AN INTEGRATED SURFACE SUBSURFACE MODEL IN WESTERN ORANGE AND SEMINOLE COUNTIES, FLORIDA

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Abstract: Population growth of Florida in recent years has resulted in a significant increase in the demand for water, with potential impacts of continually increasing withdrawals from the Floridan Aquifer System (FAS) occurring on the surface-water regime and the water-table aquifer. Previous modeling studies have focused on the FAS impacts but raise important issues regarding the surficial domain. The current study addresses the conjunctive issue of impacts of water withdrawals from any regime on the surface and subsurface regimes of the hydro-cycle, in Western Orange and Seminole Counties (WOSC). An integrated surface-water groundwater model has been developed for the analysis by telescopic refinement of the existing regional groundwater flow model for East Central Florida. The Surficial Aquifer System is conceptualized in greater detail to capture the relevant physics that may dominate at the smaller scale of investigation. The unsaturated and surficial flow domains have been rigorously treated, to extend the groundwater flow analysis into a conjunctive framework. The soils map of the region was used to parameterize the unsaturated flow properties and soil-dependent evapotranspiration parameters such as field capacity and wilting point. The land-use, land cover map delineated surficial flow properties such as infiltration characteristics and surficial flow roughness, as well as plant-dependent evaporation / evapotranspiration parameters like Leaf Area Index. The extensive surface drainage features that exist within the domain were also integrated into the model from available databases developed by the counties for flood management. Model development, parameterization, calibration, and significant results are discussed in the context of making improved long-term water management decisions using a conjunctive modeling approach in terms of meeting the increased supply goals as well as sustaining other surface water interests.

INTRODUCTION

The St. Johns River Water Management District (SJRWMD) is responsible for managing water resources within its jurisdiction including supply, quality and protection of natural systems. The District has developed a regional groundwater model (McGurk and Presley, 2002) in east-central Florida (ECF) for use in guiding the permit application process. The model included the entire hydrologic budget to determine groundwater recharge by accounting for runoff and unsaturated-zone evapotranspiration losses. However, the region contains several surface-water features that are inter-connected or internally drained and the ECF model's ability to adequately address the effects of pumping of the Floridan Aquifer System (FAS) on water levels in the surficial aquifer system (SAS), or on the numerous lakes and wetlands in the region is of concern. The ECF groundwater model was therefore assessed against an Integrated Surface-water / Groundwater Model (ISGM) that includes the unsaturated zone and surficial processes and has a better characterization of the Surficial Aquifer within the WOSC region. Other objectives of the integrated modeling study included:

- Characterizing trends in stage of groundwater and surface water monitoring stations (i.e., calibrate the model to emulate the available surface and subsurface flow data).
- Predicting steady-state and transient effects of projected future FAS withdrawals on water-table elevations and on connected lakes and wetlands.
- Addressing / quantifying grid-scale errors of the ECF model (i.e., examining if finer grids can produce more accurate results given currently available data)
- Addressing / quantifying the conceptual errors of the regional groundwater flow model in terms of the approximations used for handling surface water features (i.e., examining if more refined modeling of the unsaturated zone and surface water physics can produce more accurate results given currently available data)
- Examining the long-term transient effects of increased Floridan Aquifer pumping upon the water table and on connected lakes and wetlands.

MODEL CONSTRUCTION

The MODHMS (MODFLOW-based Hydrologic Modeling System) finite-difference code was used to develop the model for this study due to its flexibility and capability in handling the required flow physics. MODHMS is based on the popular USGS groundwater flow modeling code MODFLOW and includes several additional modules – the pertinent ones for this project include fully integrated modeling of subsurface flow, overland flow, channel flow and pond routing capabilities; capability of handling the required flow and boundary conditions; state-of-the-art robust and efficient solution schemes for large 3D problems with high heterogeneities (including robust drying / rewetting schemes, Newton Raphson linearization and efficient iterative sparse matrix solvers); and ability to easily process input and output data-files with the ViewHMS processor. Finally, besides robust unconfined simulation capability, a robust unsaturated zone flow capability provides flexibility to investigate various levels of complexity. Details of the governing equations and solution schemes are provided in Panday and Huyakorn (2004) and HydroGeoLogic (2001).

