Department of Science and Technology
Government of India

and

United Nations Development Programme

IND/95/002 – GIS-based Technologies for Local Level Development Planning

Mission Report

on

Training Workshop on Ground Water Modelling and on Visiting Selected Sites and Reviewing Data Collections and Data Needs

by:

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Prepared on behalf of the United Nations Department of Economic and Social Affairs
Division for Sustainable Development

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EXECUTIVE SUMMARY

This Consultant spent three and half weeks in India under the project **IND/95/002 – GIS-based Technologies for Local Level Development Planning**. The first two weeks were dedicated to instructing at a Training Workshop on Ground Water Modelling. The rest of time was spent in visiting various institutions/agencies in Mumbai, Bangalore, Calcutta and Ludhiana, and in joining two field trips to Kolar district in Karnataka and to Bankura district in West Bengal.

The Workshop, which was attended by between 15 and 20 participants from various parts of the country, concentrated on two major pieces of computer software: (1) the United **Nations Ground Water for Windows** (known as GWW) data base and ground water information system (GWIS) package and (2) **Visual MODFLOW**, a commercial state-of-the-art ground water modelling package.

During the Workshop and in interactions after the Workshop, the Consultant repeatedly emphasized the need to create a GWIS for any size ground water project prior to attempting to quantify the resource by a modelling approach. Ground water models need a lot of integrated and mutually dependent data. Data may exist already but in a user-unfriendly form (paper files, abandoned data bases, reports, etc.). The software package Ground Water for Windows was delivered on a CD to each participant at the Workshop.

Evaluating the indigenous GIS package developed at Indian Institute of Technology, Mumbai, the Consultant suggested improvements to include, process and present ground water information in various forms dedicated to the ground water discipline. The functionalities that are not a part of GRAM++ or, for that matter, none of currently available GIS packages, are the following: (a) lithology at well sites, (b) time series of water quality eventually pointing at deterioration of quality, (c) depth-related water quality in layered aquifers, polluted aquifers and in coastal aquifers, (d) various chemical diagrams developed to display water quality or usability for irrigation, (e) lithological cross sections and fence diagrams showing lithology over a distance, (f) time diagrams of ground water abstractions – an indispensable information for any modelling study, and more. These functionalities can be linked to GRAM++ either as an independent programming sub-project or by establishing a link with the GWW package. Both approaches require a considerable programming effort.

The field visits to Rampatna watershed in Karnataka (Kolar District) and to Upper Gandheswari watershed in West Bengal (Bankura District) revealed the need for improving the data collection. The recommendations were made for (a) obtaining accurate elevations of water observation points using GPS and reporting absolute elevations of water table rather than or in addition to depth-to-water, (b) running short-time and unsophisticated pumping tests in as many as practicable dug and bore wells using pumping test software developed for large diameter wells and/or fractured aquifers, (c) making inventories of all abstraction wells with some information on locations, rates and schedules, (d) delineating and inventorying such surface features as waterlogged areas, tanks and ponds, and (e) paying more attention on streams and their base flow (that is, the contribution from the ground water).

It is also suggested that DST through this project supplies the software package Visual MODFLOW to several lead institutions. The cost is about $1000 per package with universities qualifying for discounts. Center for Study of Man and Environment (CSME), Salt Lake, Calcutta and Centre for Water Resources Development and Management (CWRDM), Kerala should be given a priority since they are expected to prepare a mathematical model of the Rampatna and Upper Gandheswari watersheds, respectively. The package can be obtained from various commercial software vendors.

Considering the importance of simulating the fate of arsenic in ground water of West Bengali aquifers, it is also recommended that the National Institute of Hydrology at Patna receives a copy of the software. Another package may be delivered to JNU in New Delhi, School of Environment, for tutoring students in making advanced mathematical models of ground water flow and solute (contaminant) transport and fate. All together, it is suggested that the project supplies up to four copies of the software.

As far as the staffing GIS offices in various districts throughout the country is concerned, the recommendations is to have at least one professional from the general field of agriculture, geology or hydrogeology supervising its functioning. If left to computer graduates to run such offices, the whole idea of interacting with local farmers, planners and decision makers may make the whole endeavor an academic exercise. The success and usability of a well designed GIS system depends on at least three factors: (1) its design and functionalities, (2) the completeness of the data base to create various displays (normally in map form), and (3) readiness of the staff running the GIS office to distribute information, enlighten end users, and provide knowledgeable explanations of outputs.

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Preface

Terms of Reference for this mission are shown in Appendix A. The itinerary and time table of the Consultant's mission to India under the project **IND/95/002 – GIS-based Technologies for Local Level Development Planning** are shown in Appendix B.

Basically the mission had two components:

(1) Training Workshop on Ground Water Modelling; and
(2) Field visits to pilot sites and interaction with representatives of government institutions (line departments and universities).

Acknowledgment

The Consultant is grateful to the UNDESA for the nomination and trust placed on Consultant's abilities to perform the tasks as specified in Appendix A, and also to Indian Government as represented by Department of Science & Technology in accepting the nomination.

The friendly attitude by all counterparts and people met during the mission is sincerely acknowledged. The Consultant is thankful to Dr. R.K. Midha, Advisor and Project Director, DST for organizing various aspects of the mission and offering logistic support for running the Workshop and visiting field sites; to Dr. S. Mukherjee for organizing the Workshop at Jawaharlal Nehru University; to Dr. D. Dutta for accompanying the Consultant in field trip to Ludhiana, Punjab; to Dr. Prithviraj for escorting and accompanying the consultant in Mumbai; to Mr. S.K.Pal for escorting the Consultant and accompanying him in the field trip to Bankura; to Dr. Bannur for being a host in Bangalore and accompanying the Consultant to Kolar district; to Dr. P.K. Sharma for organizing round table discussion on the ground water in Punjab and demonstrating the work in his Centre for Remote Sensing; and to all people attending the workshop or interacting with the Consultant.

PART ONE

TRAINING WORKSHOP ON GROUND WATER MODELLING

INTRODUCTION

The Workshop started on 30 November and terminated on 11 December 1999. The list of participants, officially delegated by DST and other institutions, is reproduced in Appendix C. Each session was attended by additional observers mostly from the Jawaharlal Nehru University (JNU) which was the sponsor of the Workshop. Normally about 20 people attended the Workshop each day.

Five computers and one color printer were made available by JNU and one data show to connect Consultant's computer with large screen was provided by DST.

JNU's School of Environmental Sciences and its Remote Sensing Laboratory were the organizers of the Workshop. The Workshop was inaugurated by opening addresses delivered by Dr. D.K. Dutt, former Chairman of CGWB, presently advisor to the World Bank; Professor Dr. J. Subba Dao, Dean, School of Environmental Sciences, JNU; and Dr. R.K. Midha, Advisor and Project Director, DST. Professor Dr. S. Mukherjee coordinated all logistics related to the Workshop and participants. Organization was fine. The only drawback were computers. Only three computers worked as required. The other two were often down, requiring a lot of attention, and when worked they were extremely slow.

During the Workshop this Consultant acted as an instructor and as a resource person. He instructed participants about availability of various pieces of software, web sites and e-mail addresses, and contact people. He also printed several e-mail communications dealing with such aspects as "how to model space-dependent anisotropy of a layer" or "how to model horizontal wells", as the answers to the questions raised by several participants. Participants were advised to subscribe (free) to an Internet forum at **groundwater.com**. This is a forum of 2000+ hydrogeologists and professionals in other ground-water-related disciplines from all over the world. Chances are that one or more of these professionals will always have an answer to any question posted by anyone and would be willing to share their expertise and experience.

HANDOUTS

Participants at the Workshop were given the following handouts:

Notes on mathematical modelling (40 pages) prepared by the Consultant specifically for the workshop. The handout has the following sections:

- What is an Aquifer Model?
- How a Model is Created?
- How Good is a Model?
- Prerequisites for Constructing a Model;

- Equations;
- Input to and Output from Model;
- Basic Steps in Making a Model; and
- Modelling Software Packages.

In addition to issues such as "What is a Model?", "Which data are required to make a ground water model?", "Which phases a modelling project has?", etc., the handout contained description of major software packages used today for simulation of ground water flow and solute transport. The Notes acted as a resource material for people interested in obtaining software and it included addresses of web sites for downloading, contact persons, etc.

Training Tutorial for GWW[1]. A 101 pages publication which guides the user through 5 days sessions to become familiar with the GWW software. It was created by this Consultant and is dated January 1997. It is also uploaded to Internet as a link to this Consultant's web site at http://www.geocities.com/athens/forum/7309 and to http://www.geocities.com/eureka/8409 . This last web site is the GWW-dedicated site.

Day One: Ground Water Information Systems (GWIS) Notes. Eight pages introduction to Ground Water Information Systems and interactive work with GWW to retrieve some maps, cross sections, lithological logs, etc. Notes were prepared as a "warming up" of participants to start working with computers using the examples already created with GWW.

Workshop Example for Visual Modflow: Sunrise Fuel Supplies Company. The original example for Visual Modflow (48 pages) prepared by the software owner **(WHI)** and nineteen additional pages prepared by this Consultant to extend the example to simulating solute fate and transport.

Kokhu Model (Mathura Refinery). The example (20 pages) prepared by this Consultant to simulate the hydrogeology and fate of a pollutant within the Kokhu area including the Mathura Refinery north of Agra. The computer files for this example were sent to the Consultant as e-mail attachments via DST, Delhi from National Geophysical Research Institute (NGRI) at Hyderabad as a courtesy of Dr. Dhar. The example notes were prepared as **Q**uestions and **A**nswers.

Ganma Basin Model. Example (6 pages) prepared for this Workshop for a model created by NGRI.

Modelling Shallow Aquifer Response To Drought: Case Study Rautahat District, Terai, Nepal. A five pages paper discussing the Rautahat Model, prepared by this Consultant and presented at the International Symposium held in Delhi in 1989 (Water Resources in Drought-prone Areas).

Ground Water Information System of Jordan: A Working Paper. A paper prepared by this Consultant in 1995 discussing the need for data in a country-wide GWIS under a National Water Master Plan project.

[1] Ground Water for Windows software was created by this Consultant for the United Nations in 1994-95. The current version, 1.31, dates back to November 1996. Updates and upgrades are currently underway.

SOFTWARE

Two major pieces of software were presented and worked with: (1) **Ground Water for Windows (GWW)**, which was prepared for the United Nations in 1994-95 by this Consultant and his associate Dr. D. Braticevic and (2) **Visual MODFLOW** from Waterloo Hydrogeologic, Inc. (WHI), version 2.8.1. Build 107 dated October 23, 1999.

The first package is normally in the public domain, except the latest version, 1.31, which is the author's version. Yet, participants were instructed that the software could be freely copied and used without any copyright violation. The second package is a commercial product, a state-of-the-art in the ground water modelling field, and can be purchased from various software vendors, including the owner (Waterloo Hydrogeologic, Inc.; e-mail Sales@flowpath.com).

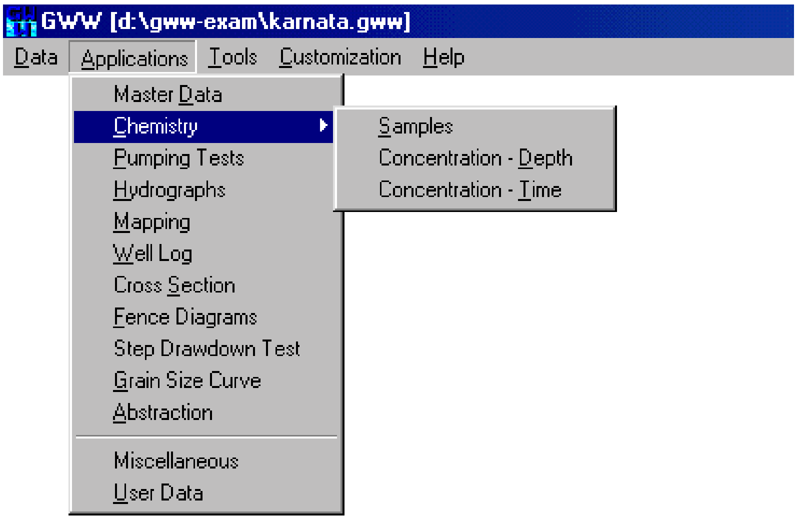
At the end of the Workshop each participant was given one CD with the GWW software, some examples, a complete set of programs and documentation for the **Processing Modflow for Windows 4.1** (PMWIN 4.1) package, and scaled-down (up to 4500 modelling cells) free version of the most recent version of Processing Modflow for Windows (version 5.0). Processing Modflow for Windows software is the second widely used ground water modelling package. Its use was also demonstrated to the participants, some of whom have already worked with an earlier version of the package[2]. The preference for either Visual Modflow or Processing Modflow is subjective. The former has by far better graphical interface (both in pre- and post-processing) while the latter may have a better input data structure and more modules.

User Manual for GWW (about 500 pages) is uploaded to one of this Consultant's Internet websites at http://www.geocities.com/eureka/8409.

