Remediation time frames are normally fixed by a number of management and regulatory issues without consideration of the interaction between remediation cost and the time constraint. This work looks at the implications of the time constraint by considering time as a decision variable in the optimization process. We utilize a multi-objective optimization of a hypothetical contaminated aquifer that results in a trade off curve of total remediation time vs. remediation costs. This curve allows decision makers to view the full range of options for time and cost. The cost function includes treatment, pumping and management costs. The multi-objective problem is formulated to minimize the design cost while also minimizing the remediation time. The Niched Pareto Genetic Algorithm (NPGA) has been modified to allow enforcement of water quality constraints. The addition of this constraint enforcement is developed by two methods. The first method initiates a penalty in the fitness values as the enforcement mechanism. The second uses the niching domination to apply the constraint. Each of these methods is innovative in remediation optimization work. Comparisons of the two methods are presented. Three sets of numerical computational experiments are performed to produce tradeoff curves of cost and total time. The experiments increase in computational effort as the complexity of the time variables increases. In each experiment the cost objective will be a function of pumping rate. The first experiment will use a single management period, where total time is the decision variable. The second will use multiple management periods of fixed length, where the number of management periods is the decision variable. The third will have the number of management periods and the length of the periods as decision variables. This method of investigation in to the impact of time as an optimization variable incorporates the full range of management possibilities. Comparisons of the three experiments are presented as tradeoff curves of total remediation time vs. cost.

H11C MCC: Level 2 Monday 0830h

Recent Advances in GIS and Data Visualization in Regional-Scale Groundwater Modeling I Posters

Presiding: **C Zheng,** University of Alabama**; P Hsieh,** U.S. Geological Survey

H11C-0877 0830h POSTER

Use of GIS and Data Visualization Tools for Modeling Aquifer Architecture and Generating Aquifer Vulnerability Maps at a Regional Scale

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The Grand Forks aquifer aquifer is one of the first aquifers in the province of British Columbia to undergo a full hydrogeologic characterization because of its importance as a water supply. It is also being used as a case study area for modelling the impact of climate change on groundwater. The aquifer consists of a layered sequence of glacial and alluvial sediments overlying bedrock, which from the top down are comprised of gravel, sand, silt and clay. Aquifer hydrostratigraphy was defined based on some over 300 water well records contained from in the BC Ministry of Water, Land and Air Protection Water WellWELL Database. Lithology data were first standardized to correct errors in syntax, grammar and spelling, recognize equivalent terms, and classify the materials into dominant types so that calculations involving the database could be more easily undertaken. Standardized data have beenwere then used to construct an aquifer architecture model that can be used as input to a numerical groundwater flow model and to construct a vulnerability map. The three-dimensional aquifer architecture model was developed in the data visualization software (GMS) by first constructing cross-sections, and later, generating a solid model that represents the layering and spatial heterogeneity of the aquifer. The bedrock surface was modeled using geostatistical techniques to produce a bedrock digital elevation model (DEM) that better constrains the lower bound of the model. Layers were imported into the numerical groundwater flow code, Visual MODFLOW, and are being used to model current climate conditions and climate change scenarios for the Grand Forks region. A GIS was also used to capture the spatial variability in the input parameters that are used to construct vulnerability maps. Using the DRASTIC approach, indices were assigned to each of seven hydrogeologic parameters. A rastor map was generated for each. A digitized soils map was used to assign soil material and soil topography indices to soil polygons. Indices for depth to water, aquifer media at the water table, aquifer conductivity and impact of vadoze zone were derived from well lithology data, and were interpolated within the GIS to provide a continuous surfaces. Spatial variability in recharge reflects both natural recharge and estimates of return flow from water pumped to irrigate cropsirrigation. The rastor maps for each parameter index were weighted and added togethersummed to produce the DRASTIC vulnerability index map. The use of GIS and data visualization software is invaluable for effectively managing the volume of data and representing spatial variability in regional aquifers.

H11C-0878 0830h POSTER

Automated Geographic Simplification Tools for Development of Regional Scale Groundwater Flow Models

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The analytic element method is well suited for modeling regional scale saturated groundwater flow. Recent advances enable the solution of models with tens of thousands of hydrogeologic features over scales of hundreds of kilometers. In order to implement such models, automated techniques are desired to translate regional scale conceptual models and/or readily available hydrologic base maps into model features. A suite of tools derived from standard cartographic generalization operators have been developed to perform these simplification tasks. Highly detailed digitized surface features (e.g. river and lake boundaries) are simplified into representative elements and strings of elements using algorithms designed to capture important geometric and physical properties. These simplified models are more computationally efficient and achieve similar (often nearly identical) results. In addition, a general framework for application of simplification operators to vector-based numerical models has been developed.