The area selected for the WOSC-ISGM is delineated in the land-use map of the area shown in Figure 1. The sub-basins in this study area include the Wekiva River basin, Little Wekiva River basin, Soldiers Creek Reach, Gee Creek, Island Lake, Cranes Roost Outlet, Mirror Lake Outlet, Long Lake basin, Lake Lovely Outlet, Trout Lake Outlet, Lake Apopka Outlet, and Unnamed Lake District. Some of these basins are internally drained while others have some form of surface outlet thereby providing evaluations of both types of basins within the ECF region. The selected domain boundary lies along basin or sub-basin boundaries to adequately accommodate boundary conditions for the surficial domain, as a no-flow condition across the basin divide along the boundary. This area was selected for discretizing the surface as well as subsurface domains, with use of telescopic refinement from the District's ECF model to provide lateral boundary conditions in the underlying aquifers.

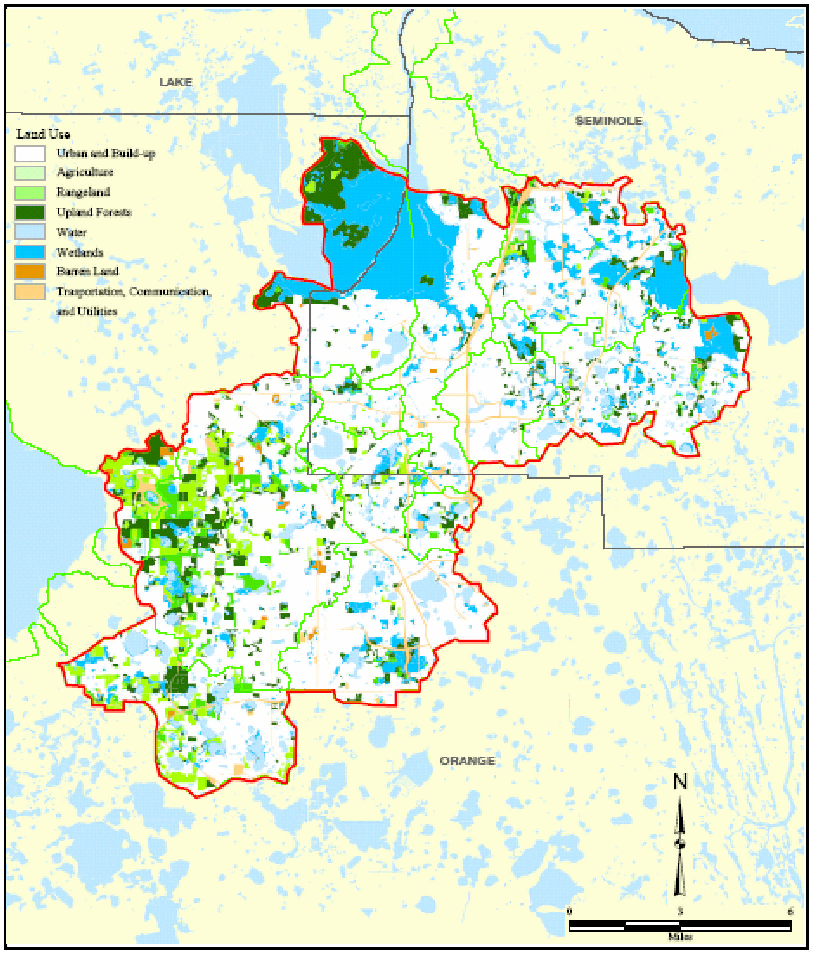

Figure 1 Land use / Land cover map and model domain.

The aquifers of interest include the SAS, and the FAS comprised of the Upper Floridan Aquifer (UFA) and the Lower Floridan Aquifer (LFA). The model was conceptualized based on the ECF model of SJRWMD and includes the SAS; the productive Upper Zone and a lower Dolostone Zone of the UFA; and the freshwater portions of the LFA. The SAS was further subdivided into four numerical layers to include the deeper stratigraphy and the unsaturated zone which was parameterized (for hydraulic conductivity, moisture retention and relative permeability) based on soil maps of the area using pseudo-transfer functions (van Genuchten 1980, Carsel and Parrish 1988). The Floridan Aquifer layers were parameterized according to the ECF model.

