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Project GSA899002

Dr. Kirk Nelson
United States Bureau of Reclamation
Mid-Pacific Region
2800 Cottage Way
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Subject: Transmittal of Project Materials As of Dec 31, 2012 Adaptive Water Operations and Planning Decision Support Using Reliability-Based Global Optimization and Integrated-Hydrologic HydroGeoSphere Model

Dear Dr. Nelson:

As requested by the United States Bureau of Reclamation (Reclamation), we have prepared this letter to (1) summarize the status of the project tasks as of Dec 31, 2012 and (2) transmit relevant project materials to the Reclamation.

1.0 CONTRACT SUMMARY

On August 30, 2011, AMEC Geomatrix, Inc. (merged into AMEC Environmental and Infrastructure [AMEC] on January 1, 2012) was initially awarded a contract (reference number R11PD20257) to collaborate with Reclamation staff to conceptualize and develop the framework of a decision support system (DSS) for undertaking optimal water operations and planning decisions under various uncertainties. The period of performance is from September 1, 2011 to December 31, 2013. The scope of work for AMEC Geomatrix include the following tasks:

- Task A1: Develop Conceptual Design of DSS and Construct the Main Module/DSS Structure
- Task A2: Develop a Linkage between DSS and HydroGeoSphere (HGS)
- Task A3: Develop a Water Operation Module
- Task A4: Benchmark the Performance of DSS

The scope of work undertaken by Reclamation's staff include the following tasks:

- Task R1: Develop an Objective Function Evaluation Module
- Task R2: Develop an Optimization Module
- Task R3: Develop Stochastic Simulation Modules
- Task R4: Develop a GIS-Based Visualization Module
- Task R5: Documentation and Outreach Activities

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The AMEC's and Reclamation's tasks are interrelated and the project required close interactions between AMEC and Reclamation's staff.

On September 18, 2012, the Reclamation requested AMEC to provide a price proposal for an expanded scope of work under Task 4. The Reclamation modified the end date of the period of performance from December 31, 2013 to December 31, 2012. AMEC submitted a cost proposal with a statement of assumptions that Task 4 will take 6 months after the completion of software development and the scope of work cannot be completed by December 31, 2012.

Due to personnel and administrative changes within the Reclamation, Reclamation informed AMEC that Reclamation staff no longer continued their tasks and Reclamation planned to terminate the contract on December 31, 2012. On December 6, 2012, AMEC was requested to stop work after December 31, 2012 and to transmit relevant project materials to the Reclamation with this document to summarize the status of the AMEC's tasks.

2.0 BACKGROUND

Recently, simulation-optimization tools have become available to water source managers for optimal and cost-effective management of the resources. Furthermore, physically-based numerical models are increasingly being applied to simulate the outcome of different water management strategies. Most of these simulation and optimization tools are limited to simple hydrologic models and linear-programming optimization models and do not have the flexibility to deal with non-linearity of the objective and constraint functions. In addition, these tools have been developed in a deterministic framework and do not consider the uncertainty in the model parameters, as well as operational and regulatory constraints.

Due to complexity of hydrologic systems, the managers' knowledge of such systems is most often incomplete and predictions of future circumstances are inherently uncertain. In most of these models, it is apparent that constructed future events will not happen exactly as models predict. Therefore, valuable decision support tools are needed to assist water managers in assimilating water-resource data, simulating the response of hydrologic processes under fully integrated surface-water and groundwater systems, coping with uncertainties, and making optimal decisions.

In this work, it was proposed to link a robust HGS numerical model and a Differential Evolution (DE) optimization model. The end product of this research and development (R&D) work will be a valuable simulation-optimization tool for water managers to account for uncertainties associated with model parameters, forecasting of hydrologic events, water supplies, and water demands; and to reduce subjectivity in making decisions under constraints and conflicting objectives. Furthermore, the developed tool will provide an integrated framework for building, evaluating and communicating the net impact of their decisions to different stakeholders.

The main goal of this work is to conceptualize and develop the framework of a decision support system (DSS) for undertaking optimal water operations and planning decisions under various uncertainties. The DSS will comprise of several modules linked with each other to facilitate optimal objective decision-making subject to specified constraints.

