monitoring wells are created using the "create new event" tool. Once the well layer is generated, clusters are formed using the specialized "cluster" tool that initiates the algorithm to form clusters. The sensor nodes of each cluster are represented with different shapes and colors in order to differentiate which node belongs to which cluster. Next the cluster-head algorithm is triggered by the "cluster-head' tool in order to assign a node from each cluster as the cluster-head and once a node is chosen, it glows and grows in size. MapObjects is extremely helpful in developing this type of graphical representation. Data collection is then initiated by checking the related check box allowing data to flow from the individual nodes to the cluster-head (Fig. 3). Aggregated data in the cluster-heads is then forwarded to the base station and entered into the geodatabase. This type of simulation is controlled by a timer function and again MapObjects enabled showing the movement of data from the cluster-heads to the base station. This simulation can also be continuously repeated in order to depict the random selection or rotation of cluster-heads.

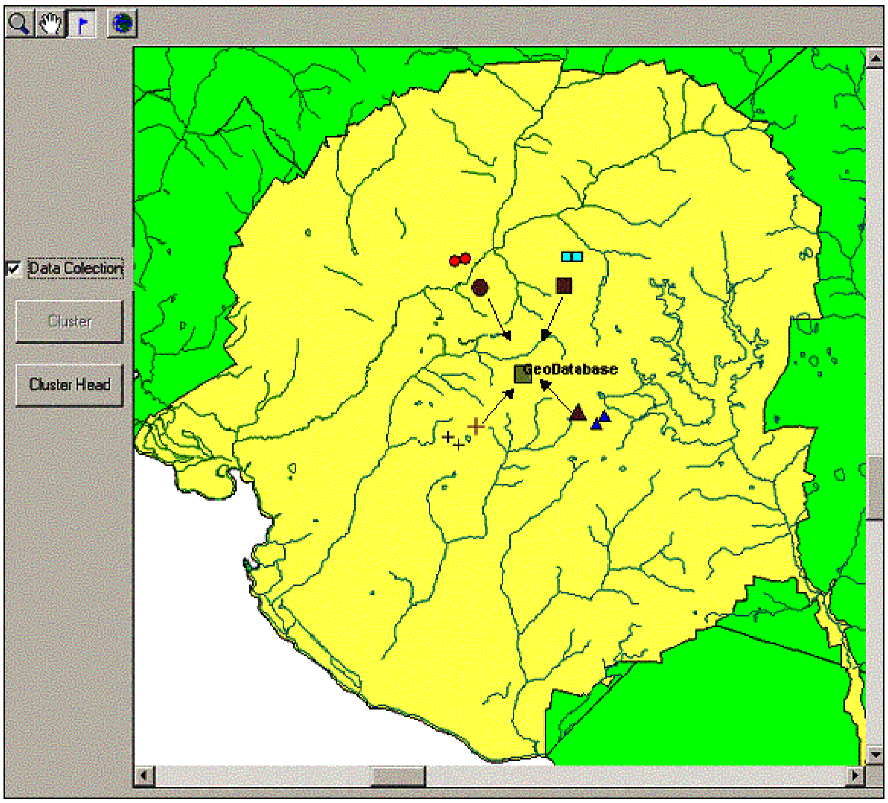

Figure 3: Cluster head data transmission to the base station

DATA ANALYSIS AND VISUALIZATION VIA INTEGRATION OF GIS INTO THE MODELING ENVIRONMENT

Sensor derived measurements collected in the field, are wirelessly transmitted to an in-house geodatabase via the sensor network described. A geodatabase is simply a modernized version of a database management system (DBMS) which allows the storage of both attribute and spatial/geographic information. Previously 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, may be entered as fields in each theme feature table of the database. Additional fields can then be generated to accommodate the field parameters measured by the sensors and transmitted to base. This new innovation developed by ESRI (Environmental Systems Research Institute) is a far superior structure for storing and managing spatial data and helps to simplify data management tasks. Shapefiles or coverages can then be easily generated from the geodatabase and the resulting files directly imported into the groundwater modeling software GMS 4.0, in order to run models such as MODFLOW and MT3DMS.

A MODFLOW simulation in GMS can be constructed 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. 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 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 ArcView 3.x and ArcView Spatial Analyst tools into the modeling environment. 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. With the inception of ESRI's Internet map server application ArcIMS, 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.

CONCLUSION

Although this GIS application for remote surveillance of groundwater contamination is still in its developmental stages, it should be tested within the next coming year. Generating a conceptual model should prove advantageous by improving the efficiency of deployment in the field and high-level representations of the target site should enhance the modeling process and the accuracy of results. Finally, utilization of a geodatabase and integration of GIS within the modeling environment will allow input data to be shared more easily between processing systems.

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