The conceptual model of the various hydrologic cycle components within the domain was based on the ECF groundwater model. Sources of water to the modeled system include precipitation, rapid infiltration basins (RIBs), water applied to the land surface as agricultural, golf course, recreational, and landscaping irrigation, and septic tank effluent. The major sinks of water from the system include pumping and evapotranspiration (ET) which was conceptualized as a combination of transpiration and evaporation. Lateral boundaries may allow for inflow or outflow through prescribed head conditions supplied by telescopic mesh refinement from the ECF model. For the ECF modeling effort, all surficial sources were subject to overland runoff using the SCS curve number approach and to estimated unsaturated zone ET, to provide a value for the groundwater recharge. However, for the conjunctive surface / subsurface model, these are internal processes governed by the physics of flow.

A physically-based, spatially-distributed approach was used for quantifying the surface water flow domain. Generation of runoff is modeled as a function of the topography, land cover features and the soil's overall drainage characteristics. ET is modeled as a function of the land cover and the soil moisture properties. Detailed topographic, land-use, and soil-type maps were used to areally distribute the data across the model region. Land-use maps (see Figure 1) were used with pseudo-transfer functions to provide overland flow roughness coefficients, the vertical conductivity of the surface, and leaf area index (used for ET computations). Soil-type maps were used to provide field capacity and wilting point moisture content information (Carsel et al., 1988). Area weighted averages were used to provide grid-block values. The values of the pseudo-transfer functions were varied within suggested limits during calibration, to give similar overall behavior for runoff and ET as the ECF model. No-flow conditions were provided along the lateral watershed boundaries of the surficial model layer.

A surface-water features layer was superposed on top of the surficial model layer to accurately simulate features which may be smaller than a grid-block size, and to convey water through canals or conveyance structures. The surface-water features in the study area include small lakes and ponds which are characterized by their stage-volume relationships and may be internally drained or connected via conveyance structures to other similar features or to channels, streams, and rivers. Geometric details of surface-water features, the conveyance flow and geometry characteristics, and linkage information among surface-water features was available from existing ICPR (Interconnected Pond Routing) models used by counties for planning purposes (Streamline Technologies, Inc., 1995). The ICPR models were used to directly import these complex node-link features into the WOSC-ISGM as depicted in Figure 2.

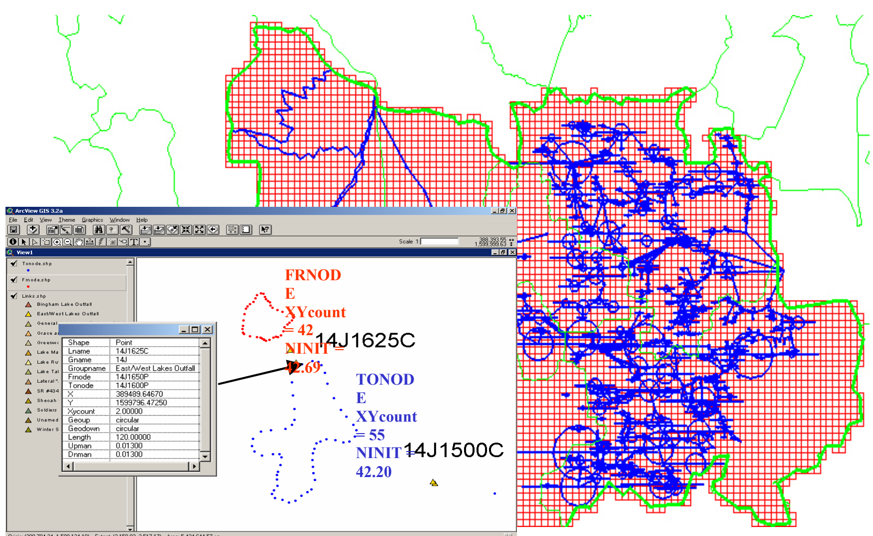

Figure 2 Hydrology from ICPR databases

RESULTS

Model development progressed from increasing grid resolution to enhanced SAS conceptualization and inclusion of unsaturated-zone flow. Table 1 summarizes the mass balance components for some of the simulations performed during systematically developing the subsurface component of the WOSC model from the steady-state 1995 ECF dataset. Data updates were also performed; therefore, a one-to-one comparison is not entirely possible. However, it is noted that reducing grid-size from 2500 to 1250 ft created a large impact on surficial aquifer head (resulting from finer resolution of RIBs) as compared to a further grid-size reduction to 625 ft. In addition, using a realistic distribution of SAS properties causes a reduction in overall model error. Use of real soil functions further reduces the RMS error (which is slightly larger than for the ECF model) but increases the average error (which is still much smaller than for the ECF model).