Demonstration of the DSS under this project will be limited to an experimental example using a simple application of the HGS model. This R&D project falls under the authority of Water Supply, Reliability, and Environmental Improvement Act - Title I: California Water Security and Environmental Enhancement – Authorizes the Secretary of The Department of the Interior to implement water supply technology and infrastructure programs aimed at increasing and diversifying domestic water resources - Public Law 108-361

3.0 TASK A1: DEVELOP CONCEPTUAL DESIGN OF DSS AND CONSTRUCT THE MAIN MODULE/DSS STRUCTURE

A high-level conceptualization of the DSS and the framework for developing and linkage of constituent modules is the key to capturing the sources of uncertainty and achieving scalability and adaptability. The DSS was developed in the form of a modular framework with individual modules accomplishing one or more of the following modules which need to be included in the DSS:

- Main module – primary control
- Flow simulation module
- Water system operation module
- Performance/reliability evaluation module
- Objective function evaluation module
- Optimization module
- Stochastic-process simulation module
- GIS based visualization module

3.1 Conceptual Design

Figure 1 depicts the relationship among these modules. The DSS computes the optimized water system operation schedule of decision variables, such as (1) groundwater extraction, q, (2) surface water withdrawal, s, and (3) water flow into or from the regional reservoir, f. The procedures will be applied at appropriate time intervals using the latest collected data to adaptively update the water operation schedule. The uncertainties considered are addressed using a Monte Carlo simulation approach. The stochastic realization generator produces a pre-selected number of equally likely scenarios (1000 realizations for example) that capture the variability of the uncertain quantities considered. Subsequently, for each realization, the global optimizer uses the generated baseline observations, and the trial values of the decision variables to calculate the resulting water system response. The global objective function is defined as the probability of meeting the pre-selected performance criteria and can be evaluated by counting the number of realizations that satisfy these criteria. The global optimizer continues the iterative procedure to search for a target operation schedule that maximizes the objective function.