GROUND WATER DATA COLLECTION AND PROCESSING PRIOR TO MAKING A MODEL

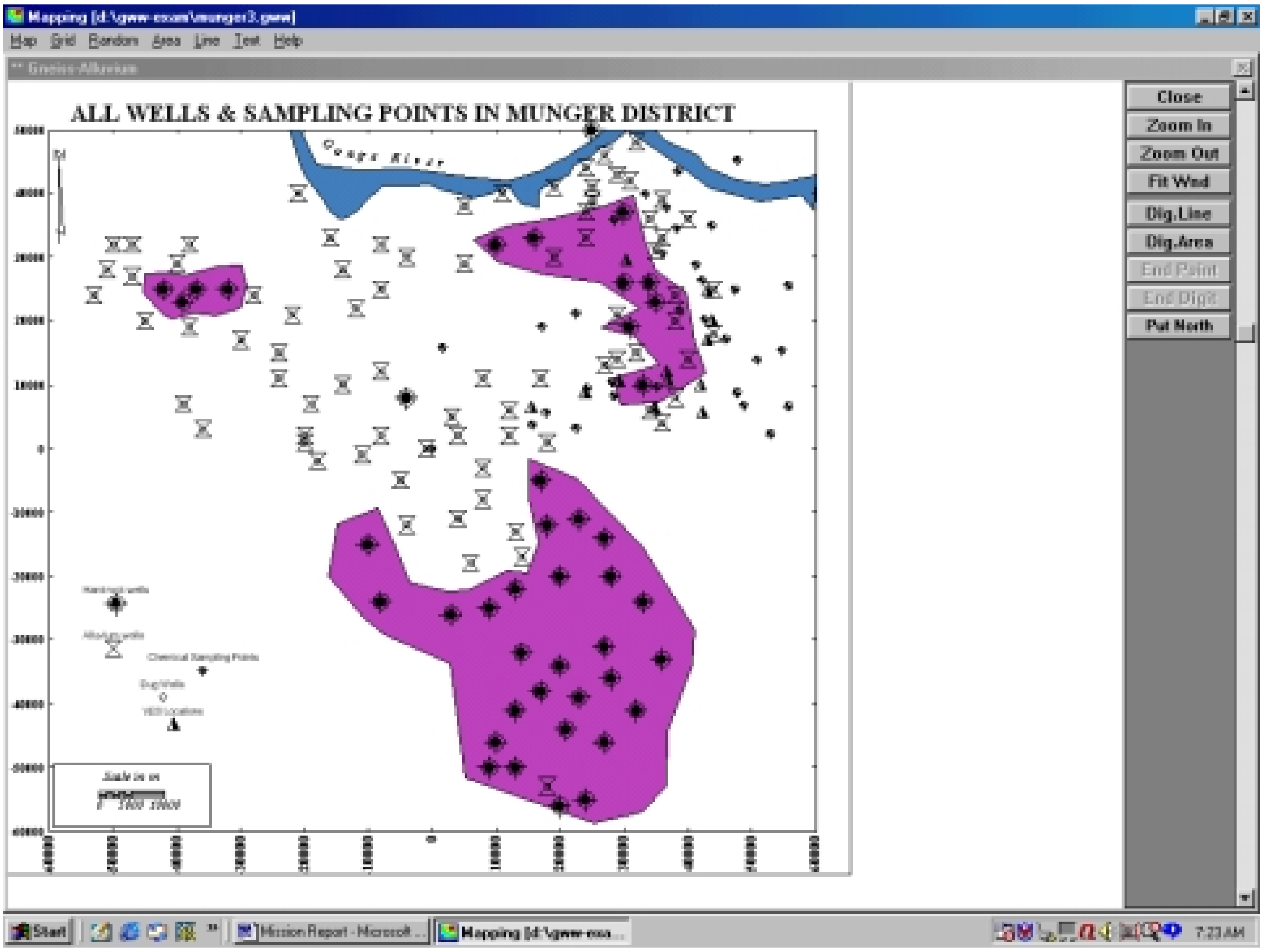
The entire Workshop was structured around ground water data and processes to be simulated. The need for data, quality and quantity of data, visualization of an aquifer system to be modelled, etc. were emphasized using the Ground Water for Windows software. The GWW stores, processes, analyzes, interprets and presents the following (shown in the figure below) thematically grouped data:

[2] Biswajit Chakravorty, S.K. Tyagi, and possibly some other. NGRI's staff are using Visual Modflow, version 2.7.xx.



The participants worked with:

- Creating a data base from ASCII files using the Munger district as an example. The following data were used in Munger: locations of wells, chemical samples (anions, cations, TDS, EC, hardness, pH, and metals), VES (vertical electrical soundings), lithology of dug wells, and water levels in pre- and post-monsoon seasons from the 1992-1995 period.
- Creating various thematic maps such as the one showing the TDS (total dissolved solids), water levels for a selected date, and ground surface elevations for the district. One of maps created for the Munger district (without having any digitized boundaries or other lines and polygons, and without a dxf file as a background map) is shown below. It "re-creates" a geology of the surface using lithology from dug wells.



- Understanding the hydrogeology of the Munger basin (mainly lithology) from wells in the data base and creating a conceptual model (number of layers, boundaries, recharge, constant head for the Ganma River, etc.).
- Preparing input for the Munger model (ground surface elevation, bottom of aquifer, transmissivity distribution – all from “random files”, or xxx.XYZ files).

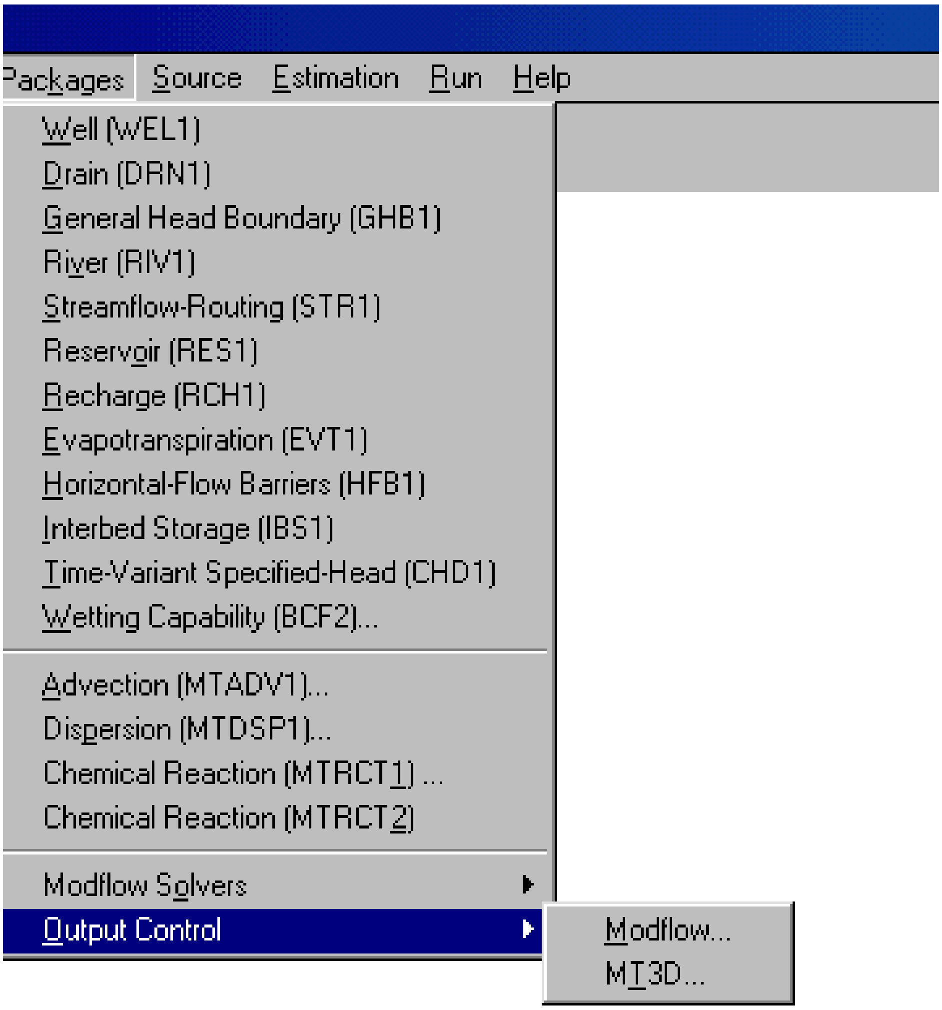
GROUND WATER MODELLING

The topics covered in the Workshop included the following:

- Principles of modelling;
- Objectives of ground water modelling;
- Phases of a modelling project;
- Data requirements;
- Modular structure of MODFLOW and processes it simulates;
- Discussion of differences between modelling a porous medium (e.g., an alluvial aquifer) and a fractured rock aquifer. Discussions on applicability of MODFLOW and similar codes to hard rock terrains.

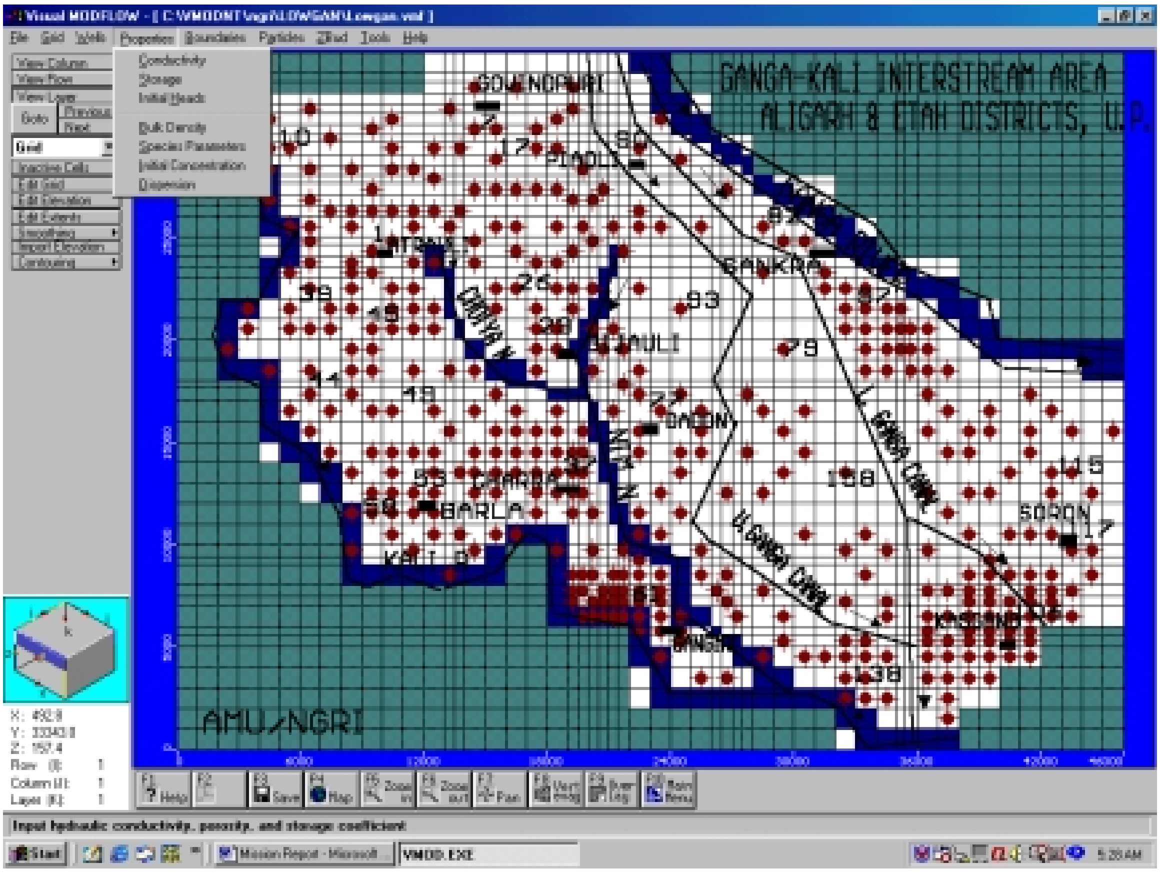
More than 50% of the time spent in the Workshop was a hands-on experience, at least for participants who were sitting around computers. The rest was spent on instructor’s presentations and discussions. Knowing that more than 70% of India is underlain by hard rocks (notably metamorphics such as granite, gneiss, amphibolite, and basalts), a lot of time was spent on discussing how can a code such as MODFLOW be applied to simulating ground water flow in such rocks. The consensus was that it could be used as an approximation for simulating flow through the weathered upper part and through interconnected fractures immediately under the weathered portion. The value of such a model would be mostly in integrating an aquifer’s recharge and discharge components for a basin into its model and to arrive at a cumulative water balance (budget) for the whole modelled area.

The processes that are of importance in a ground water model are shown below in one of input data screens from Processing Modflow for Windows 4.1. MODFLOW in both “processing” versions (Visual and Processing) comes with one or more versions of the flow code MODFLOW and solute transport code MT3D.



The data parameter input options are shown below for Visual MODFLOW. The example on the screen is the Lowgan model prepared by NGRI and sent to the Consultant as an attachment to e-mail. This example was also used in the Workshop. The aquifer modelled is the Ganga-Kali interstream area, an alluvial aquifer heavily exploited by drilled wells. The input parameters that describe an aquifer system are as follows:

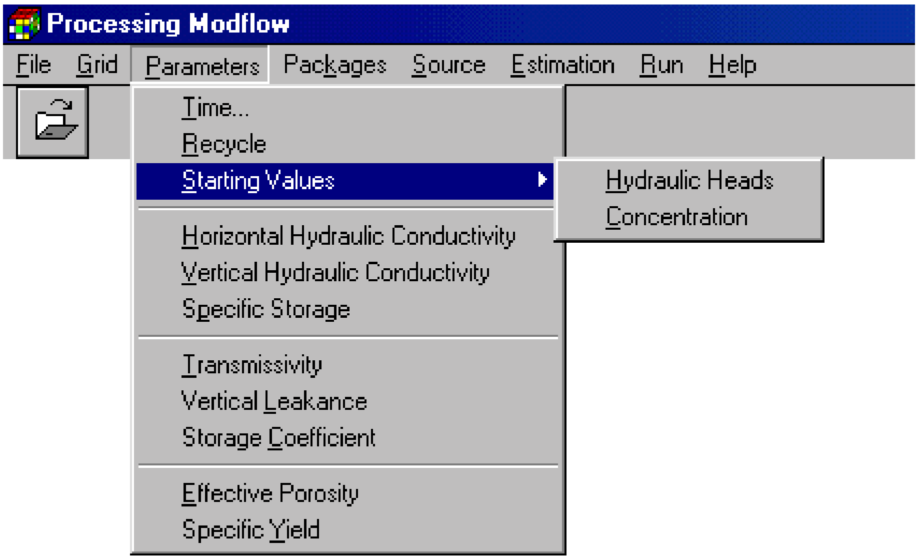
- Hydraulic conductivities for each cell and each layer in the model;
- Specific yield or effective porosity (unconfined layer) and/or storativity (confined layer); in most cases both storage properties;
- Transmissivity (only in Processing Modflow);
- Leakance;
- River bed conductivity and thickness; and more.