Table 1 Mass balance components for various simulation cases.

		Base case [2] ECF regional model	2500 Grid updated data	1250 ft Grid fine boundary	625 ft Grid updated data	625 ft Grid new ICU	add 2 model layers in SAS [5]	Real Soil
Maximum Head Error [1]								
	Layer 1	-	10	10	2	10	5(U)/2(L)	0(U)/0(L)
	Layer 2	-	1	<1	<1	1	<1	0
	Layer 3	-	1	<1	0	1	0	0
	Layer 4	-	0	0	0	0	0	0
Mass Balance								
Inflow:								
	Well	705,352	703,911	894,096	901,884	901,884	901,884	901,884
	Constant Head [3]	24,651,973	17,495,096	25,497,124	34,542,144	34,503,087	34,665,021	33,932,744
	Ponds [4]	15,349	6,151	4,770	11,294	11,189	10,009	142,517
	Recharge	18,708,918	19,899,245	21,061,552	21,889,542	21,889,542	21,889,542	23,549,521
	Total	44,081,592	38,104,403	47,457,543	57,344,865	57,305,703	57,466,457	58,526,666
Outflow:								
	Well	6,965,165	6,921,240	6,994,085	7,395,147	7,395,147	7,395,147	7,395,148
	Constant Head [3]	20,480,765	15,635,012	25,458,282	35,107,216	36,181,370	36,201,299	37,873,500
	Ponds [4]	36,392	69,306	94,338	127,625	125,863	132,627	50,680
	River	1,359,034	2,581,557	2,244,135	2,166,318	2,010,428	1,226,323	1,135,146
	Drain	4,143,753	6,119,277	5,500,683	5,192,185	5,205,433	5,213,219	5,238,369
	ET	5,818,766	6,778,010	7,166,018	7,356,372	6,387,460	7,297,839	6,833,900
	Total	38,803,875	38,104,403	47,457,543	57,344,866	57,305,704	57,466,457	58,526,744
Head Residuals								
	Average	1.8972	1.1607	0.6954	0.929	1.2452	0.1869	0.9966
	RMS	3.4311	4.6572	4.5267	4.38	4.045	4.3876	3.4277
Maximum (absolute)		8.127	13.5	11.78	11.8	11.72	12.73	8.261

1. Maximum Head Error is based on visual inspection of the head contours and is compared to previous run (previous column on this sheet).

2. Values in Mass Balance differ slightly from WOSC model because polyline marked to digitize sub-area is approximate.

3. Constant Head in Base Case (regional model) is the sum of Xmin, Xmax, Ymin, and Ymax as given by GW Vistas when the regional model is digitized along the Local Boundary. In all other cases Constant Head represents the mass-balance across all lateral boundaries of the local model.

4. Inflow and outflow for Ponds is obtained by digitizing area just around two locations with Constant Heads that are present in Layer 1.

5. SAS is divided into an upper (U) more conductive unit and a lower (L) less conductive unit as per available observed data

Further model development included incorporation of surface hydrology and hydraulics. The model was then calibrated to average 1995 conditions and to transient conditions from June 1995 through September 1999. NEXRAD data provided transient daily rainfall input at a fine spatial resolution and associated transient simulations with the ECF model provided lateral boundary head conditions for the subsurface. It should be noted that sensitivity analyses performed later, indicated a lack of sensitivity to lateral subsurface boundary head fluctuations at nodes more than 4 flow-connections away from the lateral groundwater boundary. Hence, the system influence is vertically dominated and not controlled by the lateral boundary fluctuations that are dependent on regional simulations. The maximum error of the steady-state model in the subsurface was 7 ft with an RMS of 3.2 ft. The maximum error for the surface-water observations of 14.8 ft occurs adjacent to a subsurface prescribed lateral head boundary condition which biases the results locally. The RMS error for the surface-water domain was 3.17 ft, and spring fluxes were within 0.5 cfs of their average 1995 observed values. Figure 3 shows the simulation results of transient calibration at a few water-level and flux observation locations, selected from a total of 36 subsurface observations; 51 surface water-level observations; 1 spring-flux observation; and 7 stream flux observations.