URL: http://www.groundwater.buffalo.edu

H11C-0879 0830h POSTER

Enhancement of Aquifer Vulnerability Indexing Using the Analytic Element Method

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Indexing methods are used for the evaluation of aquifer vulnerability and establishing guidelines for the protection of ground-water resources. The principle of the indexing method is to use map layers of various influences on ground water to determine the overall vulnerability of an aquifer to anthropogenic stresses. The analytic element method (AEM) of ground-water flow modeling can be used to enhance indexing methods by rapidly calculating a potentiometric surface based primarily on surface water features. This potentiometric map can be combined with a digital elevation model to produce a map of depth to the water table. This is an improvement over simple water table interpolation methods because it is physically based and properly represents surface water features, hydraulic boundaries, and changes in hydraulic conductivity. The AEM software, SPLIT, is used in a geographic information system based graphical user interface to improve an aquifer vulnerability assessment for a valley-fill aquifer in western New York State. A GIS-based graphical user interface allows automated conversion of hydrography vector data into analytic elements.

H11C-0880 0830h POSTER

Application of GIS and Visualization Technology in the Regional-Scale Ground-Water Modeling of the Twentynine Palms and San Jose Areas, California

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Application of GIS and visualization technology significantly contributes to the efficiency and success of developing ground-water models in the Twentynine Palms and San Jose areas, California. Visualizations from GIS and other tools can help to formulate the conceptual model by quickly revealing the basinwide geohydrologic characteristics and changes of a ground-water flow system, and by identifying the most influential components of system dynamics. In addition, 3-D visualizations and animations can help validate the conceptual formulation and the numerical calibration of the model by checking for model-input data errors, revealing cause and effect relationships, and identifying hidden design flaws in model layering and other critical flow components. Two case studies will be presented: The first is a desert basin (near the town of Twentynine Palms) characterized by a fault-controlled ground-water flow system. The second is a coastal basin (Santa Clara Valley including the city of San Jose) characterized by complex, temporally variable flow components - including artificial recharge through a large system of ponds and stream channels, dynamically changing inter-layer flow from hundreds of multi-aquifer wells, pumping-driven subsidence and recovery, and climatically variable natural recharge. For the Twentynine Palms area, more than 10,000 historical ground-water level and water-quality measurements were retrieved from the USGS databases. The combined use of GIS and visualization tools allowed these data to be swiftly organized and interpreted, and depicted by water-level and water-quality maps with a variety of themes for different uses. Overlaying and cross-correlating these maps with other hydrological, geological, geophysical, and geochemical data not only helped to quickly identify the major geohydrologic characteristics controlling the natural variation of hydraulic head in space, such as faults, basin-bottom altitude, and aquifer stratigraphies, but also helped to identify the temporal changes induced by human activities, such as pumping. For the San Jose area, a regional-scale ground-water/surface-water flow model was developed with 6 model layers, 360 monthly stress periods, and complex flow components. The model was visualized by creating animations for both hydraulic head and land subsidence. Cell-by-cell flow of individual flow components was also animated. These included simulated infiltration from climatically variable natural recharge, interlayer flow through multi-aquifer well bores, flow gains and losses along stream channels, and storage change in response to system recharge and discharge. These animations were used to examine consistency with other independent observations, such as measured water-level distribution, mapped gaining and losing stream reaches, and INSAR-interpreted subsidence and uplift. In addition, they revealed enormous detail on the spatial and temporal variation of both individual flow components as well as the entire flow system, and thus significantly increased understanding of system dynamics and improved the accuracy of model simulations.

H11C-0881 0830h POSTER

GIS integration in applied ground water resource modeling

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Groundwater modeling employs spatially distributed data in the construction of models as well as in the presentation of the models to vested interests and decision makers. Numerous commercial groundwater modeling interfaces have attempted a GIS like integration within the modeling system, with some what limited success. We will show a complete modeling development-execution-result analysis procedure which is fully rooted in a GIS environment. All model setup/input as well as results are in a GIS, thus easing access and applicability. A key aspect of the process is that the resulting model is independent of the modeling code. The procedure utilizes spatially distributed information on soil type, climate and land use to develop maps and time series for recharge. At the same time a geological editor integrated in a GIS interface is used

to develop a geological model. Calibration information is also placed in the GIS. Information regarding surface water bodies, drainage, and so on is translated to the model framework within the GIS. Geospatial queries and SQL programming are used to translate these to a modeling grid. The GIS is utilized in developing input to and processing results from particle tracking modeling for well fields and critical river reaches. Maps of for example ground water age, which formations contribute to the flow system, and degree of utilization (sustainability) are easily available. Furthermore, as the results are integrated in a GIS this improves analyses as well as capabilities to communicate results to vested interests and decision makers.