- 

Processing Modflow input parameter data screen looks as shown below. Both screens (Processing Modflow and Visual Modflow) indicate the need for various categories of data to be collected and prepared for the model. Much of the model input should come from a GWIS to be established using the GWW package or some other software.

The data that should come from a data base (a GWIS) are production wells (locations, rates and schedules), geometry of layers (top and bottom), parameter distribution (conductivities, transmissivities, storage properties), recharge (areal distribution).

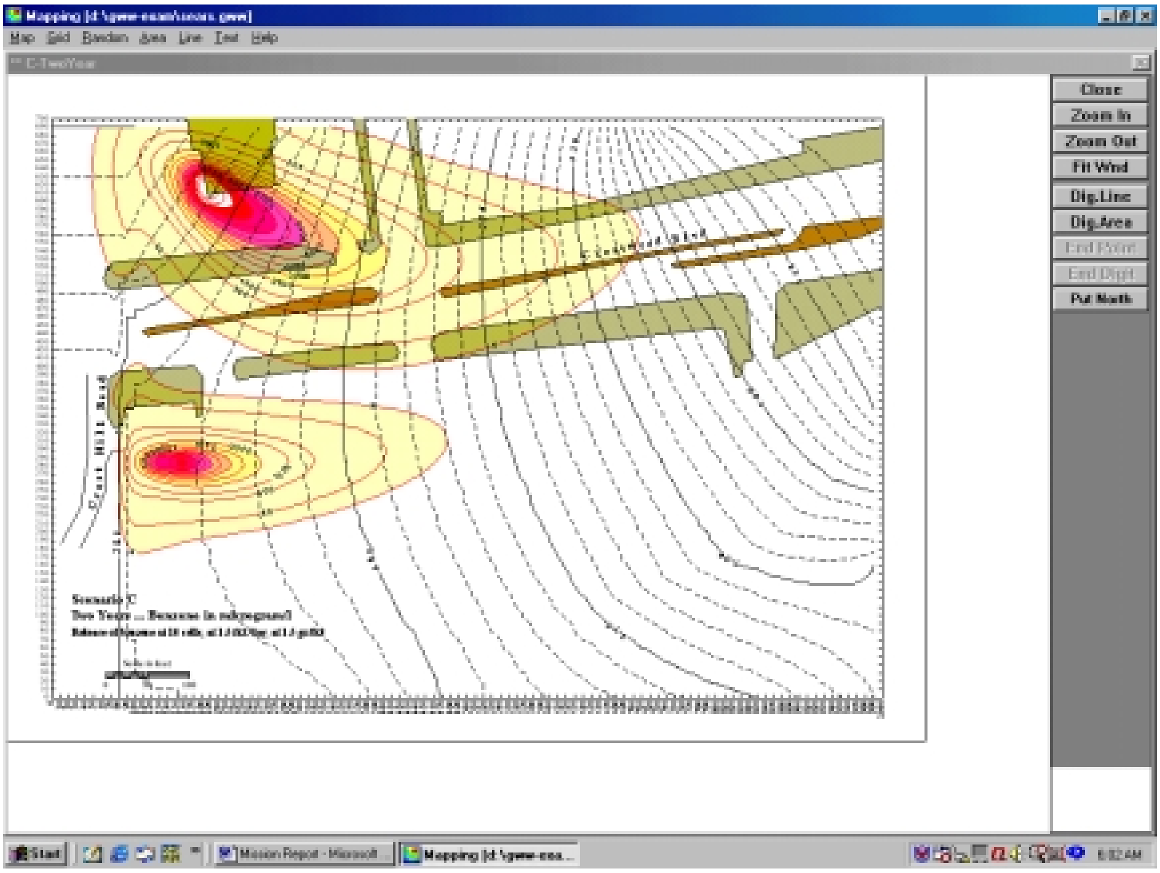
A GIS software (such as ArcView and/or GRAM++) can be used to prepare maps showing locations of surface streams, supply canals and their command areas, drains, ponds, etc. although the software such as GWW can do the same thing. The advantage of using the GWW software to create maps is that all data needed are already stored in the GWW's own data base. The disadvantage is that GWW creates only vector maps while raster maps as created by a GIS-dedicated package such as GRAM^{++} are more appealing and professionally looking.



In the Workshop, the participants were exposed to processing the fate of a solute (a contaminant). The following processes were discussed and simulated in working examples:

- Advection
- Dispersion and diffusion
- Sorption
- Decay.

The linkage between a GWIS package such as GWW and modelling software such as Visual MODFLOW) is illustrated in the following figure. Visual Modflow was used to process data, create a model and run it, and GWW was used to import the modelling output (a map of a contaminant showing both water head elevation contours and solute concentration contours). Participants at the Workshop were exposed to using GWW as a post-processor to modelling in creating maps similar to the one shown below. The advantage of using a ground water dedicated software such as GWW to a mapping software such as Surfer, ArcView and/or GRAM^{++} is in the fact the GWIS created with GWW stores ALL data used to create a conceptual model, then used as input data for the model; it also stores ALL maps created by the model. Outputs of the model such as piezometric map could also be plotted on cross sections showing depletion of the ground water resource, or cone of depression, or simply the difference between an initial water head and model produced head.



Conclusions and Recommendations

(1) Some of Workshop participants have already had a previous experience using the Processing Modflow (an earlier version, for DOS). Staff from NGRI is using Visual Modflow (an earlier version). They did send input data files for several models that they created (Ganma, Lowgan, Kokhu) but they did not send their delegates to attend the Workshop.

(2) Modelling of solute transport and fate of pollutants is also not a new thing to Indian hydrogeologists/modellers. A model of arsenic content in ground water in a West Bengali aquifer was discussed at the Workshop. (During the visit of this Consultant to Calcutta-Bankura, the origin and remediation of arsenic-enriched ground water was an issue that this Consultant discussed at length with Dr. B.C.Poddar, Emeritus Scientist with the Center for Study of Man and Environment.) More about arsenic in ground water can be found in Appendices C and D.

(3) For most of participants this Workshop was their first encounter with (a) ground water modelling and (b) modelling software such as Visual Modflow. For all of them, the presentation of and work with the Ground Water for Windows (GWW) was their first experience with such software.

(4) It is recommended that prior to any ground water modelling, all ground water data plus all data on water quality, locations of surface water features, data on rainfall, evaporation, and especially all data on abstraction and ground water level monitoring wells be integrated into a Ground Water Information System (GWIS). Such a GWIS would be project oriented. Location of wells and other distributed features must be expressed in Cartesian coordinates (X and Y). A background map of the area to be modelled prepared either as a dxf or a bmp

file would greatly enhance the modelling process. The GWIS of the project would contain various maps, cross sections, fluctuations of water levels, quality of water varying with depth and time, all this leading to making a conceptual model which then would be translated to a real model in either Visual or Processing Modflow (or any other selected modelling package).

(5) To create a GWIS for a model, the boundaries of the modelled area, of rivers and other surface features must be digitized and presented in ASCII files.

(6) The data for rivers and other surface water features must include the time-varying stages at selected segments (river reaches or branches), permeability of streambed, geometry of a stream (notably the width at various stages).

(7) Recharge to the model from rainfall must be documented for various categories of ground surface cover: soils, vegetation and crop covers, man-made structures (tanks or ponds, artificial recharge areas, built-up areas, etc.). Irrigation practices must also be documented and return-from-irrigation rates/quantities into the subsoil must be quantified.

(8) Geometry of layers into which the whole system would be vertically discretized must be known, prepared as a "random" file with three values at selected points: X, Y, and Z, where the "Z" value is one of the following: ground surface, top of a layer, or bottom of a layer.

(9) Models must be calibrated, that is model output (heads) must be compared with historic behaviour of water levels in observation wells. There is no point in making a model without having observation wells with known evolution of ground water levels over at least one year period.

(10) In hard rock terrains (such as the ones in Kolar and Bankura districts which this Consultant visited), attention should be paid to the following data items:

- Thickness and description of the upper weathered zone;
- Description of the base rock underlying the weathered upper zone (type, interconnectivity, size of fractures);
- Location and extension of waterlogged areas and surface water tanks as recharge ponds;
- Locations, depth, diameters, and pattern of use of dug wells;
- Water level fluctuations in dug wells; and
- Intermittent surface streams showing the width of the stream at various stages. (It was noted in Bankura and Kolar districts, that is in the Upper Gandheswari and Rampatna watersheds, that the dry river bed extends over a width in places reaching 100 meters, while at very low stages the flow is over a several meters width only.)

(11) In hard rock terrains with intermittent surface streams, the base flow to streams from ground water in dry season should be evaluated and quantified. This will serve as one of calibration procedures for the model.

(12) In any model, hard rocks or not, one of outputs is the water balance (or budget). The balance must be checked for the whole model and for selected zones. Both Visual Modflow and Processing Modflow allow for such an interpretation. In hard rocks, in particular, one must check the model's output in terms of stream recharge in selected cells which might be overcalculated if the streams are incorrectly simulated.

(13) Finally, software such as MODFLOW can be used in hard rock terrains only if the simulated domain is weathered or more or less uniformly fractured (with interbedding planes and systems of fractures dissecting blocks in a way that resembles, at a different scale, an equivalent porous medium).

(14) It is recommended that DST purchases several copies of Visual Modflow, version 2.8.1. build 107 or later (if produced after October 23, 1999). The cost of one copy is about

US$1,000 (without WinPEST, which is an automatic parameter estimation module). Universities may expect some discount. One copy of the software should be sent to CSME in Salt Lake, Calcutta for modelling the Upper Gandheswari watershed and the other to Kerala, Center for Water Resources Development & Management for modelling the Rampatna watershed[3].

[3] Again, the e-mail address to order the software from or to request additional information is sales@flowpath.com. For an eventual discount, please advise the company, Waterloo Hydrogeologic, Inc., Canada that the software order is for the use in the government project supported by UNDP, as requested by this Consultant.

PART TWO

VISITING SITES, INTERACTING WITH GOVERNMENT OFFICIALS AND REVIEWING DATA COLLECTION AND DATA REQUIREMENTS RELATED TO GROUND WATER

Introduction

After the end of the Workshop, between 12 and 18 December, the Consultant traveled to Mumbai, Bangalore and Calcutta, with field visits to Kolar District (Rampatna watershed) and Bankura (Upper Gandheswari watershed). The findings presented in this report are based on very short visits to various institutions, and checking only a small portion of data in reports and talking to people who were not principal investigators. A longer visit especially in Mumbai and Bangalore would have been more beneficial.

<u>New Delhi, Indian Institute of Technology</u>

On 29 November, Dr. Sandhya Rao from Indian Institute of Technology made a presentation of **SWAT** (Soil and Water Assessment Tool) model to this Consultant. (The same presentation was repeated to the participant in Training Workshop on Ground Water Modelling on 10 December.) SWAT was created by Texas A&M University in 1980's and was revised in 1990's.

The presentation covered the following:

- SWAT – Hydrological model;
- SWAT – ArcView pre- and post-processing interface for Indian catchments;
- GRAM^{++} – SWAT interface;
- GIS-based water resources applications;
- IMD (Indian Meteorological Dept.) data conversion application;
- Soil parameters general application; and
- Soil series data base.

One of features that this Consultant finds very beneficial is the creation of a soil series data base. When finished, characteristic data for all soil series will be available for all India.

In the SWAT model, one of inputs foreseen to arrive at the quantity of water available at an exit point from a catchment is <u>ground water</u>. It appears that nothing has been programmed as far as the ground water input is concerned. Such an input could come (or is expected to come) from a mathematical model of the <u>catchment</u>. This would be an approximation only since ground water aquifers and surface water catchments do not necessarily coincide. The processes involved in evaluating available ground water under any catchment are sufficiently complex that their inclusion into a model such as SWAT would not be justified. Ground water availability is arrived at by simulating ground-water-controlling processes in a dedicated ground water model. It appears that a ground water model would need to be run first and then use its outputs as inputs into SWAT.

Alternatively, there are several existing software/modelling packages that integrate surface water, soils, and ground water into a unique model. However, these are real numerical models, with the space discretized into either finite elements or into a finite-difference grid. One of such models is MODFLOW-SURFACT (versions 1999 and 2000[4]). E.g., the newer versions of this package have two surface water components: one for overland flow and one for channel flow. The incorporation of the surface water components is fully coupled with the ground water (saturated and unsaturated). Yet, in this model the emphasis is on the ground water modelling with the surface water components acting as a kind of boundary conditions (controlled and more or less known input). In SWAT, the emphasis is on soils and surface water plus land use, and the role of ground water is reduced to producing a number representing the quantity of ground water available to contribute to the water potentials in a catchment.

Other software packages that link all sources of water in an area (surface water, unsaturated zone – soils, and ground water) are the following:

- MODBRANCH (U.S.Geol. Survey)
- StreamLink (U.S.Geol. Survey)
- SUTRA (Saturated-Unsaturated model, U.S.Geol. Survey)
- MODFE (U.S.Geol. Survey)
- VS2DT (modelling infiltration, U.S.Geol. Survey)
- SHE or MIKE SHE (European Hydrologic System)

The first two packages link the ground water model MODFLOW to a surface water model (BRANCH).

