EVALUATION OF UNITED STATES GEOLOGICAL SURVEY GROUND-WATER FLOW MODELS OF COASTAL GEORGIA AND SOUTH CAROLINA

DEPARTMENT OF NATURAL RESOURCES
ENVIRONMENTAL PROTECTION DIVISION
GEORGIA GEOLOGIC SURVEY

Atlanta

1999

PROJECT REPORT 38

EVALUATION OF UNITED STATES GEOLOGICAL SURVEY GROUND-WATER FLOW MODELS OF COASTAL GEORGIA AND SOUTH CAROLINA

Performed as part of the Georgia Environmental Protection Division's Interim Strategy to protect coastal Georgia from salt-water intrusion

DEPARTMENT OF NATURAL RESOURCES
Lonice C. Barrett, Commissioner

ENVIRONMENTAL PROTECTION DIVISION
Harold F. Reheis, Director

GEORGIA GEOLOGIC SURVEY
William H. McLemore, State Geologist

Atlanta

1999

PROJECT REPORT 38

Georgia Department of Natural Resources

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March 12, 1999

To: The Upper Floridan Technical Advisory Committee

From: William H. McLemore
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Subject: Project Report #38--Evaluation of United States Geological Survey Ground-Water Flow Models of Coastal Georgia and South Carolina.

Attached are three reports describing evaluations of United States Geological Survey (USGS) flow models of coastal Georgia and South Carolina. These evaluations were performed as part of the Environmental Protection Division's (EPD's) Sound Science Initiative, which is part of EPD's Interim Strategy to protect coastal Georgia from salt-water intrusion. The evaluations were performed by the consulting firms of ARCADIS Geraghty & Miller, Camp Dresser & McKee, and Law Engineering and Environmental Services, Inc.

The models were finite difference MODFLOW models covering the Floridan Aquifer and included: the USGS 1989 RASA Model, the 1991 EPD-USGS Coastal Model, the Garza and Krause 1992 Savannah Vicinity Model, the Randolph and Krause 1990 Glynn County Model, and the Smith 1988 Beaufort-Jasper County (South Carolina) Flow Model. When combined (but excluding the Smith 1988 Model), these models form a "telescoping"-model package.

With the above in mind, the three consultants were charged with the following: reviewing the appropriateness of USGS assumptions; appropriateness of USGS quality assurance procedures; appropriateness of the models' grid discretization and cell sizes; appropriateness of hydrogeologic boundaries, such as the Gulf Trough; documentation of model input parameters, such as Q, K, T, aquifer thickness, recharge, upward and downward leakage, lateral flow, etc; geographic/spatial density of input parameters; input parameters assigned to appropriate grid cell; appropriateness of steady-state simulations; justification of steady-state versus transient simulations; model input parameters; and data weaknesses. Each consultant's evaluation is provided in the remainder of this Project Report.

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Georgia Sound Science Initiative Review of Groundwater Flow Models

Developed by the USGS in Coastal Georgia

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1. Introduction

As a result of rising concerns over saltwater intrusion near Hilton Head Island, South Carolina and in Brunswick, Georgia, in 1996 the Georgia Environmental Protection Division (EPD) initiated an interim strategy for groundwater management, affecting 24 counties along the Atlantic coast of Georgia. Following are the objectives of the plan:

1. Conduct expanded scientific and feasibility studies.
2. Require comprehensive water supply plans for the 24 counties.
3. Create advisory committees.
4. Cap groundwater use in selected cities and counties.
5. Reduce groundwater use in Chatham County.
6. Allow interim groundwater use in areas with little impact.
7. Encourage and promote conservation.

The interim strategy is a plan to collect additional data and information and to develop a plan to manage groundwater resources threatened by saltwater intrusion in the Floridan aquifer along the Atlantic coast. This is a 10-year plan that will result in a broad-based approach to protect and sustain the groundwater resources for the 24 counties in Georgia and adjacent areas in the states of South Carolina and Florida.

The interim strategy calls for an aggressive management plan for resources during the planning phase to ensure that management scenarios are not precluded. Cooperation among industry and local municipalities has been encouraging in the early stages of the planning phase. Following detailed and comprehensive studies, including substantial input from stakeholders, a final strategy will be developed by December 31, 2005.

In 1997, the General Assembly passed legislation that mandates the development of a coastal groundwater management strategy. The legislature called for a study committee composed of stakeholders and headed by representatives from the legislature to develop a plan to prepare a long-range management plan for the coastal resources. The study committee met several times to discuss the elements of a comprehensive assessment of the coastal resources, as well as the data and information needs for a successful study.

As a result of preliminary committee meetings, the members formed an Upper Floridan Technical Advisory Committee (TAC) to provide guidance for the technical and scientific studies aimed at filling data gaps and improving our understanding of the system. The TAC is comprised of stakeholder members, supported by the technical staff of the U.S. Geological Survey (USGS), Georgia EPD, and selected industry consultants.

A series of scientific studies were identified from these initial meetings, which should be undertaken to enhance our understanding of the groundwater resources and how the system reacts to stresses. Enhanced understanding is essential to develop a plan on which stakeholders can rely and decision makers can use with confidence.

One of these studies included the development of a reliable groundwater model or models that can be used as a tool to simulate and predict management decisions. This project is the first step in developing these models. Specifically, this project includes the review and evaluation of five specific existing groundwater flow models. The review covers the assumptions specific to each model and the construction, calibration, sensitivity analysis, verification, and reporting processes. The evaluation was conducted to determine the usability of each of the models. Finally, recommendations were given regarding future use of these models along with a proposed plan of action for future modeling efforts.

2. Summary of Documents and Electronic Files Reviewed

At the request of Georgia EPD, the USGS has made all of the Regional Aquifer System Analysis (RASA) models available to Sound Science Initiative reviewers via the Internet. The files are currently located on the USGS ftp address fs1dgadrv.er.usgs.gov (144.47.32.102). Through an anonymous login, the files can be found in the subdirectory var/ftp/pub/gwmodels. The files are stored in unix format and are archived (tar'd) and compressed (Z). This was done on a Data General computer running Data General's Unix operating system. ARCADIS Geraghty & Miller also reviewed the actual reports that document the development and use of the models.

The following files were downloaded and reviewed as part of this study. The RASA Model and the Savannah Model were actually run to evaluate a hypothetical scenario requested by Georgia EPD.

2.1 RASA Model

The file "pp1403-d.tar.Z" contains the model described in Hydrology of the Floridan aquifer system in southeast Georgia and adjacent parts of Florida and South Carolina (Krause, R.E., and Randolph, R.B., U.S. Geological Survey Professional Paper 1403-D, 1989, 65 pp.). The associated file "pp1403-d.tarfiles" is the file list.

2.2 Savannah Model

The file "ofr92-629.tar.Z" contains the model described in Water supply potential of major streams and the Upper Floridan aquifer in the vicinity of Savannah, Georgia (Garza, Reggina, and Krause, R.E., U.S. Geological Survey Open-File Report 92-629, 1992, 49 pp.). The associated file "ofr92-629.tarfiles" is the file list.

2.3 Brunswick/Glynn County Model

The file "wrir90-4027.tar.Z" contains the model described in Analysis of the effects of hypothetical changes in ground-water withdrawal from the Floridan aquifer system in the area of Glynn County, Georgia (Randolph, R.B., and Krause, R.E., U.S. Geological Survey Water-Resources Investigations Report 90-4027, 1990, 32 pp). The associated file "wrir90-4027.tarfiles" is the file list.

2.4 Coastal Model

The file "ggsbull-116.tar.Z" contains the model described in Water-supply potential of the Floridan aquifer system in the coastal area of Georgia--a digital model approach (Randolph, R.B., Pernik, Maribeth, and Garza, Reggina, Georgia Geologic Survey Bulletin 116, 1991, 30 pp). The associated file "ggsbull-116.tarfiles" is the file list.

2.5 Smith Model

The file "Smith.zip" is the model described in Ground-Water Flow and Saltwater Encroachment in the Upper Floridan Aquifer, Beaufort and Jasper Counties, South Carolina (Smith, B.S., U.S. Geological Survey Water-Resources Investigations Report 87-4285, 1988, 61 pp).

3. Model Review

This section documents the review and evaluation of the five existing groundwater models: the USGS RASA Model, the EPD Coastal Groundwater Model, the Savannah (Hilton Head) Model, the Glynn County Model, and the Smith (Hilton Head) Model. Items evaluated for each model include purpose, objectives, calibration, description of how the model was used (and how it relates to parent model), brief summary of results, limitations of the model, and any defects or errors detected by ARCADIS Geraghty & Miller.

3.1 USGS RASA Model

The RASA Model was developed with the following primary objectives: (1) identify the types of data that are needed to understand the flow system and indicate what data are lacking; (2) provide a working hypothesis for testing and evaluating various concepts of the flow system; and (3) provide a tool that can be used to evaluate alternative methods of resource management and to estimate the development potential of the aquifer system.

The groundwater flow model included data to describe the hydrogeologic system that included (1) precipitation, stream flow, evapotranspiration; (2) aquifer characteristics, including thickness, specific capacity, hydraulic conductivity, and transmissivity; (3) hydraulic head; (4) confining-unit characteristics, including thickness, vertical hydraulic conductivity, and leakage coefficients; and (5) water use.

Based on our review, the RASA Model appears to adequately represent hydrologic conditions in the Upper and Lower Floridan aquifers and is a suitable tool to understand regional flow conditions in the Floridan aquifer. The model is not considered to be state of the art in the present day, strictly on the basis of grid resolution. The same modeling study undertaken today would have used substantially more grid cells to represent the model domain; however, the general approach would be similar. The RASA Model, while suitable to examine flow conditions on a regional scale, contains many limitations that reduce the usefulness of this model for managing groundwater resources threatened by saltwater intrusion in the Floridan aquifer along the Atlantic coast.