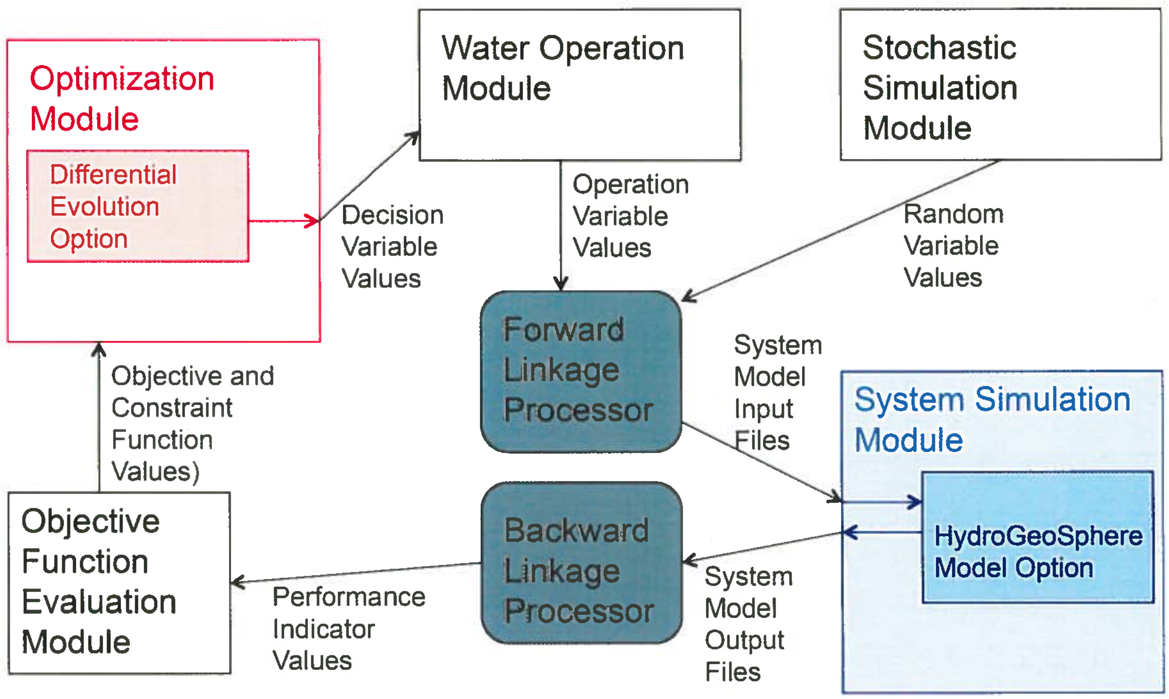

Figure 1. Conceptual structure of DSS

3.1.1 Stochastic Realization Generator

The stochastic realization generator consists of various models that produce statistically independently and equally-likely realizations of the uncertain quantities considered. The other models are conditioned on the latest historical data collected and their realizations will be generated periodically if needed. These models might strongly depend on rainfall and temperature factors, so the outputs from these models might be correlated to some degree. A stochastic climatic model will be used to generate realizations of rainfall and temperature variables, which are inputs to the stochastic models. It is important that the same climatic model realization is used to generate a single sample of realizations of related quantities, such as water demand, surface water availability, and baseline groundwater levels.

3.1.2 Evolutionary Global Optimizer

The Evolutionary Algorithm (EA) is a class of global optimization methods. Among many EA methods published in the literature, the Differential Evolution (DE) method has been reported as one of the most efficient algorithms. The solution starts with an initial population (a collection of individuals) in which their associated values (a vector of decision variables) are chosen either randomly or strategically. Through cross-over, mutation, and selection processes (known as genetic operators), the population evolves into the next generation that gradually improves the objective function value toward a global optimum. In the DSS framework, the constraints considered are nested within the DE iteration. Each DE iteration involves a search scheme that manages genetic operators to provide a subsequent generation or a preliminary solution. The resulting solution is further mutated (adjusted) by the water system operation procedures, which searches for the new production schedule that satisfies all the constraints and minimizes the differences resulting from operator adjustment. The DE-iteration continues until the solution converges.

3.1.3 Objective function

The objective function is defined as the probability that all performance criteria are met. The global optimization (Evolutionary Algorithm) searches for a solution that maximizes this probability value.