Mumbai, Indian Institute of Technology

In Mumbai, on 14 December 1999 the Consultant visited Indian Institute of Technology. The indigenous GIS software package GRAM^{++} was demonstrated to him by various programmers and graduate students (each being responsible for the component he/she helped programmed). The Consultant met with Dr. Krishna Mahon for a very brief time. Dr. Mahon is the prinicipal investigator for the development of a web-based geographic information server around GRAM^{++}.

Dr. Mrs. J.K.Suri was partly present during the presentation.

In the same Institute, a presentation of Energy Module titled “Spatial Decision Support System for Energy Planning at District Level in Bankura” was made to the Consultant by graduate students, after which he met with Professor Rangan Banerjee, the principal investigator.

[4] MODFLOW-SURFACT 2000 is the forthcoming extension of MODFLOW-SURFACT. It includes options to perform surface water modelling, groundwater modelling and integrated surface water-groundwater modelling. It provides full integration of surface-water features such as overland flow and channel flow with the unsaturated/saturated groundwater flow equations. Software makes the utilization of simultaneous solution schemes that rigorously couple the surface water and groundwater flow regimes. Of interest to Indian conditions would be the feature that fractured porous media simulations are done using dual porosity and discrete fracture representations.

GRAM stands for **G**eo-**R**eferenced **A**rea **M**anagement and has been around for quite some time in its DOS implementation. Its recent upgrade to the Windows platform is done as one of activities of this project in order to provide a cheaper replacement for commercially available GIS packages such as ArcView (or ArcInfo).

GRAM^{++} is a standard GIS software modified for Indian conditions. Its main interface is made ready to link with various additional modules to be programmed by various Indian institutions. GRAM comes with the following modules:

- Core GRAM
- GRAMNET
- Geo-SQL
- Data Conversions

GRAMNET analyses resources networks like roads and irrigation channel network (e.g. Chhatna block of Bankura District). Core GRAM has standard GIS software features such as search using any attribute and reduce a large set to user-selectable criteria is available. Data are imported as dbase files/tables (using e.g. ACCESS database software) and maps with x,y referenced points are generated. It appears that GRAM cannot import a 4-column data file (x,y,z, and point label as the fo9urth column). It works in exactly the same way as ArcView, for example. Various contents (layers) are selected and listed on the left menu bar, and after checking one by one the display shows various overlays. This Consultant was told that about 85% of ArcView's functionalities were implemented in GRAM. The advantages of GRAM over ArcView are in the following areas: (a) network model in GRAMNET, image processing (very detailed), and on-line digitizing (a feature also available in GWW). This Consultant checked the on-line Help and noticed that its index could be expanded.

Digital Elevation Models (DEMs) are generated in GRAM as rasterized maps. In vector processing, the Consultant noticed that the interpolation algorithm for gridding random (scattered, point) data uses only the inverse square distance method (same as the GWW package). This may not be sufficient. Some set of data produce a better interpolated grid for contouring with kriging or other solution algorithms (e.g., the inverse distance to any power, minimum curvature, polynomial regression, radial basis functions - a diverse group of data interpolation methods including the multiquadric method by many considered the best, etc.).

<u>Adding a Module to GRAM^{++} to Process Ground Water Data?</u>

GRAM^{++} is a dedicated GIS software intended to produce various thematic maps using data base files, tables, shape files (from ArcView), etc. However, the ground water data processing and visualization is not only done in map view but in many various other aspects (graphs, time series, cross sections, fence diagrams, etc.). Several examples of how ground water data need to be presented for evaluation of ground water availability are appended to Appendix F. All this needs to be prepared before a ground water system is evaluated by a mathematical model.

The following categories of processed ground water data using the software which is not a GIS dedicated package[5] are produced for this report:

[5] The presentations are prepared using GWW software.

- A lithological log;
- A cross section;
- A fence diagram;
- A chemical diagram pointing at quality of ground water for irrigation (Wilcox diagram);
- Another chemical diagram pointing at the origin of water (Piper diagram);
- A hydrograph (water level fluctuation);
- A time series of ground water quality showing deterioration with time; etc.

It would be improper to require that a dedicated GIS software such as GRAM^{++} should have all functionalities to process ground water data and prepare such graphical presentations. In one version, GRAM^{++} may have a link to GWW or a similar package[6] which would do the processing and presentation. The data could remain stored in the package that would do the processing (e.g., GWW), or better in a common data base package (such as Oracle). Yet the question would remain, what would be the role of GRAM^{++}? In another version, the data would be stored in Oracle and the processing done using a set of tools (similarly what GWW does today). This set of tools would take data from Oracle and process various graphs and sections. Only when a map need to be created the processing would be turned to GRAM^{++}.

Export of attribute tables in shape file format (which GRAM^{++} can import) would need to be programmed in some future version of GWW software.

<u>Bangalore, Karnataka State Council for Science & Technology</u>

People met during the two-day visit:

- Prof. M.N. Srinivasan, Secretary of Karnataka State Council for Science &Technology (KSCST)
- Dr. C.R. Bannur, NRDMS State Incharge
- B.S. Ramaprasad, Co-ordinator, Indo Norwegian Environmental Project
- Sri Abhijit Dasgupta, Secretary to Government of Karnataka, Planning, Institutional Finance & Statistics & Science & Technology Departments
- Dr. M. Sekhar, Assistant Professor, Indian Institute of Science
- Mr. V.S. Prakash, Director, Drought Monitoring Cell
- V. P. Dinesan, Centre for Water Resources Development and Management, Kerala

During the visit this Consultant met with secretary to Government of Karnataka, Mr. A. Dasgupta, recently appointed to supervise the Science & Technology Department. Mr. Dasgupta was not familiar with the project. This was a kind of briefing for him. The Consultant used the opportunity to mention the need for collecting data prior to evaluation and quantification of ground water resources.

On 14 December the Consultant made a presentation of the GWW software to a group of about 15 professionals that included professors Sekhar, Sridhar (both from IISc) and Srinivasan, Mr. V.S. Prakash, Dr. Bannur, and others.

[6] EquisGeology, EquisChemistry

On 15 December the Consultant accompanied with Dr. Bannur and Mr. V. P. Dinesan made a field visit to Rampatna watershed of the Kolar District. Before commenting on the data currently being collected in the Rampatna watershed, the ground water situation in the Kolar District will be described.

This Consultant read the report by V.S. Prakash dated April 1995 and titled **"Ground Water Resources and Development Potentials in Kolar District"**. The highlights of the report are the following:

- Total district area: 8,240 km^2, out of which 7,163 km^2 available for development.
- 1994 census puts the number of wells in the district at 44,692 out of which 25,098 are bore wells and 19,594 are dug wells.
- Density of wells is about 9.7 well/ km^2
- Seven taluks (blocks) belong to so called "dark" category. It is defined as having > 80% ground water already developed. To "grey" category belongs one taluk (about 70% development), and to "white" category three taluks with development <50%.

The report calculates that the available 219 MCM/yr (million cubic meters per year) can create additional irrigation potential of 36,580 ha to be serviced by about additional 1,131 dug wells and 14,906 bore wells.

Long-term ground water withdrawals of > 0.1 m/yr result in the decline of water levels. It is also reported that over an area of 2,800 km^2 the point draft of more than 0.1 m/day resulted in about 1400 villages experiencing an excessive ground water abstraction. As a consequence, the number of dug wells that have gone dry is about 18,344.

<u>Rampatna Watershed</u>

Here below are some pertinent data about this watershed.

<u>Catchment</u>:	Bairasagara
<u>Taluke (block)</u>:	Chickballapur and Gudibanda
<u>Area</u>:	16.1 km^2
<u>Climate</u>:	around 800 mm (semiarid), 75 rainy days, temperature from 35 to 20^{o}C
<u>Ground surface elevation</u>:	from 820 to 1200 m above M.S.L.; plain at 840 to 860 m AMSL
<u>Land use</u>:	agriculture primarily
<u>Source of Irrigation</u>:	ground water (predominantly; using dug wells and borewells), tanks
<u>Soils</u>:	yellowish red to dark brown, clayey

There are 120 borewells and 20 dug wells in the Rampatna watershed. Seven bore wells and 7 dug wells are turned into observation wells. Water samples are taken from 15 wells for seasonal analyses of quality of water. Water levels are monitored from bore wells at a frequency of one to two months a measurement, while from dug wells the measurements are taken biweekly.

Some special studies are also undertaken in the watershed. This is the use of tritium isotope to study the recharge to aquifer. The project has digital data: contours at a scale 1:50,000 at every 20 m interval, watershed boundary, sites and shapes (polygons and points) of villages, roads, and measuring points. Also available are maps on land use and soil types.

The project intends to run pumping tests from bore wells drilled through weathered metamorphic rocks and upper parts of fractured but solid bedrock. The plan calls for 3 such tests each of about 6-8 hrs duration.

The lithology of the watershed is typical for much of India: an upper part consisting of not more than 10 m of weathered mantle with a mixture of clay, silt, rock fragments and sand overlying solid but fractured rocks, a basement or bedrock. The bedrock consists primarily of granite and gneiss.

At the time of visit, the Rampatna River was dry. Noticeable was its width (at one place more than 50 m) and coarse sand with gravel (of decomposed granite-gneiss) river bed. Many dug wells were also almost dry (water at depth greater than 8 m).

This Consultant recommends the following work to be done in this watershed:

- Use GPS (global positioning system) to obtain absolute elevations and locations of ALL dug and bore wells in the watershed. The accuracy that would satisfy is up to 10 meters for location and less than 20 cm for elevation. Use a complex GPS instrument which intersects more than one satellite for more accurate elevation measurements. Use GPS also for selected points along the stream. This work should be done immediately. The depth to water table is not a sufficient parameter. A model or a GWIS needs elevations, and potential (heads, water table elevation) contours in absolute elevations (expressed in meters above sea level).
- Create immediately a GWIS (use GWW to start), transferring all elevations, depth to water (as time series), chemical samples, and inventory of all dug and bore wells.
- Create piezometric maps (showing water table elevations in absolute values) in pre- and post-monsoon periods). Do not rely only on water levels as obtained from observed wells. Use additional points along the river course.
- Conduct pumping tests in as many bore wells as economically feasible. This Consultant prefers to have more test values for transmissivity from shorter tests than less values from longer tests. Two hours test in this kind of rocks would be sufficient. Thus, several wells could be tested in one day. If there will be a problem with power supply which would stop the pump earlier than designed, do not discard the test. Resume pumping when power is returned but insist on very precise reporting of time (in minutes) when the pump stopped and when it started again. Observe water levels throughout the pumping, nonpumping, and after pumping. Measure the elevation and report accurately from which point depth to water during the test was measured. The software such as GWW allows the interpretation of pumping test results even under the conditions that the pumping was not continuous.
- Acquire the software that interprets tests in fractured rocks, as well as in large diameter wells (dug wells). The software packages that do one or both are **AquiferWin32** (e-mail aquifer@groundwatermodels.com, web site http://www.groundwatermodels.com), **Aquitest** by Geraghty&Miller, Inc., and **AquiferTest** by Waterloo Hydrogeologic, Inc.[7]
- Download from Internet the new software package for pumping test analysis in fractured rock aquifers. Do it from web site at http://www.uovs.ac.za/igs/software.htm. The software does, among other things, the delineation of borehole protection zones and tests the fitness of the water for domestic use.

[7] The same company that makes and distributes the Visual MODFLOW modelling software. Its e-mail address is reported earlier.

- Arrive at some estimates of the use of ground water from bore wells (eventually from dug wells, although it appears that their use has been discontinued; each or most of dug wells have now a bore well next to it).

It appears that this watershed can be modelled using the Modflow software, at least to arrive to a water balance for the watershed on a cumulative (zonal) scale. The parameters in making the model could be as follows:

- Two layered model; upper layer the weathered medium, lower layer the fractured solid rock.
- Size of the watershed (less than 20 km^2) makes it possible to use a fine grid with about 100x100 m cells size. Translated into the model, the total number of cells would be less than 2500 in one layer including inactive cells. Total number of cells 5000, which is quite acceptable for today's computers.
- Hydraulic conductivities would be obtained from pumping tests.
- Effective porosities (specific yields) will have to be estimated since the pumping tests of short duration do not yield reliable values. That is because of the "delayed gravity yield" concept which requires, in silty and clayey media, a very long test for draining above the water table to be completed. (Several hours test, even if there is a nearby observation well, would most probably produce a value such as 0.0005 although the medium would be considered unconfined. Such low values are absolutely unacceptable for unconfined aquifers.)
- Recharge to the upper aquifer from rainfall. Test various percentages (time dependent), between 10 and 25%.
- Boundaries to more or less coincide with the watershed, especially the northern one. Assume no-flow across boundaries. Low-elevation boundary to be obtained after piezometric contour maps are created. The outflow from the modelled area could be through the Rampatna stream or across a constant head boundary as an approximation.
- Simulate the following processes: impermeable boundaries, recharge from rainfall and seepage tanks, abstraction from bore wells, interaction between the stream and ground water in the weathered aquifer; input hydraulic conductivities for upper and lower layer, and storage properties for both layers. Remember that the order of magnitude of effective porosity in the upper layer could be between 0.10 and 0.15, and in the lower layer, provided it becomes unsaturated 0.01 to 0.05. The hydraulic conductivities of the weathered medium could be within the range 1 to 3 m/day, and that of the fractured medium underneath not greater than 2 m/day.