The RASA Model was not used in the past as a management tool to reduce or stop saltwater intrusion along the Atlantic coast. The model was used primarily to understand current declines in water levels of the Floridan aquifer system in response to increased pumping. The model was also used in other higher resolution modeling studies as a parent model to define boundary conditions in the smaller model. The RASA model is suitable for these purposes.

The RASA Model was calibrated (initially) to two distinct steady-state flow conditions: a period representative of pre-development conditions (one in which no pumping stresses or average recharge conditions existed) and a period representative of observed conditions in May 1980. The final calibration was performed in an iterative fashion between the two modeled periods to ensure that acceptable simulation results were achieved using a single numerical representation of the flow system. At a later date, the model was also calibrated to a 1985 data set. It is our opinion that calibration to multiple data sets (each exhibiting distinctly different hydrologic conditions) adds to the robustness of the model and the level of confidence that can be placed in simulated results (predictions of future conditions under defined changes to hydrologic stresses).

Based on our review, the RASA Model was adequately calibrated to meet the stated objectives of the regional modeling effort. However, several issues should be considered prior to additional use of the model as a predictive tool or as the foundation for additional subregional modeling efforts. The following suggestions are offered:

- The model should be re-calibrated to a more recent data set(s). It is our understanding that 1998 potentiometric surface maps are being developed for the Floridan aquifer system. This data set represents a well-distributed set of observed water levels throughout the study area.

- Continued measurement of water levels throughout the yearly cycle to better approximate and average yearly conditions.

- Recalibration should consider the effects of seasonal fluctuations in water levels as they relate to seasonal stresses. The simulation of average yearly conditions may be more appropriate considering the fluctuations in agricultural stresses (and to a lesser degree public supply pumpage). This assumes that more detailed and complete pumping records are available than have been in the past.

- Because of the potential future use of the model as a base for transient seawater transport modeling, a transient flow calibration should be considered to demonstrate the ability of the model to adequately reproduce transient system responses.

The items described above relate only to calibration and the model framework as it is currently constructed. Further consideration should be given to better detail (resolution) of the model and simulation of the surficial aquifer. Many of the seasonal stresses are imparted on the surficial aquifer and therefore, their impact on the Upper Floridan cannot be simulated. The overlying surficial aquifer is treated as a constant head (though aerially variable) source sink layer for leakage to and from the Upper Floridan. The model was configured to use spring conditions during 1985 as the base condition to evaluate postulated pumping impacts. Significant increases in agricultural pumping and irrigation have occurred over the past 10 years, much of which has occurred in the Miocene aquifer. The model cannot evaluate impacts to the surficial or Floridan aquifer from pumping in the Miocene aquifer. The prescribed water table constituting the fixed head layer (uppermost model layer) may require revision for future use of this model if the impacts of agricultural and/or other pumping has significantly depressed the water table.

Ordinarily, the surficial aquifer (Model Layer 1) is simulated as an active free-water surface. Several problems have been identified with treatment of the surficial aquifer as a constant head layer. The primary problem is that the fixed water table becomes an infinite source of water to the model. Groundwater is recharged into the model at whatever rate is necessary to maintain the specified head in all surficial aquifer cells. The model is calibrated by adjusting the leakance coefficient between the surficial aquifer and the Upper Floridan (Layer 2) until heads in the Floridan water levels match observed heads. This could result, however, in an unrealistic amount of water recharging the surficial aquifer. The model may also provide too much recharge to the Upper Floridan, resulting in reduced drawdown at pumping wells. An added problem during transient simulations is that the heads in the surficial aquifer will never fluctuate because of changes in pumping or recharge, which is also unrealistic.

Simulating the surficial aquifer as a fixed head layer is reasonable only if little is known about the surficial flow system, both in terms of flow system continuity and aquifer properties, and only if there is a weak hydraulic connection between the surficial aquifer and the Upper Floridan aquifer. By treating the surficial aquifer as a constant head layer, no calibration is required to obtain a match between observed and calculated heads. In essence, the calculated heads are the observed heads.

In summary, neither method of treating the surficial aquifer in the numerical model is perfect; each method has problems. The active free-water surface method should be used in future modeling primarily so that realistic recharge estimates can be input directly into the model and so that water levels in the surficial aquifer can fluctuate in response to pumping during the transient simulations. Transient analysis will be required in the future to simulate drought conditions and for saltwater intrusion transport. A model that includes an active surficial aquifer must also include reasonable recharge rates, and conductivities in the surficial aquifer are more flexible and better suited to evaluate current and postulated withdrawals from the surficial including Miocene units of the Hawthorn Formation.

It is evident that more data are needed in this area of the model to better determine the interaction between the surficial aquifer and Upper Floridan aquifer. Researchers should especially study the separation of regional and local flow systems in the surficial aquifer.

The USGS RASA Model is not suited for direct use to evaluate withdrawals in other aquifer units other than the Floridan aquifer, however, it can be useful to future modeling studies. It is a good building block for a more detailed regional groundwater flow model, or it can continue to be used as a base for detailed subregional models. Individual grid blocks of the RASA Model are 16 square miles each. The model lacks the necessary resolution to evaluate flow conditions in the direct vicinity of any given well but can evaluate regional impacts from that well. The model can only be used qualitatively to evaluate potential hydraulic effects on the surficial aquifer (lake stages, spring flows, vegetation) from pumping in the Floridan by evaluating the change in computed flow, i.e. recharge from the surficial aquifer. The model can also be used to predict changes in seaward flow of freshwater to infer changes in stress on the freshwater/saltwater interface.

3.2 Savannah (Hilton Head) Model

The Savannah Model was developed to evaluate the effects of additional pumping on water levels near known sites of saltwater encroachment at Hilton Head Island and Brunswick. The model is a subregional model developed from the RASA Model. The model contains significant enhancements to horizontal mesh resolution and was calibrated to 1985 conditions. The calibration resulted in an improved match between observed and simulated water levels. While the improved discretization was necessary to meet the objectives of the study with improved accuracy, the model suffers from the same limitations of use as described above with the RASA study. The Savannah Model differs from the RASA Model only in size and resolutions; the general structure (layering) of the model and treatment of the surficial aquifer are the same as the RASA Model. During the analyses using this model, the Glynn County model was also used to evaluate impacts; to the south. The telescoping set of models generally performs well to evaluate flow stresses and head impacts; however, it is always more complicated when dealing with multiple models rather than a single model.

Analyses performed during this investigation demonstrated that the model could be run in steady-state mode to evaluate pumping effects and that transient effects were generally small. However, it should be recognized that transient simulation will be essential for future saltwater intrusion modeling.

During calibration, the Savannah Model transmissivity distribution was refined to take advantage of the finer computation mesh. The changes to transmissivity were reintegrated in the parent RASA Model, and attempts were made to ensure that the values were consistent with the Smith Model (Smith 1988). The Smith Model was developed specifically to evaluate flow conditions near Hilton Head Island.

The calibration of the Savannah Model is significantly improved over the RASA model. It appears that this model is very reliable for prediction of hydraulic impacts to the Upper Floridan aquifer. The calibration is certainly adequate for regional aquifer analyses (Savannah, Hilton Head, and surroundings).

The model was used to evaluate pumping alternatives, either effects of additional stresses or relief or relocation of current pumping stresses. The results were presented only as impacts to the hydraulic head distribution. The model results were not used to make predictions on the potential for saltwater intrusion. The impact analyses performed evaluated ways to reduce drawdown in the vicinity of Hilton Head (and other areas where indicator nodes are located). These are good examples of the appropriate use of these models. However, it is clearly stated in this model report that "... stabilizing potentiometric heads at indicator sites at current levels might not prevent future lateral migration of seawater. Landward encroachment will continue to occur along previously established head and concentration gradients. The Savannah area model simulates lateral flow of water of constant density and cannot address conditions of variable-density flow, such as landward encroachment of seawater into freshwater aquifers." To evaluate actual potential for saltwater migration, a variable-density model must be developed. None of the models reviewed as part of this study are variable-density models.

3.3 Brunswick/Glynn County Model

This model was developed with the objective of evaluating development potential of the Upper Floridan aquifer in coastal Georgia, such that the development would result in no change in groundwater levels in areas of known saltwater intrusion. The model was also developed in this area because of concerns about the upward migration of saltwater and the potential for contamination of the aquifer in Brunswick, Georgia.

This model was developed in a similar fashion as was the Savannah Model. The model use is nearly identical to the Savannah Model, and the model contains the same inherent limitations on use. This model is not calibrated quite as well as the Savannah Model; however, it is felt that the calibration is generally adequate for regional flow analysis.

3.4 Coastal Groundwater Model

This model was developed with the objective of evaluating development potential of the Upper Floridan aquifer in coastal Georgia in a similar manner to the models discussed above. This model in particular was developed to encompass a larger area than either the Savannah or Glynn County models. The model contains identical structure to that of the RASA, Savannah, and Glynn County models. The Coastal Model's grid resolution is 2 miles on a side for each grid block. This model contains greater resolution than the RASA Model, but lower resolution than the Glynn County or Savannah models. The Coastal Model, because of its size, can simulate hydraulic effects over a larger area than the Savannah or Glynn County models, which adds greater flexibility and ease of use than the other models. The Coastal Model contains identical assumptions and limitations of use as mentioned previously with the RASA and other USGS models for coastal Georgia.