H11C-0882 0830h POSTER

The Use of Geographic Information System Technologies in a Groundwater Model of the Chicot Aquifer System

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The flexibility and scalability of a regional scale groundwater model can be improved by utilizing Geographic Information Systems (GIS) technology in all aspects of the modeling effort. A groundwater model of the Chicot aquifer in southwestern Louisiana is currently being developed to assist in the development and management of the groundwater resource. Georeferencing the model allows model developers to incorporate different types of data, often from different sources, following a single coordinate system. For example, the Louisiana Department of Transportation and Development (LADOTD) maintains a GIS water well database that allows water wells to be easily incorporated into the model as analytical element wells; this database can be combined with a specified pumping rate based on the category of use and spatial location of the well. GIS also allows for non-point data such as geological structure and hydrogeological parameters (e.g., storage, recharge, etc...) to be incorporated into the model and easily updated as more detailed information and data becomes available. In terms of scalability, the modeler can decide how detailed and what data is considered important in the model; the use of GIS allows for the information and data to either be represented as specific or lumped features. This capability is being utilized through the use of telescopic mesh refinement (TMR) to model parish-scale sections of the aquifer system. The presentation will show how GIS technologies have allowed for a vast amount of information and data to be incorporated into the Chicot aquifer regional groundwater flow model and how the use of GIS has allowed for continual model improvement through the incorporation of more accurate spatial data. Finally, we will show how rainfall data and remote sensing data, identifying the location of agricultural fields, can be combined to improve our ability to accurately incorporate irrigation-related groundwater pumping into the model.

H11D MCC: Level 2 Monday 0830h

Natural Attenuation at the Fringe: Reactive Zones in Biodegrading Groundwater Pollution Plumes Posters *(joint with B)*

Presiding: **D N Lerner,** University of Sheffield**; T Ptak,** University of Tuebingen

H11D-0883 0830h POSTER

Vertical Transverse Dispersion Controls the Natural Attenuation of Spatially Variable Plumes

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Many, if not most organic contaminant plumes are spatially variable. This presents a challenge for natural attenuation assessment using traditional methods that rely on monitoring along plume centrelines that are necessarily assumed to be unique. An alternative approach is to characterise the processes that control attenuation, and delineate where those processes occur within the plume. For example, carbon turnover in many organic plumes is constrained to biodegradation at the plume fringe where contaminants mix with electron acceptors. This mixing is influenced by concentration gradients of organics (out of the plume) and oxygen and nitrate (into the plume), and vertical transverse dispersion. Where plumes consist of complex mixtures of organics, an added factor is the preferential degradation of certain compounds (target or non-target organics) due to various microbiological concerns. Accurate prediction of natural attenuation of such plumes may be possible if spatially discrete carbon turnover processes are considered in the context of spatial plume variability. A transect of four highly detailed multilevel sampling wells were installed across a well-studied tar acid plume migrating within the Triassic sandstones in the UK Midlands. The goal of these wells was to locate the upper plume fringe and quantify degradation within those zones. The multilevel sample ports were 20 cm apart to characterise both electron acceptor and donor profiles in great detail. The primary contaminants within the plume are the phenolics (phenol, xylenols, cresols), but other compounds are present that impose a demand on electron acceptor supply (tar neutrals TEX, C4-C8 benzenes, benzofuran and tar bases pyridines, picoline, aniline). The bioactive zone appears to be constrained to a narrow zone less than 1 m thick wherein all dissolved oxygen and nitrate are consumed, with phenol persisting to depth, consistent with weak vertical mixing due to weak dispersion at the scale of diffusion. The vertical position of this fringe varies in space, suggesting that natural attenuation cannot be accurately estimated by extrapolating the reactive processes quantified at one location to the plume as a whole.