3.2 Software Structure

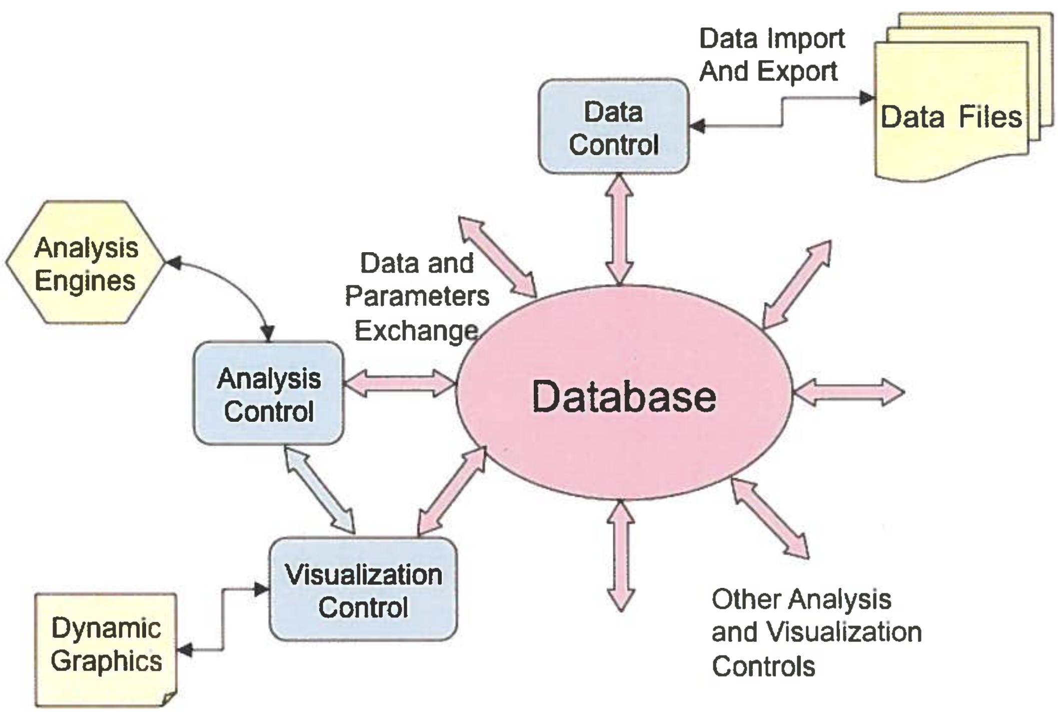

Figure 2. Software structure

Software development was focused on the following six areas: (1) centralized database, (2) graphical user interface, (3) dynamic graphics, (4) multiple input and output file types, (5) extensive help support and documentation, and (6) web access. The development will be incorporated in the following components. Figure 2 shows the conceptual data and control structure of DSS.

3.2.1 Enhancement of Software and Database Structure

The complete structure was constructed in an expandable and modular way. The code will be further developed around a centralized database. Instead of passing data through multiple data files in a wide range of formats, all data will be imported into a core database. An advantage of using a core database is data bookkeeping. Data from various sources can be stored coherently and logged systematically. In addition, the data in the database can be accessed outside the DSS using Geographical Information System (GIS) tools and other CAD software.

There will be additional codes developed to allow users to import data into a core database from data files in various common data format (such as Excel, fixed-width text, Access database, Geo-eas, Surfer grid, and Arcview shapefile). All analyses will be performed in a modular way. Each analysis module will invoke a routine to extract needed data and parameters from the database and to pass the extracted data to the analysis engine. After the analysis is completed, it will transfer the results to the database for storage. There will be additional routines to export data from the database to files in various common formats, such as Excel, fixed-width text, Access database, Geo-eas, Surfer grid, and Arcview shapefile. Visualization will be performed in a similar way. Data will be first extracted from the database, and then will be passed to the visualization module to generate graphics.

<u>Design of Database Structure</u>

The tables, queries, and data field relationship/linkages should be designed in the database. Specific standard tables will be created for each set and type of available data. Similarly, specific standard tables will be generated to store the output from various analysis engines. The relationship between the data fields in these tables will be constructed. In addition, standard queries and report templates will be built.

<u>Development of Data Import and Export Support</u>

Additional codes should be developed to import data from data files in other formats. In addition, codes will be developed for exporting data to data files in a range of formats.

<u>Development of Additional Graphical User Interfaces: Analysis and Visualization</u>

Front-end forms for the analysis modules and visualization functionalities should be constructed. The GUI will accept the user's selected parameters and trigger various analysis, visualization, and data management control modules. Default parameter values will be provided to the user and stored in the database. If the user selects to change these parameters, the updated parameter values will be stored in the database. A warning message will be displayed if the values selected by the users are not within the normal range common adopted. In addition, if the selected values are not within the acceptable range, an error message will be displayed and the user needs to re-enter a new value for the parameter.

Development of Module Linkages

Codes will be needed to link all the modules according to the framework. When the user instructs the software to perform an action through the GUI, it will invoke the appropriate control module in response to the action. The control module will extract data from the database and pass the data and user's selected parameters to the various engines (such as the analysis engines, visualization engines, and data management engines).

Upon receipt of the action request from the GUI, appropriate response will be triggered to pass control to the data import and export codes. Upon receipt of the action request from the GUI, appropriate response will be triggered to extract data from the database and to pass the data and user selected parameters to the analysis engine. After the analysis is completed, the results will be transferred to the database and displayed through the visualization module.

Linkage with Visualization Control Engine

Codes to link the new GUI with the visualization control module should be developed, especially with the visualization capability to generate dynamic graphics. The users are allowed to interactively change the attributes of the graphs and the pictures will be updated dynamically. For example, the user can change the color flooding scheme, brightness, picture scale and resolution to facilitate easy interpretation. In addition, the user can choose to display contours in natural and logarithmic scales and 3-D surfaces.