Calibration of the Coastal Model generally mimicked the approach used in the RASA and Glynn County models. The model was calibrated to three "steady-state" periods: a predevelopment period, 1980 conditions, and 1985 conditions. Similar to the RASA and Glynn County models, the Coastal Model was considered calibrated when vertical flows between similar model areas matched within 10 percent, and the mean error between simulated and observed heads was less than 10 feet. In general, because of the greater resolution of the Savannah and Glynn County models, these models may contain a higher degree of accuracy than the Coastal Model.

3.5 Smith (Hilton Head) Model

This model is the only departure from the USGS family of telescoping models. The structure of the Smith Model is inherently different than the USGS models and does not rely on the RASA Model of Georgia to predict boundary flows. The Smith Model uses estimated boundary conditions to set inflow rates of groundwater along the edges of the model domain. While the boundary flow values used in the presented simulations may be appropriate, the model lacks the flexibility of the USGS telescoping models to simulate a wide range of system stresses. Boundary adjustments are handled automatically by the USGS models, but the Smith Model would require significant modification to appropriately simulate this stress. Another significant limitation of the model is that neither the Lower Floridan aquifer nor its effects are included in the model. Therefore, the model cannot evaluate interactions between the Upper and Lower Floridan especially if the model is ever to be used to evaluate a shift in pumping from the Upper Floridan aquifer to the Lower Floridan aquifer. The assumption in this model that the base of the Upper Floridan aquifer can be treated as a no-flow boundary is not supported by the information presented in the USGS models, is not adequately described in the Smith report, and may be an oversimplification of the system. In fact, pumpage from the Lower Floridan in the Savannah area is not considered in the model.

Calibration of the Smith Model was to 1984 conditions. Neither pumpage values nor boundary conditions were changed during the calibration effort. Calibration was accomplished qualitatively by comparing potentiometric surface maps of simulated versus observed, and quantitatively by first comparing location-specific observed head values versus simulated values, and then by a statistical analysis of the root mean square error. In general, the simulated potentiometric surface matched the observed, with the largest discrepancies found in areas of cones of depression. Differences of 10 to 20 feet existed in the vicinity of the Savannah cone. The final calibrated value for the root mean square error was 5 feet. Although on paper, the calibration effort appears acceptable, the overall use and confidence of the calibrated model are limited by the restrictive assumptions inherent in the way the model was constructed.

The model was used to evaluate not only hydraulic impacts but extends some hydraulic predictions (qualitatively, but density-dependent modeling is required) to determine the change in potential for saltwater encroachment. Some predictions are made on the rate of encroachment based on velocities calculated from landward hydraulic gradients produced by pumping. Some statements are included in the Smith text regarding limitations of such calculations, but it is important to recognize that often the limitations and qualifications mentioned in the text are overlooked. This calculational approach is really appropriate only to determine the rate of migration of dissolved phase constituents that do not affect the density of the groundwater. The freshwater/saltwater interface will move in response to landward hydraulic gradients, but the interface will also move in a landward direction without a gradient reversal simply because of a reduction of freshwater flow toward the coast (buoyancy effect).

Additional simulations are presented to evaluate groundwater injection along the coast to reverse saltwater encroachment. While the model is of considerable value to evaluate the hydraulic effects of groundwater injection, assessments as to whether the interface position will move can be evaluated only by comparing the change in net flux of freshwater towards the coast. The report appears to make conclusions based on head gradients alone, not by seaward groundwater flux comparisons. It is agreed that injection should reduce the potential or lessen the rate of encroachment, but this analysis should be accompanied by additional calculations of change in seaward flux. This type of model simulation may be useful to determine the potential and future direction of the interface, but cannot be used to evaluate the rate of migration of the interface. To understand the transient nature of saltwater encroachment, a density-dependent model must be used to evaluate the effect of changing hydraulic gradients and buoyancy effects.

4. Future Use of the Existing Groundwater Models for Assessment of Alternative Withdrawal Scenarios Model Reliability/Accuracy

Assessing the reliability of a groundwater model is difficult; however, some general statements can be made regarding the reliability of the reviewed models. In discussing reliability, three concepts must be understood, as outlined below:

- Hydraulic heads computed by the model represent average values for a rectangular prism constituting the model cell. The smallest of such cells in any of the models is 0.25 miles on each side and generally well over 100 feet thick. In areas in which the model grid is coarser, model predictions are much less accurate because of the scale of the individual cells.

- The model is only as good as the database upon which model assumptions are based.

- Model parameters are representative of bulk regional properties and may not match individual aquifer or laboratory tests in wells.

Another key concept to remember when using or evaluating these models is that they are regional. Thus, the model should be used to solve multi-, county-wide problems or to assess flow system response over significant portions of a county. The concept will be especially true for future saltwater migration simulations, which will not be as accurate as the groundwater flow simulations.

The present models have generally been shown, through calibration, to reliably simulate hydraulic heads under predevelopment and recent pumping (1985) conditions. The model computes heads during these time frames generally within 2 to 5 feet of observed values. Considering the size of the model and the range in head across the aquifer system, these are reliable simulations. The fact that the models can simulate flow under both predevelopment and current conditions (1985) adds to the credibility of the models. In areas with limited data or where the model calibration is less accurate, model predictions may not be as reliable because of uncertainty regarding aquifer characteristics.

The primary importance of the surficial aquifer is to serve as a source of recharge to or discharge from the underlying Floridan aquifer. It is possible that model predictions of leakage between the surficial aquifer are in error in some locations simply because the model cannot evaluate impacts to the surficial aquifer from pumping in the Floridan aquifer. Potentially, these models may underpredict the amount of drawdown from additional pumping stress. In addition, simulated water budgets may not be accurate because of the treatment of the surficial aquifer as a infinite source of water for the underlying Upper Floridan.

5. Recommendations

It is our recommendation, given all of the current and future objectives of the project, that a Next Generation groundwater flow model should be developed to evaluate groundwater conditions in coastal areas. The new model should be based on the accumulated knowledge gained from previous modeling. Although the numerical model will look quite different than the existing models, the conceptual model will generally be similar. This basis of understanding of the groundwater flow system (the conceptual model) should be the link between the new model and the existing models.

The models currently in use were developed with the objectives of predicting regional and subregional hydraulic responses in the Floridan aquifer. The models generally met the objectives for which they were designed. However, given recent advances in computer hardware and software, the existing models can be considered out of date. The current models do not adequately address issues of groundwater use in the surficial aquifer and cannot evaluate potential water use in the aquifer in the Miocene units of the Hawthorn Formation. Also, the models cannot be easily translated to density-dependent models for use in predicting the potential for saltwater intrusion. To increase the flexibility of the models to address these other issues, it is recommended that a new flow model be developed, the details of which are discussed below. However, in the interim, the telescoping set of models is adequate to predict hydraulic response in the Floridan aquifer system.

5.1 Hardware and Software

Given recent advances in computing power (available memory and speed) of the ordinary desktop computer, it is highly recommended that a PC-based groundwater model be developed. The current state of technology is such that a 450 megahertz Pentium II desktop computer with 256 megabytes of memory is quite affordable and available. In addition, this type of system is only a small step up from the standard systems that are currently being purchased for scientific and non-scientific computing. Because this type of system (even 300 megahertz Pentium II, 128 megabytes of memory) is so common, the constructed model could be run just about anywhere, on any PC. Even the typical laptops that are currently on the market could be used for this type of flow modeling.

ARCADIS Geraghty & Miller strongly recommends the continued use of the USGS MODFLOW finite-difference model code. This code has been and remains the most appropriate code for use based on the following:

- Wide-ranging capabilities to simulate complex flow systems.
- Wide-ranging application for similar hydrogeologic conditions.
- Acceptance by regulators and the public.
- Is well documented.
- Upgrades and add-on modules are continually developed and documented.
- Can be run on windows- and DOS-based PC platforms.
- Has many pre- and post-processing modeling software packages written for its use.
- Is compatible with many saltwater intrusion-/density-dependent flow models.

5.2 Model Discretization

ARCADIS Geraghty & Miller recommends that a detailed discrete representation of the groundwater system be developed that exceeds the degree of resolution of the existing models. The model should contain the necessary site scale resolution (for example, in the vicinity of Hilton Head Island) for detailed analysis, but extend to the limits of the existing RASA Model. This would result in a larger, more complex model than is currently in use, but would be manageable given the abundance of more powerful model design software. This would result in a single model design significantly reducing the number of steps required to run the model. This does not preclude the use of telescoping models. The telescoping approach can still be used to refine other areas of the model if needed or for refinement of the model prior to development or conversion to a saltwater intrusion model.

Based on the years of modeling work performed in this coastal area, the new model should be developed with adequate resolution in areas of interest such that telescoping or model refinement would be kept to a minimum. In the vicinity of large pumping centers and other areas of interest (Hilton Head Island), grid cell spacing should be 1/4 to 1/16 of a mile. Vertical discretization (model layering) should include all of the hydrogeologic units and corresponding layers used in the existing RASA Model, in addition to several new model layers. The proposed groundwater model should contain an active layer to represent the surficial aquifer. This is a substantial deviation from the current modeling approach but is the only modeling approach that enables current impacts in the surficial aquifer and the potential for use as a secondary aquifer to be determined. This may require a substantial level of effort and probably additional data collection (water use, water levels, and hydraulic testing) to calibrate water levels in the surficial aquifer. In addition, the Hawthorn Formation (Miocene units) must be simulated as an active layer for the same reasons.