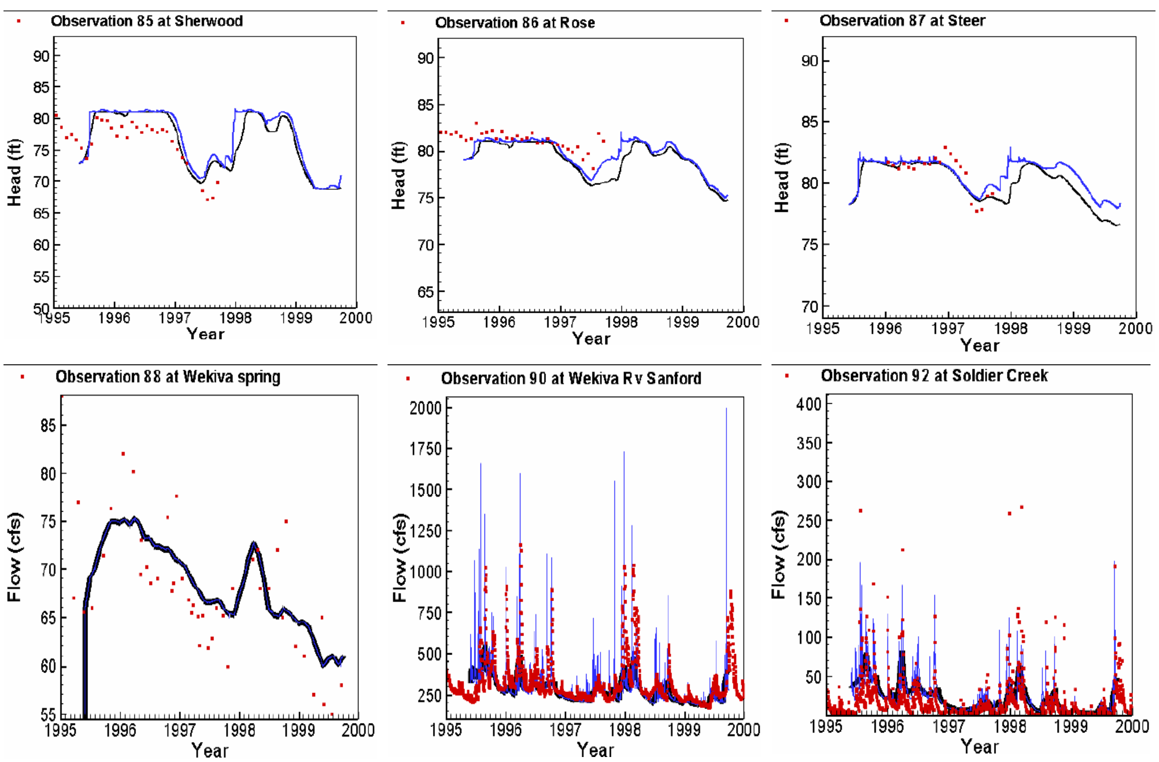

Figure 3 Calibration results including time-scale effects of daily (blue) versus monthly (black) rainfall input – red dots indicate observed values.

Figure 3 also depicts results (shown in black) from a simulation performed with monthly averaged rainfall inputs compared to results (shown in blue) from a simulation that used daily rainfall inputs provided by available NEXRAD data. This comparison was performed to note time-scale averaging effects since water management scenarios may include long-term simulations conducted over decades, which may be computationally burdensome and data intensive. Results of the time-averaged rainfall simulation are similar to those of the daily rainfall input case except for stream-fluxes during large storm events which may be greatly under-predicted. However, this may not be of consequence for ground water supply management situations and monthly-averaged variations of rainfall input may be adequate to evaluate water level and baseflow conditions in surface-water bodies, resulting from pumping in the FAS under transient rainfall input.