Development of Web Access Functionality

It is desirable to have the functionality to allow the DSS to access data and database through the web. This function will allow the user to have the flexibility to perform the analysis and make interpretation using the database stored in the office while performing exploration in the field. Newly collected data can be uploaded directly to the centralized database for other users to access.

Development of Help Support and Documentation

The purpose of this component is to provide the user with the technical reference information in electronic form. The help support will include:

- overview of the DSS,
- guidance on how to perform specific tasks,
- explanation of user selected parameters, their default values, common value range, and allowable bounds,
- explanation of various GUI dialog forms,
- step-by-step guidance on how a specific analysis should be performed,
- keyword indices and related essential references,

- linkage to the subject GUI.

The help support is intended to guide users who may not be proficient in using the DSS to easily navigate through the software. It also functions as a resource for experienced users to troubleshoot problems.

3.3 Task Completion Status

This task is 80% completed. The general conceptual framework and the software structure have been developed as described in Sections 3.1 and 3.2. The specific prototype based on the selected experimental example (Task A4) will need to be customized.

4.0 TASK A2: DEVELOP A LINKAGE BETWEEN DSS AND HGS

This task involves developing software for linking DSS with HGS model based on an experimental example selected by the Reclamation staff. The example was formulated using a simple application of HGS model as the flow simulator of the DSS. Customized programs for linkage of the DSS with the HGS code for the example are being developed. However, future developments could lead to a full range exhibition of user interactions with HGS program and a library of optimization and simulation applications.

AMEC developed the MathWorks MATLAB codes to link Microsoft (MS) Access database with inputs to software HGS with Graphical User Interface (GUI). The purpose is for better facilitate user interactions with HGS input files through database, so that the user can export HGS input data to a database, modify the documented data in database, and in turn, import the modifies data back into HGS input files. And the GUI helps the User to better visualize the data, modify the data, and apply established models and optimization algorithms. Eventually, the user can plot the output of HGS through GUI for ultimate control of the whole process. The developed codes provide the user with flexible interactions with the HGS program and full control of the input and output files. With the development of the GUI, a combination of optimization models and simulation tools can be added to maximize the user's interaction with the HGS program. It is apparent that the user can build his/her own "library" with input and output data together with the optimization and simulation tools.

4.1 Linkage Software Description

The software under this task includes:

(1) MATLAB code(s) that enables the user to export HGS input data from input files to MS Access database. It uses input file for Sacramento Valley water district as a prototype.

(2) MATLAB codes that enable the user to import data from MS Access database to HGS input files. It is the reverse of (1).

(3) Graphical User Interface that enables the user to specify inputs, apply optimization models and simulation algorithms, import and export input data, and visualize the output of the HGS program.

4.1.1 GrokInput2Access

This development has the capability of exporting information and data in an established HGS input file (grok input file) to the MS Access database. It utilizes the Sacramento Valley water district input files to HGS as a prototype and has an extensive coverage of topics including:

- grid generation
- general control options
- surface flow
- saturated subsurface flow properties
- overland flow properties
- specified evaporation
- et properties
- initial subsurface head
- initial surface head
- surface critical depth boundary
- river discharge
- surface precipitation flux
- solution parameters
- timestep controls
- target times, and
- output

The program allows the user to revise the established input files and the changes will be reflected in the data tables after the user runs the code. Note that the user needs to specify the right path of the database in the MATLAB code before running the program. Otherwise the program will complain about the accessibility of the database.

4.1.2 access2Grokinput

This second part of the development is the reverse of the first part GrokInput2Access. The data in the database can be exported back into the input file for the program. Multiple functions are developed for the main program, one function for each Access table. Note again that the user needs to specify the right path of the database in the MATLAB code before running the program.

4.1.3 graphical user interface

The third part of the development is the graphical user interface, which allows the user to specify the subsurface pumping rate and the routing if the user checks the checkbox, the rainfall, and the surface pumping rate. The rainfall can be imported from different models and this function is under development since the models are not available yet. The user specified inputs in these tables can be saved and exported to database through the pushbutton. There is an “Optimization” button which is supposed to import the optimization models to the tables in the GUI. This “Optimization” function will be working once the optimization schemes are put into action. The “RUN” button takes the input data from the tables specified by the user or from models, calls the database, updates the grok input files and make the HGS program run. It should create a new table updating the status. Currently this “RUN” button has a place holder and waits for the HGS program to be put into place. Finally the output of the HGS program can be displayed in the figures listed in the right side of the GUI. These figures include water head, flow subsidence and moisture content figures. At this moment, these figures are under development. Figure 3 shows the Graphical User Interface.