The Upper and Lower Brunswick aquifers are suspected of yielding similar quantities of water to that of the surficial aquifer. Currently, insufficient data exist to complete the conceptual model of groundwater flow conditions in these units. Regionally, recharging water from the surficial aquifer migrates through these units before reaching the Floridan aquifers. It is quite possible that the model may be used to refine the conceptual model of these units. Simulation of these units is also important for saltwater intrusion modeling; implicit treatment of layers is not appropriate for transport modeling because the transport distance through these units is not simulated. Considering the above recommendations, it would not be unreasonable for the model to have 250,000 to 500,000 total model cells.

5.3 Calibration and Data Collection

The model should be developed using much of the spatial data already contained in the existing model. Thus, much of the calibration work in the new models is more of a re-calibration exercise than complete development of a new model. This is especially true in the Floridan aquifer.

The seaward boundary condition used in the current models is a no-flow boundary in the Floridan aquifer that represents the freshwater/saltwater interface. This type of boundary condition is not translatable to a saltwater intrusion-type model. In the proposed model, this boundary condition should be replaced with an equivalent freshwater head boundary.

The proposed features of the Next Generation Model will produce a model that meets future objectives by containing more flexibility and could be easily converted for use as a saltwater intrusion (density-dependent) model.

The model should also be calibrated/updated to current conditions and contain all known pumping stress (public and private). It is suspected that significant increases in agricultural pumpage has occurred throughout the study area, which are not considered in the models configured for 1985 conditions. Using old base conditions from 1985 will possibly lead to erroneous conclusions of safe pumping levels and appropriate areas for future development. Work should also be started on collection of historical pumping data in preparation for future transient saltwater intrusion modeling. Data collection activities that should be performed to address known uncertainties include the following:

- Synoptic water level rounds and development of potentiometric surface maps.
- Water level and hydrogeologic data collection in the surficial aquifer and Miocene unit.
- Chloride concentrations with depth within the surficial and Floridan aquifer system.
- Transmissivity measurements in areas of proposed well fields.
- Porosity measurements in the Floridan aquifer system.

- Metering of all large production wells.

If resources are available, consideration should be given to the collection of new and additional data from the deeper portions of the groundwater system. Specifically, it is our opinion that sufficient data from the Lower Floridan is lacking and that the assumptions made regarding the lower portions of the system may need to be verified. Considering the financial impacts of such endeavors, however, it will be important for the decision makers to determine if such resources may be better spent collecting more numerous data from the shallow portions of the system (e.g., new wells in the surficial aquifer).

5.4 Saltwater Intrusion (Chloride Analysis)

Of particular concern to the current model is the nature of the saltwater interface along the Atlantic Coast. Attempts should be made to monitor the offshore interface. In areas where intrusion is thought to be occurring, such as near Hilton Head Island and near Brunswick, chloride change ratios could be computed to determine whether current chloride concentrations in the Upper Floridan were a result of seasonal variations or seawater intrusion. Rutledge[1] defined chloride change ratios as follows:

$$\text{Chloride concentration change ratio} = \frac{F(C_n - C_t)}{\frac{C_n + C_t}{2}}$$

Where: C_n = chloride concentration now (current conditions), in mg/L
C_t = chloride concentration then (predevelopment), in mg/L
$F(C_n-C_t) = C_n-C_t-10$, if C_n-C_t is greater than +10
$F(C_n-C_t) = C_n-C_t+10$, if C_n-C_t is less than -10
$F(C_n-C_t)$ = zero, if C_n-C_t falls in the -10 to +10 range.

Chloride change ratios (defined by Rutledge) range from about 0.02 to 0.2. Rutledge determined that chloride change ratios typically range from -0.5 to 0.5 along the

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[1] Rutledge, A.T., Ground-water hydrology of Volusia County, Florida, with emphasis on occurrence and movement of brackish water, U.S. Geological Survey Water-Resources Investigations Report 84-4206, 1985.

Atlantic Coast in east-central Florida. The change ratio parameters would have to be adjusted for areas included in this study, but this represents a simple analysis using monitoring of the interface to determine whether intrusion is actually occurring. This type of analysis should be used in conjunction with modeling analyses to evaluate the performance of the model.

5.5 Model Maintenance

ARCADIS Geraghty & Miller recommends that the Georgia EPD, through its continuing program of working with the USGS, utilize the capabilities, expertise, and neutrality of the USGS to develop the new model and become the model's caretaker. It is our opinion that the USGS has demonstrated their in-house expertise in developing such a model. In addition, this organization has spent years investigating and interpreting the complexities of this groundwater system.

Through the use of a PC platform for the development of the model, once completed the model can be distributed for use to other various parties. Inevitably, others will make changes to and "tinker" with the model construction or representation of the groundwater system. It is imperative, however, that there exists one keeper of the "approved" version of the model. Therefore, we recommend that the USGS be the caretaker of the model and update the model when appropriate. When updates have been made and they have been deemed technically sound modifications to the original model, the USGS could then disseminate the updated version to all interested users.

In an effort to continue with the Sound Science Program, ARCADIS Geraghty & Miller recommends the continued involvement of an outside reviewer(s) to work with Georgia EPD and the USGS throughout the model development process. The reviewer(s) should be involved in the strategy planning of the new model, data use decisions, and model development. The use of an outside reviewer should be considered a valuable step in the overall modeling quality assurance/quality control (QA/QC) procedure.

ARCADIS GERAGHTY & MILLER

Appendix A

Requested Model Simulation

Appendix A

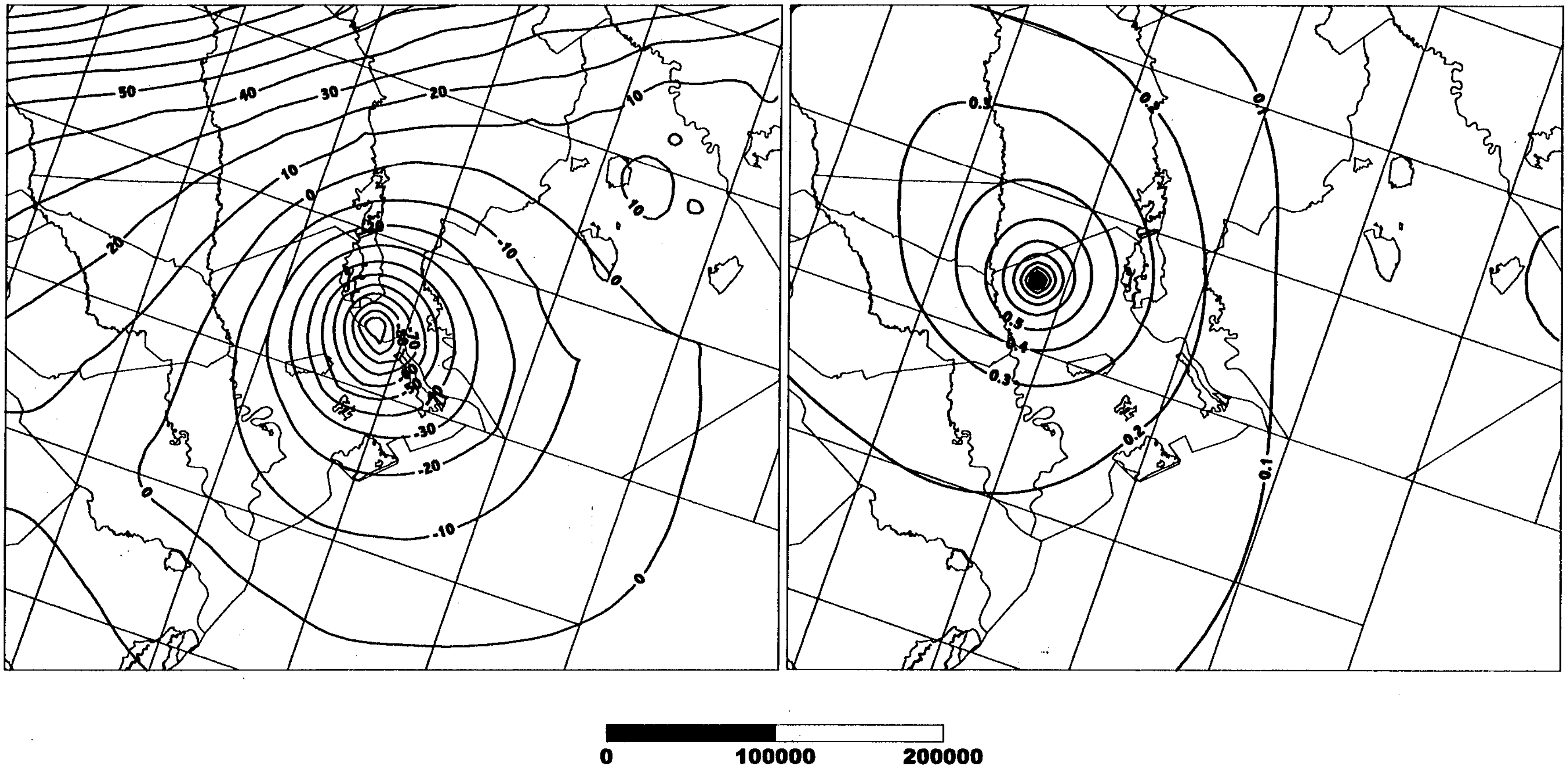
Requested Model Simulation

A simulation was performed at the request of Georgia EPD to evaluate the impacts or hydraulic effect of a 500,000-gallon-per-day injection of water into the Upper Floridan aquifer northwest of Savannah, Georgia. The injection well was placed in Row 32 and Column 29 of the Savannah Model. The simulation was performed by running the telescopic model pair (the RASA Model and the Savannah Model). The model must be run in this manner in order to supply the Savannah Model with boundary conditions that match the flow conditions induced by the injection well.