The WOSC-ISGM was further used to provide predictions of water-levels and flows for 1999 through 2025 conditions. 1995 through 1999 precipitation values were recycled to provide rainfall estimates and simulations were conducted with recycled pumping as well as with increased pumping conditions. Results are shown in Figure 4 for a few observation locations. Some water levels (47) declined throughout the prediction period for the increased pumping case, while others (13) declined during dry conditions but recovered during wet periods and still others (27) did not get affected by the increased pumping. Similar trends were also noted for stream-fluxes. A limited sensitivity analysis was also conducted to note the effects of parameters that are sensitive to steady-state conditions, on transient results (for transient calibration and prediction periods spanning 1995 through 2025). Again, it was noted that results may vary depending on the observation location, with some heads being extremely sensitive, others being sensitive only during drier conditions and yet others being insensitive to the parameter change.

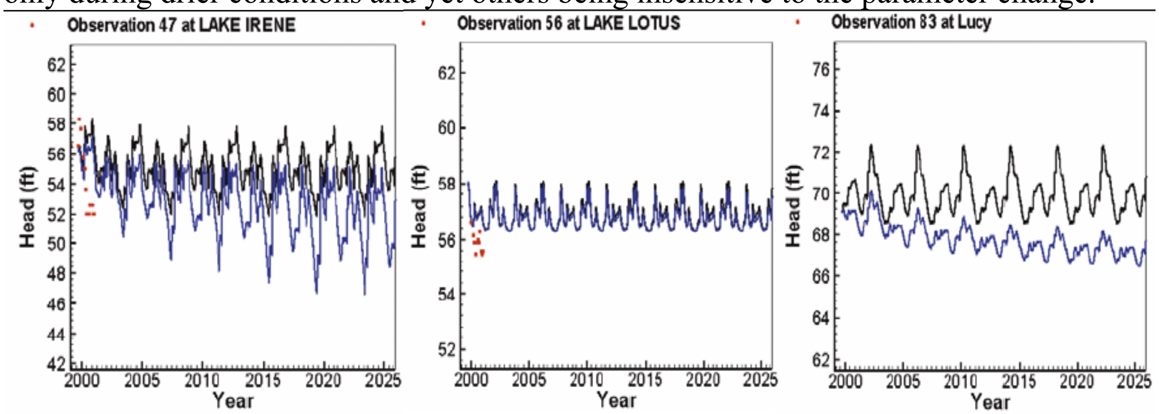

Figure 4 Water level predictions for recycled (black) and increased (blue) pumping.

CONCLUSIONS

An integrated surface/subsurface model was developed for the WOSC area. The model was constructed in a step-by-step manner from the ECF model of McGurk and Presley (2002) with inclusion of additional details within the SAS and addition of the unsaturated zone and surface-water domain to address the interactions between pumping of the FAS and water levels in the SAS or in numerous lakes, ponds, streams and wetlands in the region. Modeling objectives for the study have been achieved including:

- The model has been calibrated to emulate available surface and subsurface flow data.
- The model predicts steady-state and transient effects of FAS withdrawals on water-table elevations; water levels in connected lakes/wetlands; and stream/spring fluxes.
- Grid refinement addresses grid-scale errors of the ECF model – refinement from the original 2500 ft grid-block size indicates that results may improve significantly with

use of a 1250 ft grid providing local resolution near RIBs; however, a reduction in size to 625 ft showed reduced improvements. The SJRWMD is currently developing an updated ECF model with 1250 ft grid-block sizes. Simulations performed on the integrated model addressing time-scale issues for rainfall input indicate that monthly averaged rainfall input may be adequate for water resource evaluations and for predicting the effects of FAS withdrawals on surface-water bodies. Monthly averaged rainfall input is however not adequate to capture peak flow in the rivers.

- More refined modeling of the SAS system helps improve SAS calibration, however, a more refined unsaturated zone conceptualization does not seem to provide significant improvement on subsurface flow statistics. Inclusion of surface water hydrology and hydraulics provides a more complete picture of the hydrologic cycle and of movement of water within the domain, since the WOSC-ISGM further captures the flow dynamics and water-level fluctuations of surface-water bodies monitored within the study region.
- The long-term transient effects of increased Floridan Aquifer pumping upon the water table and on connected lakes and wetlands were evaluated by comparing results of future increased pumping conditions with results of pumping at current levels. General trends were not evident with some water levels declining continuously, others declining more during drier periods and still others being unaffected by the increased pumping.
- Future modeling efforts should include transient ET conditions, evaluate the parametric ET conceptualization with vertical equilibrium in the unsaturated zone, and address hydrologic and hydrogeologic data errors or uncertainties more rigorously.

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