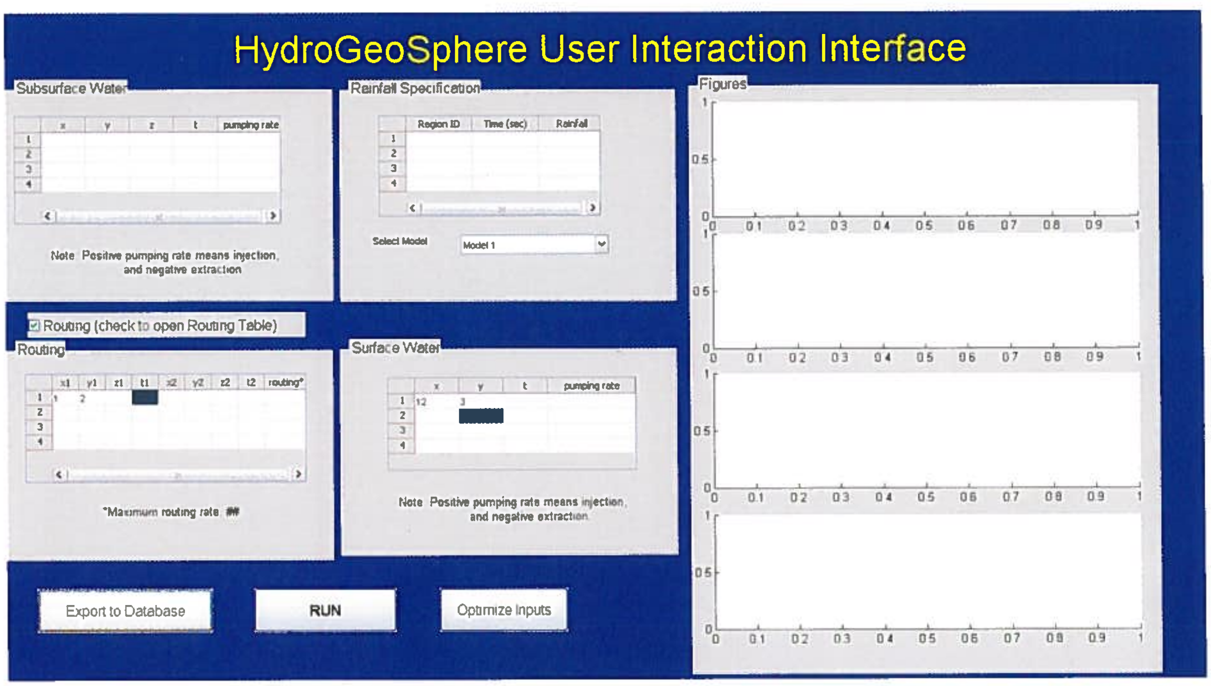

Figure 3. HydroGeoSphere User Interaction Interface

Step 1 – Specify the Subsurface Water Pumping

The table includes location (x, y and z coordinates), the time stamp (t) and the pumping rate. Note the positive pumping rate corresponds to injection and the negative pumping rate corresponds to extraction.

Step 2 – Routing

The user can decide either or not to specify routing. If the user decides to do so, he/she should check the checkbox for Routing. Then the table for Routing will show up. The tables has columns showing the initial location (x1, y1 and z1) and time (t1), ending location (x2, y2 and z2) and time (t2), and the routing rate. The maximum routing should not exceed a specific number. The number will be determined at a later stage

Step 3 – Rainfall

The rainfall table has three columns: region ID, time and rainfall. There is a dropdown menu showing models from which the rain fall information can be retrieved. At this stage, the models are not placed within the code.