Calcutta, Salt Lake, Center for Study of Man and Environment (CSME)

People met during the visit:

- S.K. Pal, Senior Scientist
- Dr. B.C. Poddar, Emeritus Scientist
- Dr. A. Biswas, Honorary Secretary of CSME

On 17 December a field visit to the Bankura District and to Upper Gangheswari watershed was organized. This Consultant spent most of time in the village of Shushunia reading the report on the Bankura District titled "Ground Water Resources Assessment and Management of the Bankura District, West Bengal". The principal investigator of this 1993 report was Professor A.K. Saha. The study and report were prepared by the Center for Study of Man and Environment. The report covered the period of study from April 1990 through May 1993.

The highlights of the report and the status of ground water in Bankura District are summarized below.

Area:	6881 km^2
Population:	2.8 million (density: 419/km^2)
Major Rivers:	Damodar (average width 490 m), Dwarkeswar, Kangsabati (Kasai)
Wheat Irrigation:	112 km^2 in 1988/89
Temperature:	Mean annual 27^{o}C
Drilling:	Three deep wells in 1958 (one 300 m deep at Govindpur), 50+ wells between 1959 and 1966.
Ground Water:	Confined in hard rock areas, in weathered residuum of some 10 to 20 m thickness, which is underlain by fractured hard rocks down to at least 50 m (below that depth hard rock terrain may be without well developed fracture systems); in lateritic and older alluvial deposits ground water is under water table conditions (unconfined). In hard rocks, the weathered upper zone and fractured lowered zone are in hydraulic continuum.
Yield of Wells:	Large diameter drilled wells in western part (hard rocks) have rather low potential. Q is from 4.6 to 43.2 m^3/day (maximum equivalent to 0.5 l/s). In eastern alluvial part, depth of wells is between 87 and 304 m and yield is better, from 94 to 183 m^3/day.
Parameters:	Hydraulic conductivities from 0.1 to 28.1 m/day; transmissivity from 7.4 to 34 m^2/day.

Objectives of the study:

1. To create a sound data base on
   (a) depth and fluctuation of water table;
   (b) hydraulic characteristics of principal aquifers;
   (c) geometry of principal aquifers;
   (d) blockwise ground water budgeting; and
   (e) chemical quality of ground water.

2. To evolve a practicable water harvesting scheme.
3. To formulate a rational ground water management plan.

Activities:
1. Collection of water level data for the hydrograph network;
2. Generation of different types of water level maps;
3. Compilation of geological maps with hydrogeological characterization.
4. Collection and compilation of lithological logs;
5. Collection of data on aquifer parameters and carrying some pumping tests in open dug wells in selected hard rock areas;
6. Collection and compilation of chemical quality data;
7. Calculating ground water potential in each block;
8. Water harvesting plan; and
9. Ground water management plan.

Data Base System for Bankura District

A "Ground Water Data Base System for Bankura District" is reported by A.K. Saha, C. Chakraborty, D. Saha, and S.P. Dasgupta in 1992. The software used was dBase III+. The system covered the total area of the district, reported to be 5881 km^2.

Some statistics about the wells known to exist within the Bankura District:

(a) Pucca (lined) dug wells	12,407	
(b) Katcha (unlined) dug wells	3,310	
(c) Dug cum bore wells	36	
(d) Hand pump	11,000	
(e) Shallow tube wells (STW)		13,002
(f) Deep tube wells (DTW)		95

CSME established a network with 117 permanent hydrograph-creating sites the elevation of which were surveyed with respect to the mean sea level. The whole data base system was created using eight thematic data base files: village level water supply status, hydrogeological details of hydrograph network, periodic water levels, chemical quality, details of Mark II hand pumps, hydrogeological logs of DTW, lithological logs of DTW, and blockwise information on different aspects.

The system has also eight data retrieval programs.

This Consultant learned that this data base and information system stopped functioning after the hydrogeological study was made. This is unfortunate because the information that exists in the computerized data base is dated not later than 1992.

Current Pilot Project in Upper Gandheswari

This Consultant reviewed the progress report titled "Development of Decision Support System for Land and Water Management of Upper Gandheswari Sub-basin of Bankura District, West Bengal". The progress report covers the period from January through August 1999. This is one of DST/UNDP pilot projects within the current "GIS-based Technologies for Local Level Development Planning" project.

The main objectives formulated for this watershed are the following:

(1) To develop a sound data base for land and water resource management of the Upper Gandheswari sub-basin;
(2) Applications of the SWAT model for betterment of land use practices through assessment of water resources available in different seasons in conjunction with meteorological factors to curb crop failure vis-à-vis drought forecasting.

The watershed occupies about 370 km^2, average slope is 1:143, average width of the watershed is 6.2 km, with the maximum width of some 9.3 km. The area under study, however, occupies only 103 km^2.

The dominant feature of the system is the Gandheswari River. Its length within the study area is 19 km. Its width near Parulia village is about 40 m. At the time of the visit, the river was flowing with a width of not more than 10 meters. The entire flow these days is the base flow, that is the contribution of ground water. The sub-basin of the Upper Gandheswari River is composed of granite, gneiss, migmatite and amphibolite anorthosite rocks.

CSME established an observation network of 40 dug wells. Depth to water is observed several times a year. Data are reported as depth to water. Infiltrometer tests were conducted at 12 locations.

The river itself was dry from 1 January through 22 May 1999. In June 1999, the total flow at an established gauging station was 0.26 MCM (an average of 8670 m^3/day, or about 100 l/sec.) In July the flow was 1.55 MCM (600 l/sec) and in August about 7 MCM (2.6 m^3/sec). The rainfall was in May 61.8 mm, in June 116.0, in July 348.7, and in August 377.8 mm.

To improve the information needed for an eventual quantitative assessment of the ground water resources the following is suggested:

(a) Establish immediately a data base with correct locations of ALL dug and eventually drilled wells for the watershed. Apply GPS to arrive at accurate elevations of measuring points. Report the elevations of the ground surface plus of measuring points (top of ring wall of a dug wells).
(b) Create a GWIS using GWW software for the watershed. Input and transfer the data from the old dBase III date base (from 1992) and add new data from the monitoring network established for this project. Input all chemical data to create a water quality component of the data base. Prepare maps of absolute elevations of water levels for pre- and post-monsoon time. Use the elevations of streambed and/or river to enhance water level (piezometric) maps.
(c) Make an inventory of all waterlogged areas. Inspect the area, locate water tanks and similar ponds, and locate them on maps. Digitize such areas and import as digitized polygons to the GWIS. This may serve as one of indicators of recharge/evaporation areas for a future mathematical model.
(d) Obtain maps created by GIS on land use and cropping pattern and use them as input data to a future mathematical model (recharge from return irrigation, e.g.).
(e) Get a good grasp on the Upper Gandheswari stream with respect to its base flow, that is inspect its bed over the entire length of 19 km and made records and comments about the stream conditions (volume of water flowing, width of stream, lithology of streambed, etc., at different segments) – all to be used as input to the model.

(f) Make as many as possible pumping tests from dug wells, using the software developed for large-diameter wells[8]. A typical test can last between 3-4 hours.

Eventually in the second year of the project, a mathematical model of the watershed can be made using Visual MODFLOW. The expected output would be total water balance for the watershed, evaporation losses through tanks and ponds, recharge to the weathered residuum, etc. Some future-forecasting scenarios could also be run attempting to arrive at some estimate of the ground water availability in the watershed.

Ludhiana, Punjab

On 20 December the Consultant accompanied by Dr. Dutta from DST made a one-day visit to Ludhiana. The visit was organized by Dr. P.K. Sharma, Director of Punjab Remote Sdensing Centre. The visit was staged as a two-way briefing. First, heads of various government institutions made thei presentation about ground water in Punjab to this Consultant, then he discussed and presented the United Nations Ground Water for Windows (GWW) software to them. Modelling ground water systems in Punjab was also discussed.

Round table discussions and presentations were attended by the following people:

Dr. P.K. Sharma,	Director, Punjab Remote Sensing Centre, Ludhiana
Dr. Dutta,	DST, New Delhi
Dr. K. Singh,	Joint Director, Punjab State Centre for Science & Technology, Chandigarh
Dr. N.K. Narda,	Professor & Head, Dept. of Soil & Water Eng'g, Punjab Agricultural University, Ludhiana
Dr. M.P. Kaushal,	Professor, Dept. of Soil & Water Eng'g, Punjab Agricultural University
Dr. D.S. Taneja,	Senior Research Engineer, Dept. of Soil & Water Eng'g, Punjab Agricultural University
Dr. Gurcharan Singh,	Joint Director (Hydrogeology), Dept. of Agriculture, Punjab State Government, Chandigarh
Er. Mohur Bansal,	Superintending Engineer, Punjab Irrigation, Chandigarh
Er. Jasbinoen Singh,	Executive Engineer, Water Resources Department, Chandigarh
Er. Rajan Aggarusal,	Ph.D. Student, Dept. of Soil & Water Eng'g, Punjab Agricultural University

The proposal and request for a new information technology project to be assisted by UNDP was discussed. The project's title is "Information Technology for Sustainable Agricultural Production System in Punjab". The highlights of the ground water situation in Punjab, as presented in the Project proposal and as discussed during this meeting are the following.

The State of Punjab is one of the intensively cultivated and irrigated areas of India. The Punjab state with about 50,000.000 sq. kilometers surface area contributes to 65% of country's food towards central pool. The state has a favourable climate, a network of canal system, abundant ground water and marketing infrastructure. Yet the price paid for extremely intensive development of ground water for food production in the past 30 years is getting too high. In most of the northern and north-

[8] Several software packages have been mentioned earlier in this report.

western parts of the state, water table is gradually declining at a rate of 25-30 cm/yr. Out of 5 million hectares, 4.3 million ha are experiencing the falling ground water table problem. Out of the 138 community development blocks, ground water in 62 blocks is over exploited. 83 blocks are already declared critical. In 22 out of the remaining 55 blocks, the ground water is brackish.

Salinity in the southwestern part of the state is another serious problem. Increased salinity results from a combination of factors: (a) irrigation without drainage with the consequence of rising water table, (b) subsurface lateral inflow without an outlet, and (c) seepage from canals carrying the water from the north to south.

It appears that there are about 0.9 million wells in Punjab. The information on ground water is being collected by three agencies: Central Ground Water Board (CGWB), Water Resources Department (Water Monitoring Cell) of the state government, and Department of Agriculture of the state government.

CGWB monitors about 4 to 5 wells in each block four times a year (Jan, Apr, Jun, Nov). In the southwestern part of the state, in which increased salinity and waterlogging are problems, each block is monitored with about 15 observation wells. Data are available from as early as 1972.

The state of Punjab has a plan to drill exploration wells to 400 m depth; one at every 800 to 1000 km^2. Lithology of various aquifers will be the objective of the study. The plan also calls for establishing a monitoring network of observation wells with one well per about 25 km^2.

Department of Agriculture keeps the data on water abstraction and has an inventory showing about 0.9 million wells. Data on monitoring water levels are available from as early as 1979. Quality of ground water is monitored in southwestern part. The staff in this directorate makes water quality maps each year. Fluctuations of water levels are observed in about 600 wells and 150 piezometers. One of identified problems is the continuity of data due to drying up of shallow wells.

This Consultant contributed to the discussion with the following input:

- All information on ground water since early 1970s and coming from various line departments and universities should be collated and integrated into one or more ground water information systems. To start without much delay, GWW software can be used in creating data bases and GWISs for blocks or districts selecting not more than 5000 representative wells in each.
- A common reference coordinate system should be used making possible merging data from individual data bases.
- Eventually available data bases (in presumably dBase III+, Foxpro or similar packages) should be converted to the GWW input format.
- Special attention should be placed on time series of water levels (hydrographs) and chemical parameters (concentration graphs).
- Create, for the beginning, a pilot data base and GWIS, to be used for “public awareness” purposes and also for getting support for the new project proposal.

Appendix A.

TERMS OF REFERENCE

A. Conduct a two week training workshop in ground water modelling with emphasis on:

- Characterization of subsurface structure – using hydraulical, geophysical and geochemical methods.
- Application of numerical and analytical flow models in fractured hard rock terrain.
- Methods involved in designing and optimization of ground water remediation schemes.

The course material and the requisite software packages should be made available by the consultant.

B. The issues covered during the training workshop would be as follows:

- Review of the status of research on ground water modelling in India.
- Considerations of certain important ground water models for application under Indian conditions, keeping in view, the climate, physiography & pedologic characters.
- Selection of a suitable model or combination of models to be adopted.
- Evaluation of the existing data available with different agencies to run the selected model. Identify data gaps and devise ways to bridge the gaps.
- Selection of the suitable sites (in different agro climatic zones) for further research in consultation with the working groups.
- Work out specific research projects to be pursued.

C. Undertake visits to field sites and interact with local Government and project teams.

D. Review and suggest functionalities to be included in the indigenously developed GIS package Geo-Referenced Area Management (GRAM ++) for integration with ground water models.

E. Submit a report to UNDESA, with appropriate comments on activities undertaken (training workshop and institutional visits), including technical comments, recommendations, and future course of action.

APPENDIX B.

Itinerary and Time Schedule of this Mission

- Arrival to New Delhi on 29 November early in the morning. Meeting in DST. Presentation of SWAT at IIT by Dr. Mrs. S. Rao. Another meeting in DST.
- 30 November. Inauguration of the Training Workshop on Ground Water Modelling and its first day.
- 1 through 11 December. Training Workshop on Ground Water Modelling. The Workshop closure on 11 December.
- 13 December. Departure for and arrival to Mumbai.
- 14 December. Presentations of GRAM++ and energy module at IIT, Mumbai.
- 15 December. Departure for and arrival to Bangalore. Meetings in Karnataka State Council for Science & Technology. Meeting with Secretary, Karanataka Government, Dept. for Science and Technology. Presentation of the Ground Water for Windows (GWW) software at KSCST.
- 16 December. Field visit to Rampatna watershed, Kolar District, Karnataka State.
- 17 December. Departure for and arrival to Calcutta. Meeting in Center for Study of Man and Environment in Salt Lake City. Departure by train to Bankura. Overnight in Bankura.
- 18 December. Field visit to Upper Gandheswari watershed and return to Calcutta the same night.
- 19 and 20 December. Writing report on this mission in Delhi.
- 21 December. Departure for Ludhiana, Punjab, attending a round table discussion of ground water status in Punjab, attending presentation in Centre for Remote Sensing, and return the same night to Delhi.
- 22 December. Meeting (debriefing) in DST and UNDP and printing a draft version of the incomplete mission report.
- 23 December. Departure from Delhi and India in early morning hours.