The model results indicate that a 1.5-foot increase in potentiometric head occurs at the point of injection. Figure 1 indicates the difference in head between 1985 simulated flow conditions and the same flow conditions with the added injection. At the indicator node located at the north end of Hilton Head Island (36,40) there is an increase in head of approximately 0.01 foot. We found the telescoping models easy to use; however, the model setup used by the USGS should be converted for use on personal computers. There is no reason that the models must be run on Unix systems and with a proprietary interface. The models and associated software could easily be converted to run in DOS on a personal computer.

DWG DATE:	12/01/98	PRJCT NO.:	GA062581.0001	FILE NO.:	1	DRAWING:	SAVAN1.SRF	CHECKED:	MPK	APPROVED:	MPK	DRAFTER:	MPK

Simulated Heads | **Simulated Change in Head**



NOTE: Injection Location (R-32, C-29) Change in Head 1.5 feet
Indicator Node (R-36, C-70) Change in Head 0.008 feet

ARCADIS GERAGHTY & MILLER

Simulated Potentiometric Heads and Change in Potentiometric Head in the Upper Floridan Aquifer with Additional Injection Well Pumping

Georgia EPD
Atlanta, Georgia

FIGURE 1

Report

USGS Groundwater Flow Model Evaluation

for the
Georgia Geologic Survey
Environmental Protection Division
Georgia Department of Natural Resources

March 1999

Contents

Executive Summary

This report presents the findings of an independent, peer review by the consulting firm Camp Dresser & McKee (CDM) of five United States Geological Survey (USGS) groundwater flow models. Four of the models form an interlocking or "telescoping" set of models ranging from a large regional model to local models designed to more accurately model specific areas of the coast. A fifth model was developed for the South Carolina Water Resources Commission to cover Beaufort and Jasper counties, and is called the Smith Model.

Prior to discussing the major findings, one important conclusion should be highlighted up front to avoid misunderstanding.

CDM finds that the models were all based on reasonable conceptual models of the area hydrogeology, were properly constructed, and well calibrated. The models have been used for various management objectives, and used appropriately. They represented the state of the art at the time of construction, and made best use of existing data. Critical findings and recommendations are intended to help improve and update the models for future use, and do not reflect on the use already made of the models in support of management decisions.

The most significant findings of CDM's analysis of the four telescoping models and the Smith model are:

- All five models appear to be well constructed, properly calibrated and have been properly applied in past reports and studies.
- The models were developed during the 1980's, when computer capabilities were limited. Today's high performance computers can accommodate models that reprise more memory and higher speeds. The grid spacing and layering scheme can be much more detailed in the areas of concern near Savannah/Hilton Head and in the Brunswick area. The existing models can serve as the basis for updating the RASA and local models.
- The models, as constructed, could still be used to assess large scale injection or withdrawals from the upper Floridan, and to make preliminary assessments of the impacts of pumping on heads near the coast. They do not have sufficiently fine grids to be used for well field design or to simulate smaller scale Aquifer Storage and Recovery schemes.

Based on the findings of the model assessment, CDM has a number of concerns about the future use of the models. These can be summarized as follows.

- The present configuration of the models does not include simulation of the surficial aquifer. Impacts of pumping in the Floridan aquifer on the surficial aquifer and associated surface water bodies cannot be assessed.

- The rate and degree of salt water intrusion is directly associated with fluxes such as the rate of downward leakage of salt water from the ocean and the rate of upward movement of brackish water from the Fernandina. The accuracy of the fluxes in all of the models is difficult to assess, and must be addressed if salt water intrusion modeling is to be attempted.

- Both the RASA and Savannah models were somewhat unresponsive to changes in pumping and boundary conditions in the Hilton Head area. It appears that the proximity of model boundaries are unduly affecting the heads simulated near Hilton Head, and the model results in this area may be less accurate than required.

- The pumping simulated in the model may be incomplete. Additional work on agricultural pumping and inclusion in future modeling work is an important part of improving the model's ability to accurately simulate fluxes.

Based upon the findings, the major recommendations are summarized below.

- The present models should be used as the basis for a new set of fully 3-dimensional models, which will include updated grids and a new, more extensive layering scheme. Both the RASA and local models should be updated.

- Although CDM sees no problem in continuing with the use of MODFLOW as the flow model code, consideration should be given to a finite element code. Finite element codes may prove to have better flexibility in designing the grid, and may also be more compatible with the codes selected for use in salt water intrusion modeling.

- Effective salt water intrusion modeling of the entire coast, of the Savannah/Hilton Head area, or of the Brunswick area may require the use of several approaches and modeling techniques to fully understand the aquifer system response to pumping.

- Three dimensional sharp interface models are well suited to analyze the long term sustainability of coastal wells, provide insight into the horizontal and vertical movement of salt water, and give estimates of the rate of advance and upconing of salt water near pumping centers.

- More traditional solute transport models can be effectively combined with the results of the sharp interface model to provide additional insight into chloride concentrations on a local scale near pumping centers.

- In selecting the software, consideration should be given to the ability of the codes to use the same basic models to perform a variety of types of simulation.

Section 1
Introduction

The Georgia Environmental Protection Division of the Department of Natural Resources (EPD) is implementing an Interim Strategy to protect coastal Georgia from salt water intrusion of the upper Floridan Aquifer. The comprehensive program is designed to answer a broad range of questions dealing with the location, cause, rate of advance, and impacts of intrusion, as well as to recommend approaches to deal with intrusion and protect future water supplies. This report presents the findings of an independent, peer review by the consulting firm Camp Dresser & McKee (CDM) of five United States Geological Survey (USGS) models designed to simulate groundwater flow in Georgia coastal aquifers.

The specific objective of the study is to evaluate the USGS's set of telescoping, finite difference MODFLOW models covering the Floridan Aquifer in the 24 counties of coastal Georgia and 4 counties of the Low Country area of South Carolina, as well as the USGS model developed for South Carolina covering parts of northern coastal Georgia and southern coastal South Carolina.

The project consisted of an initial meeting with the USGS and EPD, a period of model review and testing by senior CDM modelers, a preliminary meeting and discussion with the USGS on the findings, and a presentation of the findings at a meeting of the Upper Floridan Technical Advisory Committee, which took place on January 11, 1999. A workshop is planned for early April, 1999, during which a discussion will take place to identify and recommend salt water transport models to simulate coastal intrusion.

Section 2
Model Descriptions

Five USGS groundwater models were evaluated, all of which were developed using the USGS groundwater flow model code MODFLOW. Four of the models form an interlocking or "telescoping" set of models ranging from a large regional model to more localized models designed to more accurately model specific areas of the coast. **Figure 1** shows the area covered by each of the four telescoping models, as well as the boundary conditions selected for the regional model. A fifth model was developed for the South Carolina Water Resources Commission to cover Beaufort and Jasper counties, and is called the Smith Model. Its grid is shown in **Figure 2**. Each model is briefly described below.

2.1 RASA

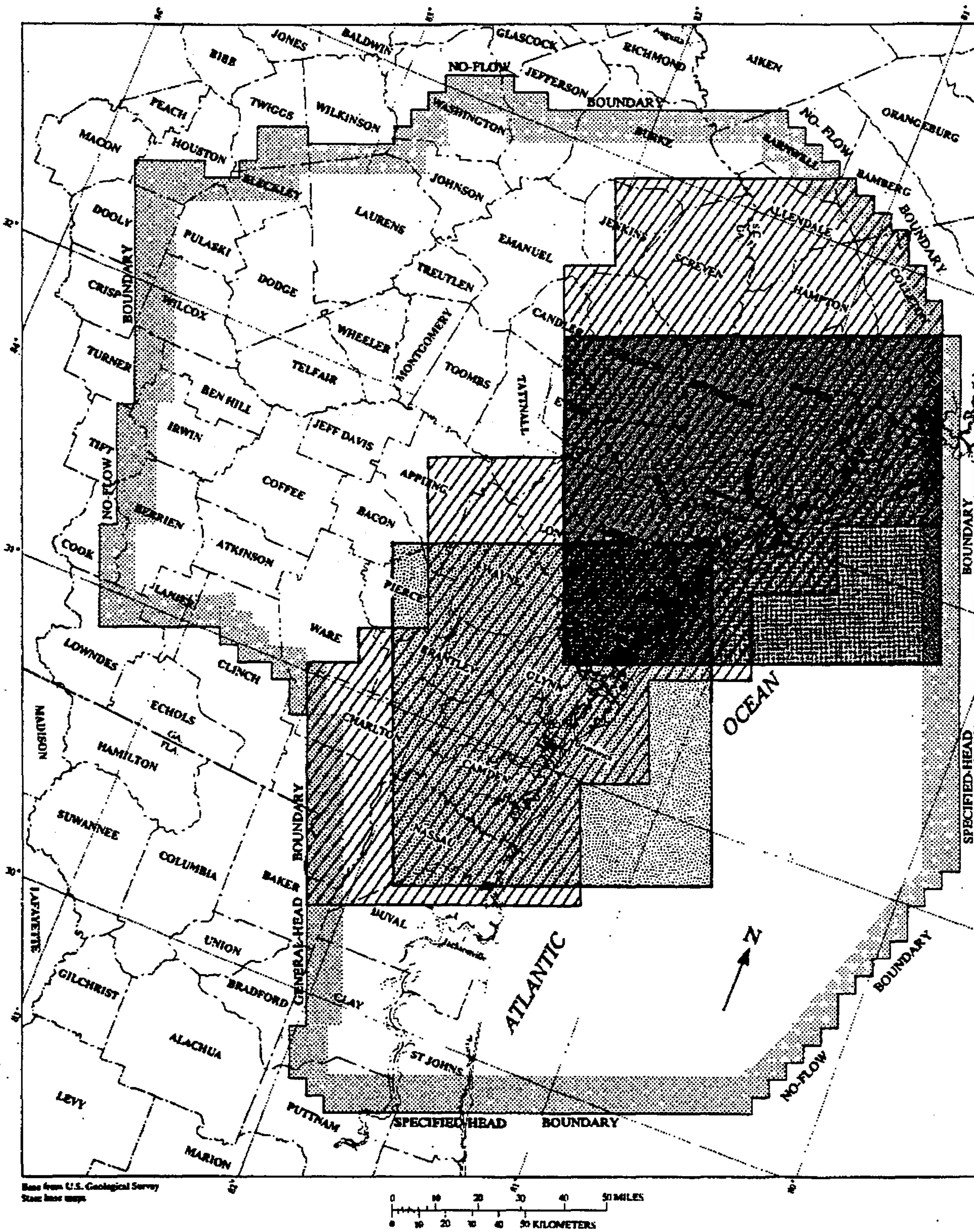
As part of the Regional Aquifer Systems Analysis (RASA) Program of the USGS, started in 1978, the USGS developed a groundwater model of coastal Georgia, including parts of southern South Carolina and northeastern Florida. The RASA model covers a large area, 53,250 square miles. Its node spacing or cell size is four miles by four miles, with a uniformly sized grid covering the entire area. There are 3328 nodes in the model. The model has two active layers: the upper and lower Floridan Aquifers; and two inactive fixed head layers: the surficial/Miocene aquifer and the Fernandina Permeable unit.