Step 4 – Surface Water

The surface water table has the same columns as the subsurface water table in 2.3.1 except the z column. Again the positive rate means injection and the negative means extraction.

Once the tables are specified or populated through applying models or simulations, the user can choose to export the information to database. The pushdown button "Export to Database" works for this purpose. Right now the function works fine. Later it can be fine-tuned so that the data can be automatically overwritten. The RUN button and the "Optimization" button are currently place-holders. So are the figures on the right side of the GUI.

4.2 Task Completion Status

This task is 50% completed. The computer codes and database structure developed before the contract was terminated were provided in the Attachments A.1 through A.3.

5.0 TASK A3: DEVELOP A WATER OPERATION MODULE

This task includes the development of a customized program that provides a simple representation of the key water operation within the domain of the experimental model. The logic for the program shall be based on a set of rules (as determined in Tasks 1 and 2).

To improve the efficiency of the HGS model, the University of Waterloo was subcontracted to add one-dimensional line elements to the HGS code. These elements simulated pipe flow and streamflow by ignoring the non-uniform flow field across a cross-section. The non-uniform flow field in pipe flow and streamflow is normally insignificant in the context of water resources management. This task is completed and the additional code is provided in Attachment A.4.

6.0 TASK A4: BENCHMARK THE PERFORMANCE OF THE DECISION SUPPORT SYSTEM

This task involves benchmarking the performance of the developed DSS using an experimental example provided by the Reclamation. An example problem has been developed for use to benchmark the performance of the DSS.

- The decision variables include groundwater pumping rates at various wells, surface water withdrawal at various locations, and water routing schedule.
- The constraints considered include the capacity of physical systems, regulatory requirements, the need to meet with demands, and water level limits.
- The objective functions were defined in the context of maximizing water availability/water supply reliability, minimizing subsidence/subsidence risk, and flood hazard.
- The random variables considered include precipitation, water demands, and hydrologic parameters.

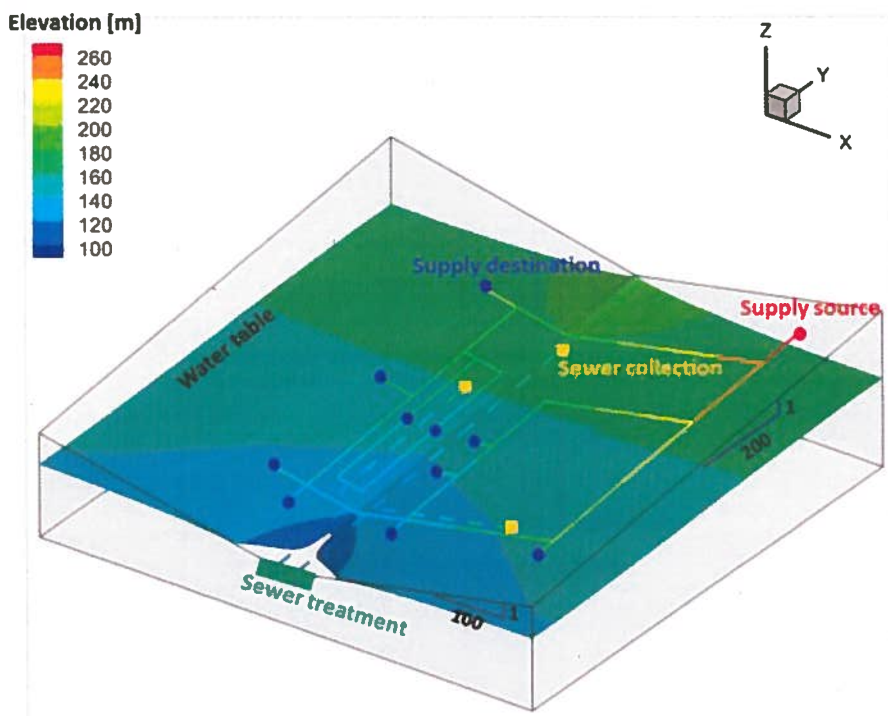

Figure 4. Conceptual Representation of the Experimental Example.

A HGS model has been developed for the example problem. The HGS model files are provided in Attachment A.5.

Sincerely yours,
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