Appendix C.

List of Participants at the Workshop in New Delhi

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Some sessions were attended by Professor Dr. S. Mukherjee, Workshop Organizer and Co-ordinator (Jawaharlal Nehru University), Remote Sensing Laboratory staff and graduate students.

Appendix D.

1. Reports on modelling presented to and evaluated by this consultant

1.1. Arsenic Pollution Study in Yamuna Sub-basin, Nadia and 24-Paraganas Districts, West Bengal, prepared by National Institute of Hydrology (Roorkee) and Central Ground Water Board, Eastern Region (Calcutta) in 1999.

The objectives of the study were as follows:

- Understanding and prediction of contaminants transport in the saturation zone; and
- Quantification of remedial measures to arrest spreading of arsenic.

Modelling methods:

- **Modflow** software (USGS 3-dimensional finite difference modelling code) was used for simulating ground water flow; and
- **MT3D**, ver. DoD 1.5, was used for simulating the fate of arsenic in ground water.
- **Processing Modflow**, ver. 3.0, was used as a pre-processor (data input and model creation) and **Surfer** package was used for creating contour maps (post-processor).

Comments on the Modelling Approach

The area of some 50 km by 30 km was divided into 100 x 100 equal size gridal network, i.e. into 10,000 cells (in one layer) having a cell dimension of 500 m x 300 m. The cumulative thickness of water bearing layers of about 80 m was divided into 8 layers each of 8 meters thickness. The total number of cells was thus 100,000 which makes this an extremely large model, almost near the maximum limit of the present-day computer software.

A typical processing of such a large model required about 6.5 hours of computer time for one transient run.

The software packages selected for the modelling are the correct ones. Modflow is the leading ground water modelling software today, widely used worldwide including India, and MT3D is also the leading solute transport and fate of contaminants package.

While the ground water flow component was very correctly handled and presented in the report, the solute (arsenic) transport and fate are just a first approximation of a more realistic behaviour of this species in ground water. Arsenic was treated as a conservative element. Its fate was simulated in advection and dispersion only, without any possibility for it being absorbed, retarded, decayed or entering a reaction of any other kind.

In the workshop, this consultant explained that a species such as arsenic does not flow with ground water (advection) and gets spread by dispersion only. It also stays as an immobile component near the site where it entered the ground water system, becomes adsorbed by clay materials, and enters some linear or non-linear chemical reactions. Only one part of arsenic flows with the ground water and leaves the proper site of its entering the system. The researchers who contributed to this modelling project are aware of the limitation they have introduced in the model. They themselves conclude that “the model requires verification of its performance after incorporating chemical reaction components, such as: adsorption, retardation and decay which are crucial for contaminant such as arsenic."

This consultant made a recommendation to Mr. B. Chakravorty, who participated in the workshop and is one of the authors of the modelling study, to consult a recent publication by the USEPA (Environmental Protection Agency) titled: "The Kd Model and Its Use in Contaminant Transport Modelling." References are provided for studying arsenic behaviour in reduction and oxidized environments.

This consultant also believes that the grid selected was most probably not the most efficient grid, considering the size of the model and the load imposed on the computer. The cells could have been square (500x500) rather than rectangular (500x300); a non-uniform grid could have been applied with finer spacing near the six sites of suspected arsenic input and coarser farther away. The grid in each layer could have been reduced from 10,000 cells in one layer to about 6,000 cells, reducing thus the computer time considerably.

2. Reports brought to attention of this consultant

Mr. M.L. Sharma, who took part in the current Ground Water Modelling Workshop, brought to attention of the consultant the following publication:

Groundwater Modelling … Proceedings of a brainstorming session on groundwater modelling held during 21-24 October 1999 at Jodhpur, India. The brainstorming session was sponsored by the Department of Science and Technology, Government of India, New Delhi.

The proceedings include several papers of general interest, notably discussions on the application of ground water models to fractured (hard rock) terrains:

- Groundwater Modelling in Hard Rock Terrain, B.K.Sahu, Indian Institute of Technology, Powai, Mumbai
- Groundwater Flow Modelling in Hard Rock Terrain, A.G. Chachadi, Department of Geology, Goa University, Panaji
- Approaches for Modelling of Hard Rock Aquifer Systems, M. Thangarajan, Mathematical Modelling Group, National Geophysical Research Institute, Hyderabad

Presenters agree on the following approaches to modelling:

- Discrete-fracture networks (DFN);
- Stochastic continuum (SC);
- Channel Network (CN); and
- Equivalent porous medium (EPM).

Only the EPM approach allows the use of finite-difference or finite-element modelling codes of which the MODFLOW code is the best known. DFN approach demands the knowledge of very detailed geometry of major fractures before a computer code can be applied. The best known code for such a simulation is FRACMAN by Golder Associates Inc. (this consultant's former employer). Its use is limited to very expensive projects such as repositories of nuclear wastes in which the cost of extensive investigation programs is justified.

Another paper that this consultant finds of general interest and the topic of which fits well into the objectives of the UNDP-DST project is:

- **Database for Groundwater Resources: Strengths and Weaknesses, by D.K. Chadha, Central Ground Water Authority, New Delhi.**

This consultant agrees with the statement that "a database must be capable of integrating itself with the state-of-the-art tools like mathematical modelling, GIS and optimization procedures, which would facilitate preparation of relevant thematic maps and overlays for the area of interest."

This means that a dedicated ground water database should not be an isolated undertaking but a part of a wider information system. The United Nations Ground Water for Windows (GWW) software package, of which this consultant is a co-author and which was amply presented to the workshop participants, is the software which creates ground water information systems, relational and object-oriented databases. Yet, it does not link to a dedicated GIS software such as ArcView or Arc/Info; neither it should be used for establishing state-wide data base management systems with tens of thousands of wells in which ground water information is just one of many sectors of information. For a local end-user, an institute, a farmer's group, a university, this may still be the best set of tools available today for processing ground water information, displaying ground water data in a meaningful, easy to interpret and present way. It is also indispensable as a pre-processor in ground water modelling work enabling a modeller to interpret information, create a conceptual model and transfer space-distributed data into the modelling software.

Other papers presented at the "brainstorming" session on ground water modelling including the following:

- **Modelling Groundwater Recharge Processes, by S.K. Sondhi and M.P. Kaushal, Punjab Agricultural University – a correct statement of approaches and empirical relationships among various parameters.**
- **Groundwater Modelling: Flow and Mass Transport Model Case Studies, V.V.S. Gurunadha Rao, NGRI, Hyderabad**
- **Remediation of Contaminated Groundwater, Shashi Mathur, Department of Civil Engineering. IIT, New Delhi**

Several case studies of ground water modelling were also presented (K. Sridharan, Manoj Shrivastava).

The general comment of this consultant is that Indian professionals do have sufficient knowledge, skill and understanding of what is the ground water modelling today, its advantages and weaknesses, especially in hard rock terrains, of currently available software (notably the MODFLOW and MT3D for simulating flow and solute transport).

They may not have been faced with the need to simulate the fate of common contaminants in ground water (benzene and other BTEX components; industrial contaminants such as TCE, DCE, etc.). This explains the lack of presentations and case studies on solute transport, processes that describe the fate of such contaminants in the subsurface (decay, sorption, retardation, etc.) and parameters associated with individual species (arsenic, e.g.). This topic was also covered, to some extent, at the current Ground Water Modelling workshop.

Appendix E.

Fractured Terrains Modelling and Arsenic. Recent discussion on Groundwater user group (Internet)

Introduction

This appendix contains some of recent discussions on Internet with reference to the ground water modelling of hard rock terrains and on arsenic. The reason for including the discussion into this consultant's report is the following:

- Hard rocks occupy more than 70% of India.
- Modflow and similar ground water modelling codes do not apply exactly to hard rock aquifers.
- Interest among participants in the Workshop on modelling hard rock terrains was high.

- Arsenic as a pollutant was simulated in a recent study in West Bengal (see Appendix D). It has increased content is of great concern in West Bengal (and Bangladesh).

This appendix is more of a "resource" nature presenting names and e-mail addresses of professionals who supplied this discussion.

1. Modelling fractured terrains

By David Watkins, Lecturer in Hydrogeology
Camborne School of Mines, University of Exeter, Redruth, Cornwall
TR15 3SE, United Kingdom; Tel +44 (0) 1209 714866; Fax +44 (0) 1209 716977
e-mail dcwatkin@csm.ex.ac.uk

I wish to add to the discussion on the use of MODFLOW for fracture flow modelling.

MODFLOW can be used to model discrete fractures. Each fracture can be represented by a column or row on the grid with width equal to fracture aperture. The hydraulic conductivity of fracture to apply can be found from the equation:

$$P = (a^3)/12$$

where P = intrinsic permeability and a = fracture aperture

So,

$$k = (\rho\ g\ a^3)/(12\ \mu)$$

where:

k = hydraulic conductivity
ρ = fluid density
g = 9.81
μ = fluid dynamic viscosity.

It is important that the interblock hydraulic conductivities are calculated using the harmonic mean. No other averaging method will accurately represent the sharp boundaries. The blocks between the fractures can be assigned k = 0 for only fracture flow or can be assigned hydraulic properties to represent a dual permeability medium. You will be limited to orthogonal fracture planes unless you use a finite element method. The grid will be highly heterogeneous with alternate large and small X and Y increments. If you are going to run advection/dispersion, you may have problems with convergence and with numerical dispersion. Particle tracking may be less of a problem. Depending on your fracture system, you may be better off using a stochastic fracture model, though consider whether your data justifies the extra complexity.

Other models available include FRACMAN developed by Golder Associates and NAPSAC developed by the Atomic Energy Authority at Harwell in the UK.

I haven't actually modelled fractures using the method above with MODFLOW but have used it with one of my own codes and obtained good results. MODFLOW should work in exactly the same way. Has anyone out there used MODFLOW for representing fractures?

Regards
Dave

2. Arsenic

Subject: Arsenic references
Date: Fri, 28 Aug 1998 09:46:37 -0600
From: "Mark Dubois" <MDUB1@corp.newmont.com>
To: groundwater@ias.champlain.edu

The following should get you started:

- Trace element removal by iron adsorption/coprecipitation: Process Design Manual, EPRI; GS-7005, Project 910-3, Final Report,Oct. 1990. (www.epri.com)

- Field evaluation of arsenic and selenium removal by iron coprecipitation,D.T. Merrill et al., Journal WPCF,vol 58,no 1, Jan 1986.

- Arsenic species as an indicator of redox conditions in groundwater, J.A. Cherry et al., Journal of Hydrology,43 (1979),373-392.

Also try searching for arsenic+/- chemistry, etc on the web or in the Citation (subject) Index.

Good luck, MD RG,CHG

==

Subject: [GW] Arsenic standard
Date: Tue, 6 Apr 1999 10:46:37 -0600 (MDT)
From: "Michael E. Campana" <aquadoc@unm.edu>
To: James Skipper <skipperj@state.mi.us>
CC: GROUNDWATER@ias.champlain.edu

Hi, Jim.

EPA may go as low as 2 ppb (0.002 mg/L); I think they're also looking at 10 ppb (0.01 mg/L) or 20 ppb (0.02 mg/L). I heard they might promulgate the new standard this summer or fall but don't know for sure.

Michael

Michael E. Campana, Professor and Director
Water Resources Program
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University of New Mexico, Albuquerque, New Mexico 87131-1217 USA
Office: 1 505 277 5249; fax: 1 505 277 5226
Home (voice/fax): 1 505 281 0689 e-mail: aquadoc@unm.edu
http://www.unm.edu/~wrp/

On Tue, 6 Apr 1999, James Skipper wrote:

> Not too long ago I read a brief article in the newspaper that stated USEPA is reevaluating their standard for arsenic, based on newer evidence of harm. Is anyone out there aware of what the proposed standard might be, and when the standard might be promulgated?
>
> Thanks in advance for any information.
>
> Jim Skipper, Senior Hydrogeologist
> Mich DEQ, ERD
> 120 West Chapin Cadillac, MI 49601
> skipperj@state.mi.us 616-775-3960 X6304

Subject: Re: [GW] Fate & Transport for Metals
Date: Thu, 14 Jan 1999 10:24:45 -0500
From: "Peter L. Kallin" <kallin@phoenix.Princeton.EDU>
To: Howard Frank <hjf@gel.com>
CC: "Groundwater.Digest" <GROUNDWATER@ias.champlain.edu>

Howard-

Fate and transport of metals is usually much more complex than for VOCs because of the redox chemistry and the fact that metals do not decay or break down like organic contaminants. If your site is a squeaky clean sandy aquifer with no organic carbon and homogeneous eH-pH conditions, you may be able to generate reasonable results assuming instantaneous equilibrium partitioning to generate a retardation coefficient.