The model is a quasi-three dimensional finite difference model simulating lateral groundwater flow and water level changes in the upper and lower Floridan Aquifers. It also simulates vertical flow between the surficial/Miocene aquifers and the upper Floridan Aquifer, vertical flow between the lower and upper Floridan, and, where present, flow between the Fernandina Permeable unit of the lower Floridan and the lower Floridan Aquifer.

As shown in Figure 1, horizontal boundaries include an eastern offshore specified head boundary, an offshore no-flow boundary, a specified head boundary to the south, a general head boundary in the south west, a no-flow boundary in the north west, and a no-flow boundary in the north. The surface is a specified head boundary, and the bottom of the model is either a no-flow boundary, or a specified head boundary where the Fernandina exists.

2.2 EPD/USGS Coastal Model

The Coastal model is contained within the RASA model, and covers an area of about 14,000 square miles. Its purpose was to help make permit decisions for groundwater withdrawal in coastal Georgia. Its node spacing or cell size is two miles by two miles, with a uniformly sized grid covering the entire area. There are 6216 nodes in the model. The model also has two active layers: the upper and



EXPLANATION

MODEL AREA

- SAVANNAH AREA (This report)
- COASTAL (Randolph and others, 1991)
- GLYNN COUNTY (Randolph and Krause, 1990)
- REGIONAL AQUIFER-SYSTEM ANALYSIS (Krause and Randolph, 1989)

Figure 1
Boundaries Of Regional Aquifer-System Analysis (RASA) Glynn County, Coastal, And Savannah Area Models

Figure 2
Boundaries And Grid Of Smith Model

lower Floridan Aquifers; and two inactive fixed head layers: the surficial/Miocene aquifer and the Fernandina Permeable unit.

Like the RASA model, the coastal model is a quasi-three dimensional finite difference model simulating the same lateral and vertical groundwater flows as the RASA model does.

Horizontal boundaries are taken as specified fluxes from the RASA model, with the exception of a small area of no-flow boundary in the north east. The surface is a specified head boundary, and the bottom of the model is either a no-flow boundary, or a specified head boundary where the Fernandina exists.

2.3 Glynn County Model

The Glynn County model is contained within the RASA model, and covers an area of about 6,080 square miles. Its purpose was to more accurately simulate existing conditions in the area of Glynn County where vertical intrusion of salt water is occurring from the Fernandina unit into the Floridan aquifer. Its node spacing or cell size varies from 1/4 mile by 1/4 mile to four miles by four miles. There are 10,340 nodes in the model. The model also has two active layers: the upper and lower Floridan Aquifers; and two inactive fixed head layers: the surficial/Miocene aquifer and the Fernandina Permeable unit.

Like the RASA model, the Glynn County model is a quasi-three dimensional finite difference model simulating the same lateral and vertical groundwater flows as the RASA model does.

Horizontal boundaries are taken as specified fluxes from the RASA model. The surface is a specified head boundary, and the bottom of the model is either a no-flow boundary, or a specified head boundary where the Fernandina exists.

2.4 Savannah Area Model

The Savannah Area model is contained within the RASA model, and covers an area of about 6,680 square miles. Its purpose was to more accurately simulate existing conditions in the area of Savannah Georgia and Hilton Head, South Carolina, with particular concern for the large cone of depression centered on pumping in Savannah and the threat of lateral salt water intrusion near Hilton Head. Its node spacing or cell size is one mile by one mile. There are 6,688 nodes in the model. The model also has two active layers: the upper and lower Floridan Aquifers; and two inactive fixed head layers: the surficial/Miocene aquifer and the Fernandina Permeable unit where it exists.

Like the RASA model, the Savannah model is a quasi-three dimensional finite difference model simulating the same lateral and vertical groundwater flows as the RASA model does.

Horizontal boundaries are taken as specified fluxes from the RASA model. The surface is a specified head boundary, and the bottom of the model is primarily a no flow boundary.

2.5 Smith Model

The Smith model is not part of the telescoping model set, and therefore is not contained within the RASA model. It covers an area of about 7,280 square miles. Its purpose was to more accurately simulate flow conditions of the Upper Floridan Aquifer to aid in planning and managing strategies to mitigate salt water encroachment near Hilton Head. Its node spacing or cell size is uniform at one mile by one mile. There are 7,280 nodes in the model. The model has one active layer, the upper Floridan Aquifer. The surficial/Miocene aquifer is simulated as a specified head boundary, and the lower Floridan aquifer is simulated as a no flow boundary.

The Smith model is a quasi-three dimensional finite difference model simulating lateral flows in the upper Floridan Aquifer and vertical groundwater flows from the surficial/Miocene into the upper Floridan Aquifer. The bottom of the model is the lower Floridan Aquifer, and no groundwater flow is assumed to occur between the upper and lower Floridan Aquifers.

As shown in Figure 2 horizontal boundaries condition assumptions are applied to model edges that are reasonably far from the area of interest. The north and west boundaries are specified head boundaries, the south boundary is a general head boundary, and the east is a no-flow boundary.

Section 3
Evaluation Approach

The approach taken by CDM to evaluate the models included a number of steps. The first step consisted of studying the modeling reports and familiarizing ourselves with the structure and assumptions used in developing and calibrating each of the models. This was followed by comparisons of the specified transmissivity values among the models.

We then selected a number of widely spaced "indicator cells" located across the entire area of the regional model, and made a series of sensitivity simulations to help gain a better understanding of the model response to changes in boundary conditions or model assumptions. We also tabulated model fluxes across boundaries for each of the sensitivity simulations, and checked to see if the results simulated on the regional model matched a similar simulation on the sub-regional models. Finally, CDM performed a test comparison of the Savannah and Smith models by comparing each model's response to a 10 million gallon per day (mgd) withdrawal of water from the upper Floridan Aquifer near the Savannah River.

Section 4
General Findings

The general findings of the CDM evaluation of the five models are presented here. Although CDM looked at numerous details and aspects of the models, only the more important findings will be discussed. Prior to discussing the findings, one important conclusion should be highlighted up front to avoid misunderstanding.

CDM finds that the models were all based on reasonable conceptual models of the area hydrogeology, were properly constructed, and well calibrated. The models have been used for various management objectives, and used appropriately. They represented the state of the art at the time of construction, and made best use of existing data. Critical findings and recommendations are intended to help improve and update the models for future use, and do not reflect on the use already made of the models in support of management decisions.

General findings of the evaluation of the models are summarized in the subsections below.

4.1 Quality Assurance Procedures

The USGS has its own, strict, in-house Quality Assurance (QA) procedures, and these were followed in the development and reporting of the model results. In general, USGS performs in-office and outside peer review by senior technical staff in other offices. In addition, the reports underwent additional review prior to publications. CDM finds that the QA procedures were appropriate and properly applied.

4.2 Model Node Spacing

The models each have different nodal spacing, and the selected cell sizes are generally appropriate for the purposes to which the models have been applied. The selection of an appropriate model node spacing depends on the objective of the modeling program, as well as the power and memory of the computer systems available. Today's computer technology makes it possible to develop larger models than was possible even three or four years ago. These models are all over five years old, thus, model node spacing is an issue if the models are to be updated.

The RASA model is a large regional model, and the four mile node spacing allowed it to efficiently cover the entire region. It is capable of simulating regional heads and drawdowns accurately. It's uniform cell size is not very efficient, however, and should be updated for future model applications. Cell size could be reduced to 1 or 2 mile spacing using today's computers, with certain areas having even tighter spacing. Even more cell size flexibility would be available if a finite element model code was selected. The smaller cell size would allow the model to take over the functions of the Coastal model, it would allow it to more accurately define the coastline location, and it would result in a more accurate simulation of the steep head gradients near the major pumping centers.

The Coastal model was used to assess pumping redistribution and potential yield in relation to drawdowns at the coast. Its two mile by two mile grid was reasonable for this use. With today's computer power, the coastal model falls in between the need for a regional model and the need for focussed, local models, and it may no longer be an effective or necessary tool for future applications.