H11D-0884 0830h POSTER

High Resolution Multi-Level Monitoring and Characterization of NA Processes

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Monitored natural attenuation is a potentially valuable risk-based remediation strategy for contaminated groundwater. The most important mass-removal process for natural attenuation is biodegradation. Certain zones or fringes of a contaminant plume offer enhanced conditions for biodegradation: microbes, nutrients, contaminants and electron donors / acceptors are not only found together but also in the required reaction ratios. Due to this fact these areas show a relative rapid degradation and provide a significant contribution to the overall reduction of mass within the plume. As can be shown by high resolution numerical simulations of reactive transport in groundwater, the spatial distribution of these highly reactive zones, compared to the volume of the whole plume, is quite small and characterized by steep concentration gradients, which can not be detected using standard monitoring procedures. High resolution multi-level sampling (MLS) in the order of 0.1m or less is an essential prerequisite for the investigation of NA processes within the reactive fringes at field scale. This contribution presents results from ongoing research on high resolution MLS at six field sites in different European countries. The focus was on an optimized site-specific hydraulic design and contaminant - MLS-material interaction. Most acceptable solutions (which means MLS resolution in the order of 0.1m) were found using sampling tubes with a small inner diameter (3-4mm). This results in a small stagnant water volume prior to sampling, but is still not problematic with respect to the flow induced hydraulic losses within the tube. Another requirement for high resolution sampling was to abandon standard sampling protocols (DIN, EPA, *ldots*) which often demand huge groundwater volumes (1 liter) for every single compound to be analyzed. To estimate the effects of the tubing material on the quality of the groundwater samples, an analytical model by Reynolds et al. (1990) was used to study the sorptive uptake of different organics by different tubing polymers, considering partitioning coefficients, intra-polymeric diffusion coefficients and tube-surface to tube-volume ratios.

H11D-0885 0830h POSTER

Determination Of Transverse Dispersivities At Lab Scale: Conservative Transport And Steady State Reactive Plumes

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Effective remediation of contaminated ground water by Natural Attenuation relies on the ability to predict and quantify the processes that occur in contaminant plumes. Transverse mixing is a significant mechanism for the fluxes of electron acceptors and donors and thus may control the lengths of steady state plumes. Especially reactive mixing, which is governed by pore-scale processes, must be well understood at the local scale. This work aims to systematically investigate the influence of aquifer material properties, e.g grain sizes, grain size distributions, porosity, and variation in ground water flow velocity on the magnitude of the transverse mixing in saturated porous media. The dispersion of a conservative tracer was determined by measuring the distribution of fluorescein plumes at the outlet of a 2D flow-through tank. The dispersion values of the respective steady state plumes were evaluated by fitting the Gaussian (normal) distribution to the measured fluorescein data points. Steady state reactive plumes have been created in the tank using two different instantaneous bimolecular reactions. A complexation between copper(II) ions and EDTA and an acid/base reaction using HCl and NaOH were chosen on account of their fast reaction kinetics. The influence of flow velocity, concentration ratio and grain size on the length of the steady state plumes have been investigated for these reactions.

H11D-0886 0830h POSTER

Large-Time Behavior of GW Pollutant Plumes Subject to Biodegradation at the Fringe: Mathematical Analysis and its Application to a Large-Scale (10 km) Field Problem

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Engineered bioremediation and monitored natural attenuation are important options for the cleanup of frequently occurring subsurface contamination by organic compounds. Because the contaminant removal occurs only when the substrates, target contaminants, and degrading bacteria are present simultaneously, the controlling mixing processes of the contaminants and substrates dictate the contaminant removal rate. Due to the complex nature of subsurface environments, in-situ bioremediation often involves many physicochemical and biological processes concurrently. Thus, mathematical modeling is a useful tool -and probably the only effective tool- to identify the rate controlling processes. As a tool for predicting the environmental impact of a spill and/or for screening the effectiveness of possible remediation technologies, its ability to correctly capture the key processes is important. However, classical modeling involving the discretized form of the governing equations over very large spatial domains and long periods is computationally infeasible at this point. In this research, we investigate the large-time solution behavior of a representative bio-reactive transport model assuming the mixing of two required substrates occurs only in the directions transverse to groundwater flow. The processes are governed by the commonly used advection-dispersion-reaction equations. The microbial growth and decay in the model are described by the double Monod kinetics terms and a linear decay term. The flow field is assumed to be uniform. We have developed a practical approach to estimate the size of the microbial reaction zone and the level of microbial concentration. We have found out that the microbial reaction rates are always limited by the transverse transport of the substrates at steady state, provided that the bulk substrate concentrations are much larger than a characteristic value determined only by the microbial kinetic parameters. Thus the reactions can be considered as instantaneous for the purpose of mathematical modeling. This simplification allows us to efficiently find the steady-state solutions for large scale field problems. We will present a field application which indicates the mixing with the ambient oxygen at the plume fringe may successfully constrain the spread

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