If your site is more typical, with excess organic carbon available for biodegradation and a mixture of oxic and reduced conditions, you have a much harder problem on your hands. Redox-sensitive metals such as **arsenic** are particularly difficult. Under oxic conditions, aqueous arsenic exists primarily as arsenate (+5), which sorbs strongly to hydrous ferric and manganic oxides, making it relatively immobile. Under approximately the same conditions that lead to the reduction of ferric oxides to the more soluble ferrous forms, **arsenate** will be reduced to **arsenite** (+3), which is much more soluble (and toxic) and hence, mobile. *Your transport model will produce total garbage for answers unless it accounts for the redox conditions.*

The most successful models I've seen integrate a conventional transport model in an iterative fashion with a chemical speciation model such as MINTEQA2 or one of its derivatives. All the ones I'm aware of are essentially research type models that require a lot of data to calibrate with any kind of confidence. Recently, Carey Grant has released a free model called **BIOREDOX** [available at :
(http://www.rovers.com/natural_attenuation.htm)] that sounds quite promising although I must confess I haven't actually tried it. I suspect he will also answer your message sometime soon.

You may want to check out:

Smith, S.L., and P.R. Jaffe (1998), "Modelling the Transport and Reaction of Trace Metals in Water-Saturated Soils and Sediments,"Water Resources Research,Vol. 34, No. 11, 1998, pp. 3135-3147.

Yeh, G. T. and V. S. Tripathi (1989). "A Critical Evaluation of Recent Developments in Hydrogeochemical Transport Models of Reactive Multichemical Components." Water Resources Research 25(1): 93-108

Dzombak, D. A. and M. A. Ali (1993). "Hydrochemical Modelling of Metal Fate and Transport in Freshwater Environments." Water Pollution Research Journal of Canada 28(1): 7-50.

If you have wetland involved with plants you may even want to look at:

Kallin, P. L. (1999) "Modelling the fate and transport of trace metal contaminants in natural and constructed surface flow wetlands." PhD Dissertation, Princeton University. (Available soon at a library near me!)

Good luck,
Pete

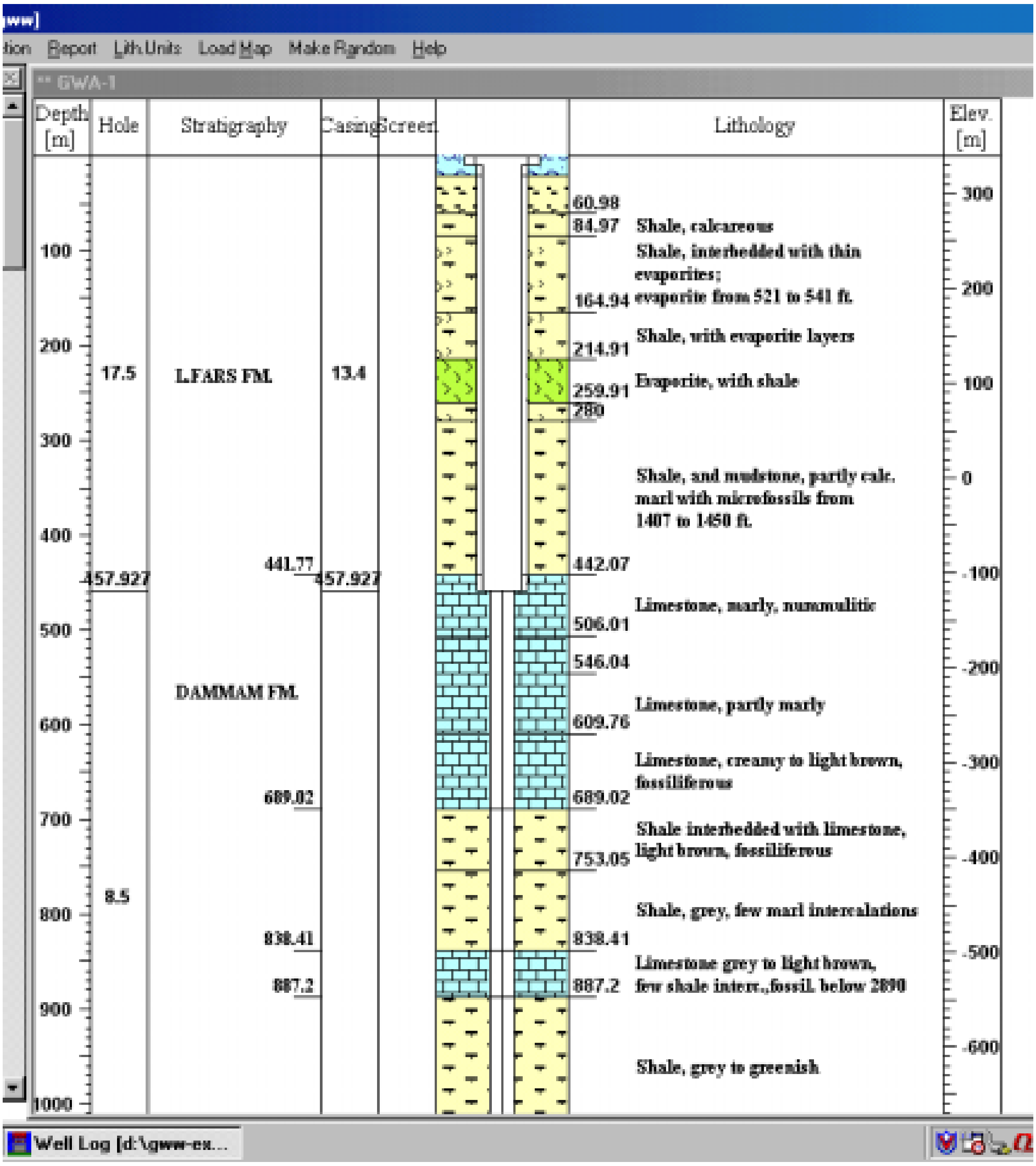
On Thu,
14 Jan 1999, Howard Frank wrote:

> I have a site where arsenic and other metals are chemicals of concern. I would like to do some fate and transport modelling for this site and I would like to know what models exist that will work for metals. Most of my experience is with VOC and I don't know if the models that work for VOC's can be applied for metals.
>
> Any suggestions would be very appreciated.
>
> Thanks,
> Howard Frank

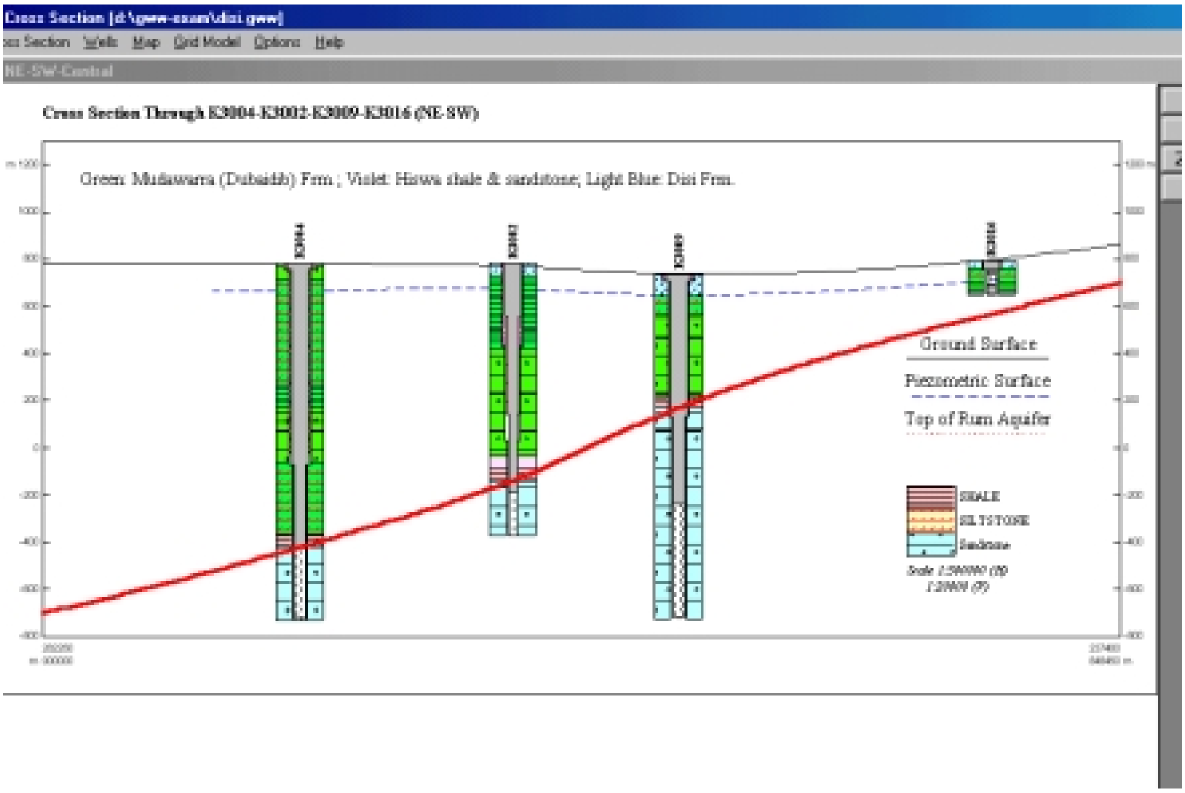
Appendix F.

Examples of Ground Water Data Processing and Presentation of Major Categories of Data