The Glynn County Model has the most advanced grid, with variable node spacing. Its 1/4 mile spacing in the area of interest is appropriate, and need not be updated. The grid is probably sufficient for looking at general movement of water in the Glynn County area, however, a tighter node spacing would be required to look at detailed upconing scenarios related to a particular well or well field.

The Savannah Area Model and the Smith model both have a one mile node spacing. This spacing was sufficient to accurately simulate the large cone of depression in the Savannah area, however it is too wide for the detailed analysis of head changes on Hilton Head. In an updated model, node spacing in the vicinity of Hilton Head should be decreased to 1/4 mile or less, which would be more suitable for simulating intrusion toward the coast, as well as to test mitigation strategies to slow or halt intrusion.

4.3 Model Layering

The telescoping models all work with only two active layers. This layering approach, although appropriate for the initial studies performed by the USGS, is not adequate for the rigorous requirements of the Interim Study. The same can be said for the one layer Smith model. The quasi-three dimensional approach of the existing models should be extended to include simulation of the additional layers listed below, or replaced by a fully three dimensional approach, with explicit modeling of each of the following layers:

- Surficial Aquifer
- Upper Confining Unit
- Miocene Aquifers (data permitting)
- Upper Floridan Aquifer
- Middle Semi-Confining Unit
- Lower Floridan Unit
- Lower Semi-Confining Unit
- Fernandina Permeable Zone

This may require a model of up to 10 layers in some areas where the Miocene Aquifer exists within the surficial deposits, however, this should not be a concern with present day PC computing capacity. **Figure 3** shows the suggested explicit model layers to be included in an updated model.

CDM is aware of the lack of data available for the Fernandina and Lower Floridan Aquifer, and the limited data available for the Surficial and Miocene Aquifers. This, however, is not a reason to avoid modeling them. In fact, the opposite is the case. We believe that models that explicitly include these units, even if based on minimal data, will greatly advance the understanding of the hydrogeology of the entire system, help to better understand the relative fluxes of water between units, and be an invaluable guide to planning additional data collection. For example, recharge and discharge of groundwater to and from the surficial aquifer can be estimated and, to a certain extent, confirmed by field studies. By developing a better understanding of surficial flows into the model, a better estimate of the balance of flows between the downward flow from the surface and the upward flow from the Fernandina can be made. In this way, estimates of upward flow from the Fernandina can be improved without the need for an extensive drilling program of monitoring wells in the Fernandina. CDM has often used modeling to help gain a better understanding of the stratigraphy prior to field investigations, thereby increasing the efficiency of the field programs that are eventually carried out.

4.4 Model Input Parameters

It was apparent that, with some slight discrepancies that do not appear to be significant, the transmissivity values (T-values) assigned to the Upper Floridan Aquifer within each of the models are generally consistent with each other and with the data. Because the models can reproduce heads under both pre-development and post-development conditions, it appears that the transmissivity values for the Upper Floridan aquifer are reasonably accurate on the scale of each of the models.

The models used the proper approach of developing T-values for larger areas of the model through the calibration process, and then comparing results with field data results. It is clear that the modelers did not patch in or automatically match local values gained from individual pump or slug tests. CDM believes that this is a sound approach to model development because it recognizes that individual, local field test results may not be representative of average aquifer properties which control hydraulic response at a regional scale. It is recommended that a similar approach be used in developing updated models.

4.5 Model Boundaries

The horizontal boundaries selected for the RASA model appear to be, for the most part, well thought out and properly defined. The USGS appears to have a good, hydrologic explanation for the no flow boundaries and for the western boundaries. The boundaries to the west are shielded by the Gulf Trough from

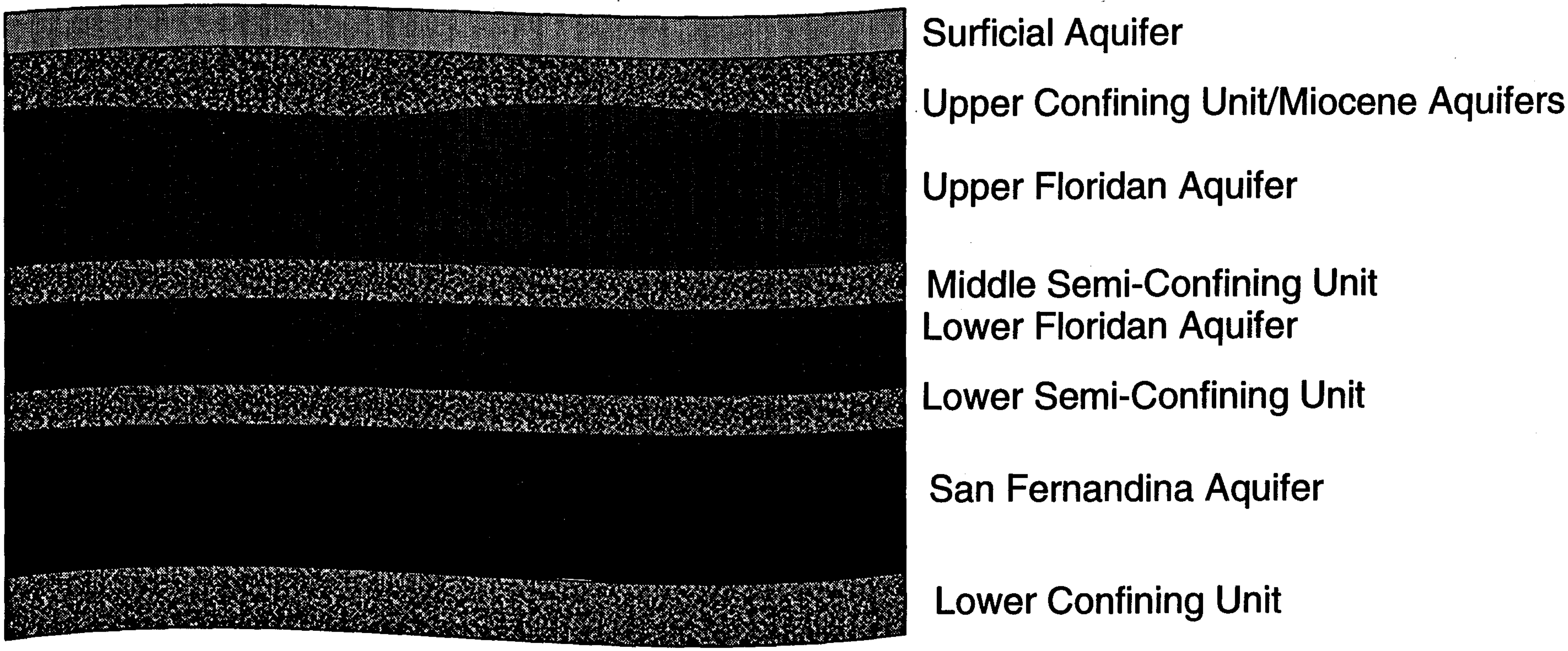


Figure 3
Hydrogeologic Units

influencing the heads on the coast, and are therefore far enough from the area of interest to have little influence on the results. The selection of no flow boundaries appear to make sense with regard to the flow patterns in the Floridan Aquifer. There are, however, several concerns about the specified head horizontal boundaries.

The specified head boundary in the northeastern part of both the RASA and Savannah model is quite close to the Hilton Head area and may be influencing the heads simulated at Hilton Head. According to existing data, a hydrologic boundary is close to Hilton Head because the aquifer pinches out, or the salt water boundary exists close to shore. The selection of a specified head boundary is used to represent this physical boundary. An examination of the response of indicator nodes in this area during our sensitivity testing illustrates the "damping" effect of this boundary (see Appendix A for the results matrix). It is possible that this boundary could result in a lack of response to pumping in both the RASA and Savannah models in this area. It is also troubling that this boundary was changed between the pre-development and post-development simulations. In updating the models, this boundary should be re-examined.

A second concern is the specified flux boundary to the south west. This boundary is the source of a significant amount of water to the model under present day conditions, and a no flow boundary under predevelopment conditions. The rationale for this is unclear. Although the boundary may be based on correct assumptions, the fact that the boundary was changed between the pre- and post-development simulations indicates that this boundary is important to the results and should be examined more closely. In updating the model, a better explanation of the hydrologic basis for this boundary should be provided, or the boundary should be changed to have less influence on the results near the coast.

The offshore boundaries appear to work for the flow model simulations of onshore potentiometric surfaces. They are not, however, necessarily accurate reflections of the location and configuration of the interface between fresh and salt water, nor do they result in offshore flow patterns that are realistic in all areas. For example, along the no flow portion of the offshore boundary, fresh water flows parallel to the boundary, and thus, parallel to the coast. The flow is more likely to be away from the coast and vertically upward. They are adequate for simulating onshore heads, and have been applied appropriately in past simulations. These boundaries, however, must be much better understood if salt water intrusion modeling is to be successful in the future.

Another concern is the vertical fixed head boundary assigned to the surficial/Miocene aquifer, and the fixed heads assigned below the model to the Fernandina permeable unit. Both have a large impact on model results, and both are based on limited data from the field. Both represent limitless supplies of water for the model because neither responds to pumping in the Floridan system. In general, this assumption is probably valid in many areas, however, the surficial aquifer specified heads are particularly important near the Hilton Head, where the upper confining unit may be thin or missing. These specified heads may contribute the perceived lack of response to pumping in the Savannah, RASA, and Smith models near Hilton Head. It will be important to better understand if this representation is sufficiently realistic, something that can be addressed if the surficial aquifer is explicitly simulated in future models.