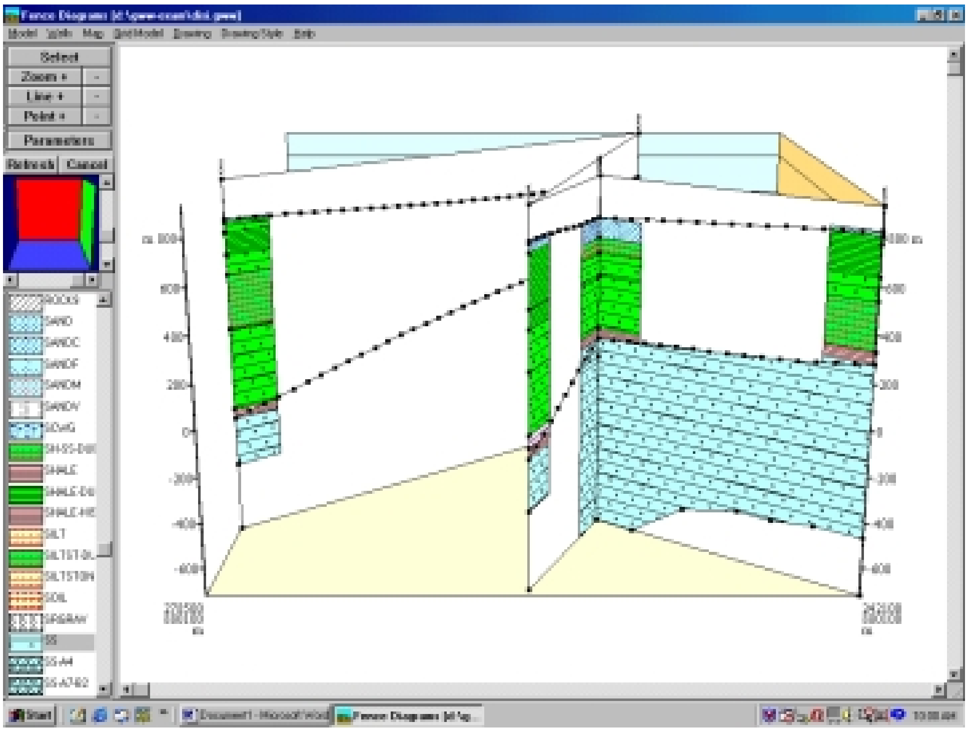
1. Lithologic Log



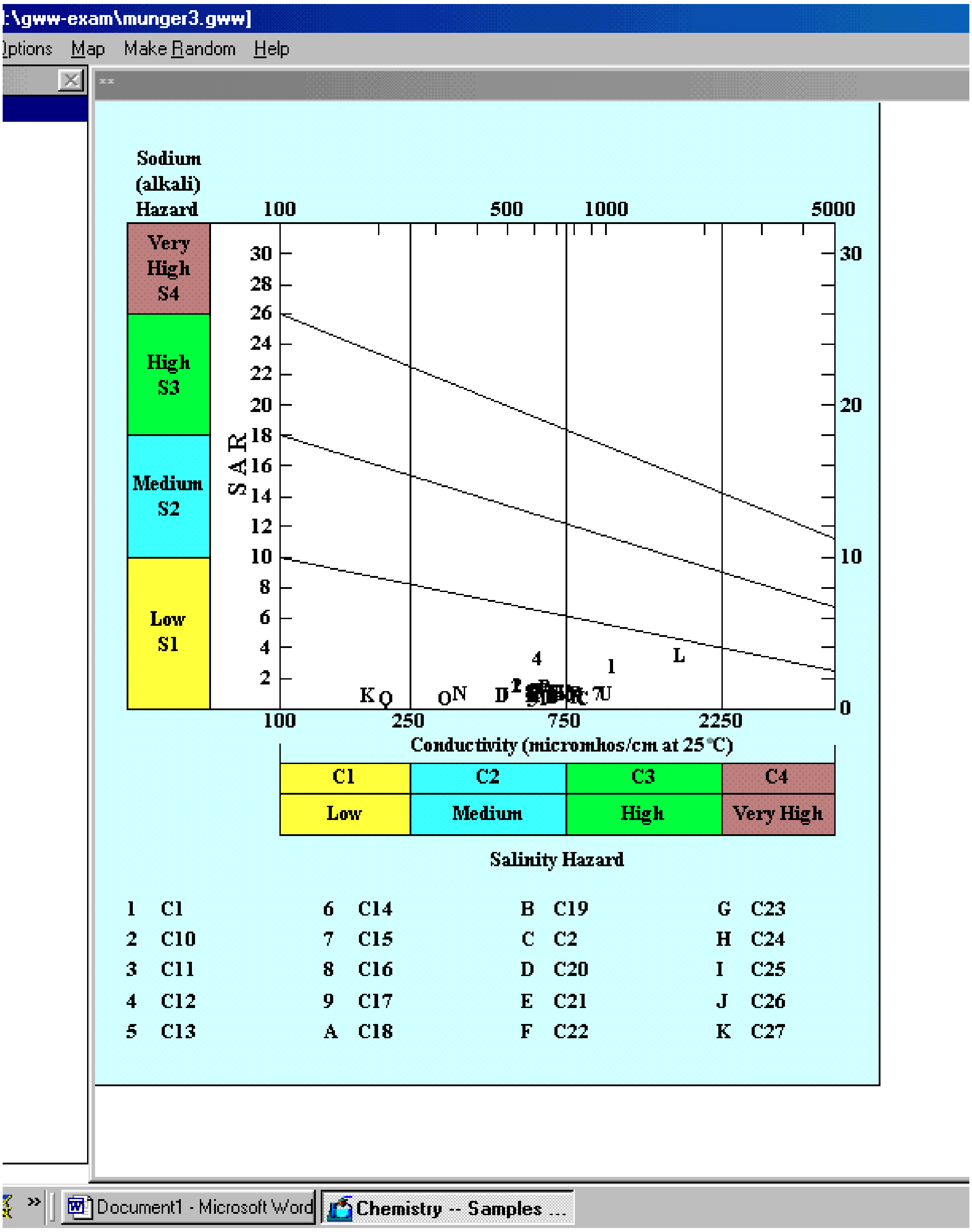
2. Lithologic Cross Section



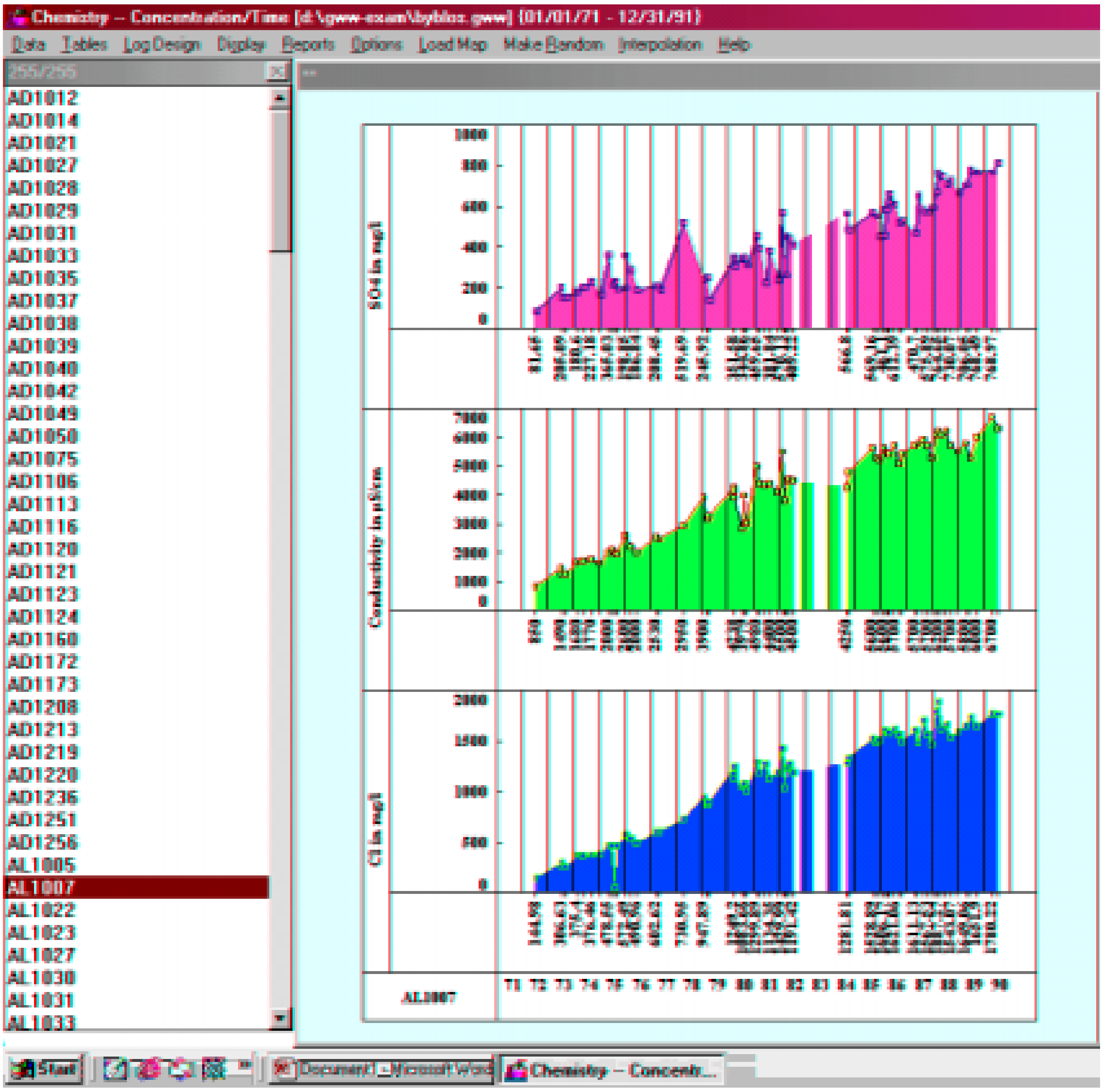
3. Fence (Block) Diagram



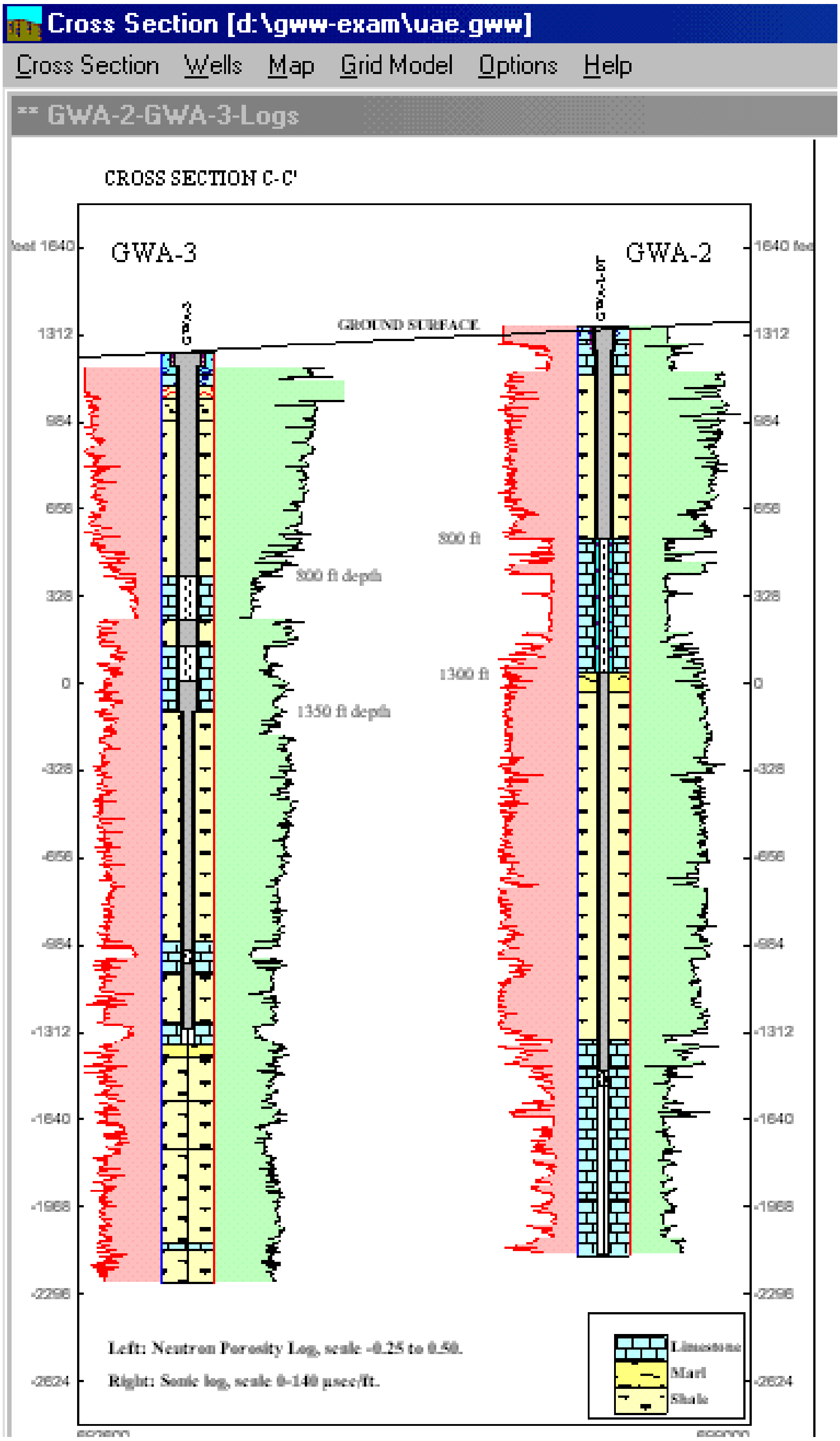
4. Wilcox Diagram (Water Quality for Irrigation) for Munger District


:\gww-exam\munger3.gww]
Iptions Map Make Random Help
Sodium (alkali) Hazard
Very High S4
High S3
Medium S2
Low S1
SAR
Conductivity (micromhos/cm at 25°C)
C1 Low
C2 Medium
C3 High
C4 Very High
Salinity Hazard
1 C1
2 C10
3 C11
4 C12
5 C13
6 C14
7 C15
8 C16
9 C17
A C18
B C19
C C2
D C20
E C21
F C22
G C23
H C24
I C25
J C26
K C27
Document1 - Microsoft Word
Chemistry -- Samples ...

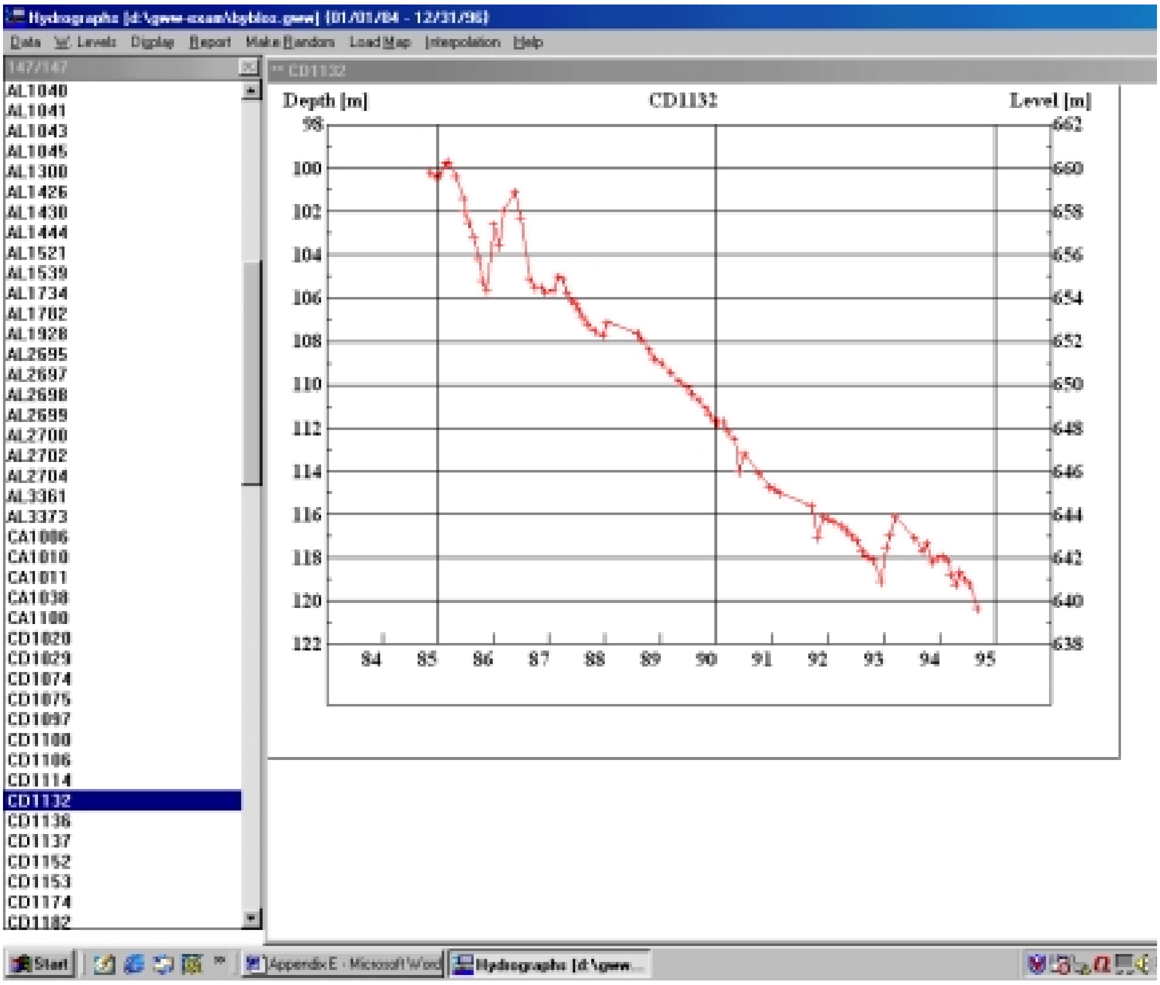
5. Time Series of Chemical Parameters (GWIS of Jordan)



6. Geophysical Logs in a Lithologic Cross Section



7. A Hydrograph (Water Level Fluctuations)



8. A Piper Diagram (Data from Munger District)