The fixed head boundary used for the Fernandina is an approach that is necessitated by the lack of data in this deep, permeable unit. As long as the induced flow upward from the Fernandina is very small relative to the amount of water and the transmissivity of the Fernandina, then this assumption can be used without concern. More insight into this unit is desirable for future model updates.

4.6 Model Calibration

Model Calibration was performed by simulating two, contrasting hydrologic conditions. The steady state simulations of the 1980's condition represents the upper Floridan Aquifer in a stressed condition through pumping. The pre-development (1880s) condition showed the aquifer in its natural state. In general, this is a good approach to calibration.

Calibration accuracy is usually measured by a statistical summary of the difference between simulated and measured head values, with the measured head values taken from a field sampling program. The difference between measured and simulated head at each monitoring well location is known as the model "error". The statistics can be given as the root mean square error (RMSE, the square root of the mean of errors squared), or the absolute average error (AAE, which is the average of the absolute values of the errors). The five models had the following calibration statistics:

- RASA Model: a AAE of 3.6 feet for 1980 conditions
- Coastal Model: a RMSE of 6.6 feet for 1985 conditions
- Glynn County Model: a RMSE of 5.1 feet for 1980 conditions and 9.9 feet for 1985 conditions
- Savannah Model: a RMSE of 4.0 feet for 1985 conditions
- Smith Model: a RMSE of 5.0 feet for 1984 conditions

The calibration statistics for all five models are within the good to excellent range (with RMSE or AAEs of less than 5 percent of the range of heads being modeled). It is our opinion that all five models are well calibrated, with the following comment.

The boundary conditions for the RASA were adjusted between the 1880s and 1980s simulations, in particular the general head boundary to the southwest and the specified head in the northeast. This is cause for concern, because it suggests that these boundaries are influencing the heads within the model in the area of interest. This is not necessarily incorrect, however, both boundaries are based on assumptions that are difficult to support through field studies, and a better understanding of these boundaries would improve our confidence in the RASA model.

The same is true for the Savannah model's northeast specified head boundary. Thus, although the calibration process did use contrasting conditions and accurately simulated both, the adjustment of boundary conditions between the two simulations makes the result somewhat less convincing.

Section 5
Simulations and Sensitivity Testing

CDM performed numerous simulations to test the RASA model's response to changes in boundary conditions and model assumptions. A results matrix has been developed which shows the response of the simulated head at indicator nodes across the study area to each of the changes made. This table is provided in Appendix A. In addition, a water balance diagram for each simulation has been prepared, and these are provided in Appendix B.

5.1 Simulations Performed

The simulations performed were:

- Base runs: 1985 conditions and predevelopment conditions as reported in the publications.
- RASLAY3: The fixed head boundaries to the west and north were changed to no-flow boundaries in layer 3.
- RASLAY32: The constant head boundary in the Lower Floridan layer offshore to the east was changed to no-flow in both layer 2 and layer 3.
- RASLOW: The Fernandina aquifer in layer 4 was changed from fixed heads to a no-flow boundary
- L1HEAD: All the fixed heads in layer 1 were raised by 20 percent.
- L3HEAD: All the heads in the offshore layer 3 fixed head boundary were raised by 10 feet.
- L3HEAD_2: offshore fixed heads in layers 2 and 3 were raised by 10 feet.
- GULFT: the transmissivity of the gulf trough was decreased by 50 %.
- MOVEOCN: the constant head boundary of layer 2 (Upper Floridan) was moved from far offshore to just offshore.
- MOVEOCN2: both upper and lower Floridan fixed head boundaries were moved to just offshore.
- MOVEOCN3: the entire coast was converted to a no-flow boundary located just offshore in layer 3 (lower Floridan).
- MOVECN4: the entire coast was converted to a no-flow boundary located just offshore in layers 2 and 3 (upper and lower Floridan)

- NOGHB: all general head boundaries in south west part of model were converted to a no-flow boundary.

5.2 Model Fluxes

CDM concentrated on the issue of simulated fluxes, because this aspect of the simulation is of vital importance to the threat of salt water intrusion along the coast. In general, fluxes within the groundwater system are difficult to measure, and models are often the best approach to estimating fluxes. **Figures 4 through 7** show box diagrams of simulated fluxes across the model boundaries, as well as between the surficial aquifer, the upper and lower Floridan Aquifers, and the Fernandina permeable unit for several different simulations of the RASA model. The flux numbers are derived from the mass balance tables for the individual simulations made by CDM on the RASA model.

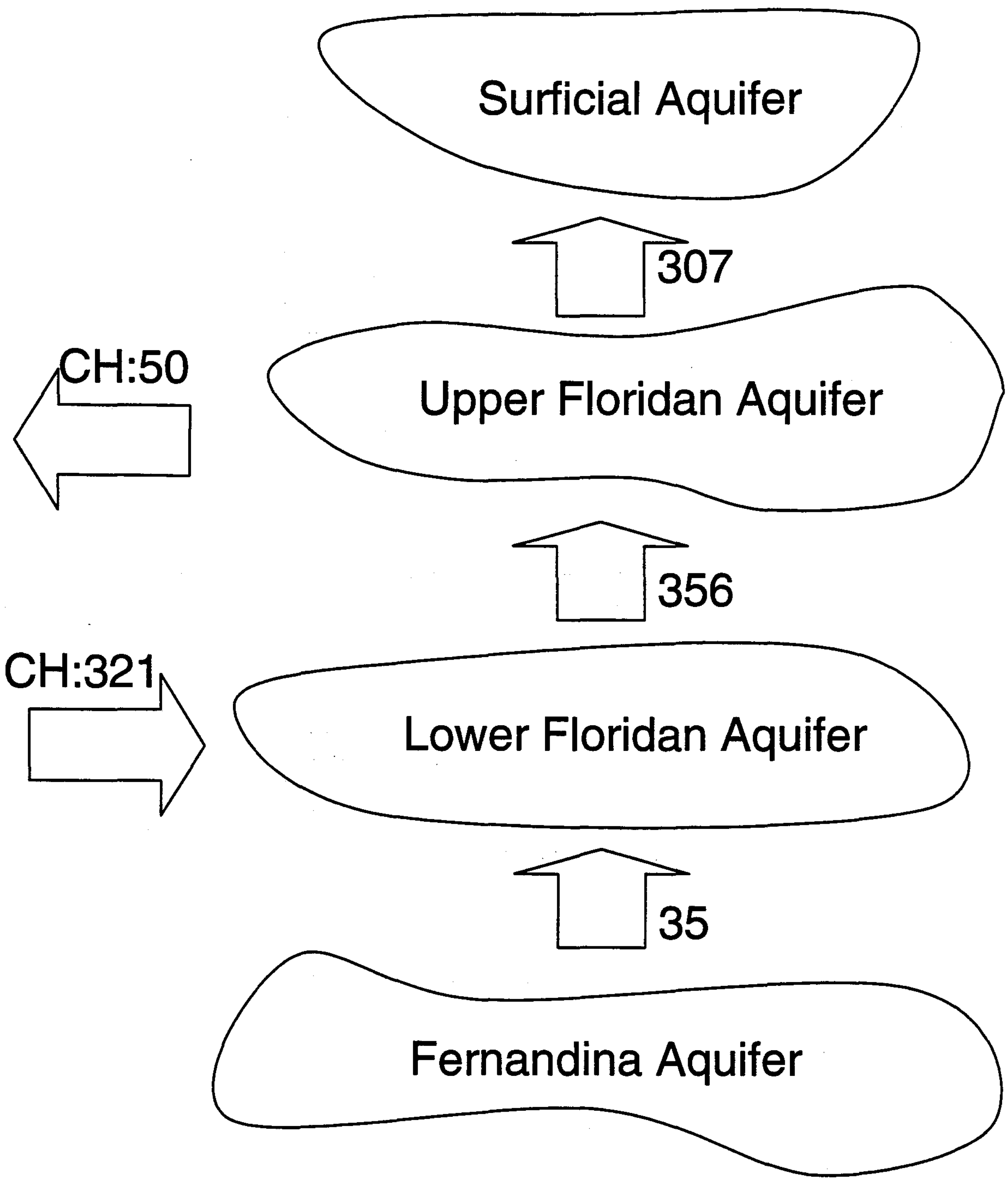
The mass balances provided in this report are intended to illustrate a point and are not presented as documented model runs. Sensitivity testing simulations were performed using the Strongly Implicit Procedure (SIP) MODFLOW solver package. For all simulations performed, the mass balance error using this solver was less than one percent for the entire model. This error was concentrated in layer 2, however, causing a mass balance error of ten percent in this layer. For this report, the model errors were redistributed across the model to make them balance. By using alternate MODFLOW solvers such as PCG2, this error may be avoided. The results of the sensitivity simulations would be the same, however, regardless of which solver is chosen - the accuracy of the fluxes is difficult to assess and both the surficial aquifer and Fernandina act as unlimited sources of water to the models.

The figures are provided to illustrate the nature of the fluxes as simulated by the models. (Flux diagrams for all sensitivity runs are included in Appendix B.) For example, under predevelopment conditions, the RASA model shows that the net inflow into the Floridan Aquifer is derived from two sources: 90 percent comes from horizontal flows into the model through the western boundary (primarily into the lower Floridan), and 10 percent comes up from the Fernandina. The surficial aquifer is a net sink for water from the Floridan aquifer in this simulation.

Under developed conditions, the fluxes are quite different. About half of the water enters the Floridan Aquifer through horizontal flows through the western boundaries, into both the lower and upper Floridan. About 1/4 of the inflow enters the Floridan Aquifer from the Fernandina below, and the remaining 1/4 comes down from the surficial aquifer above.

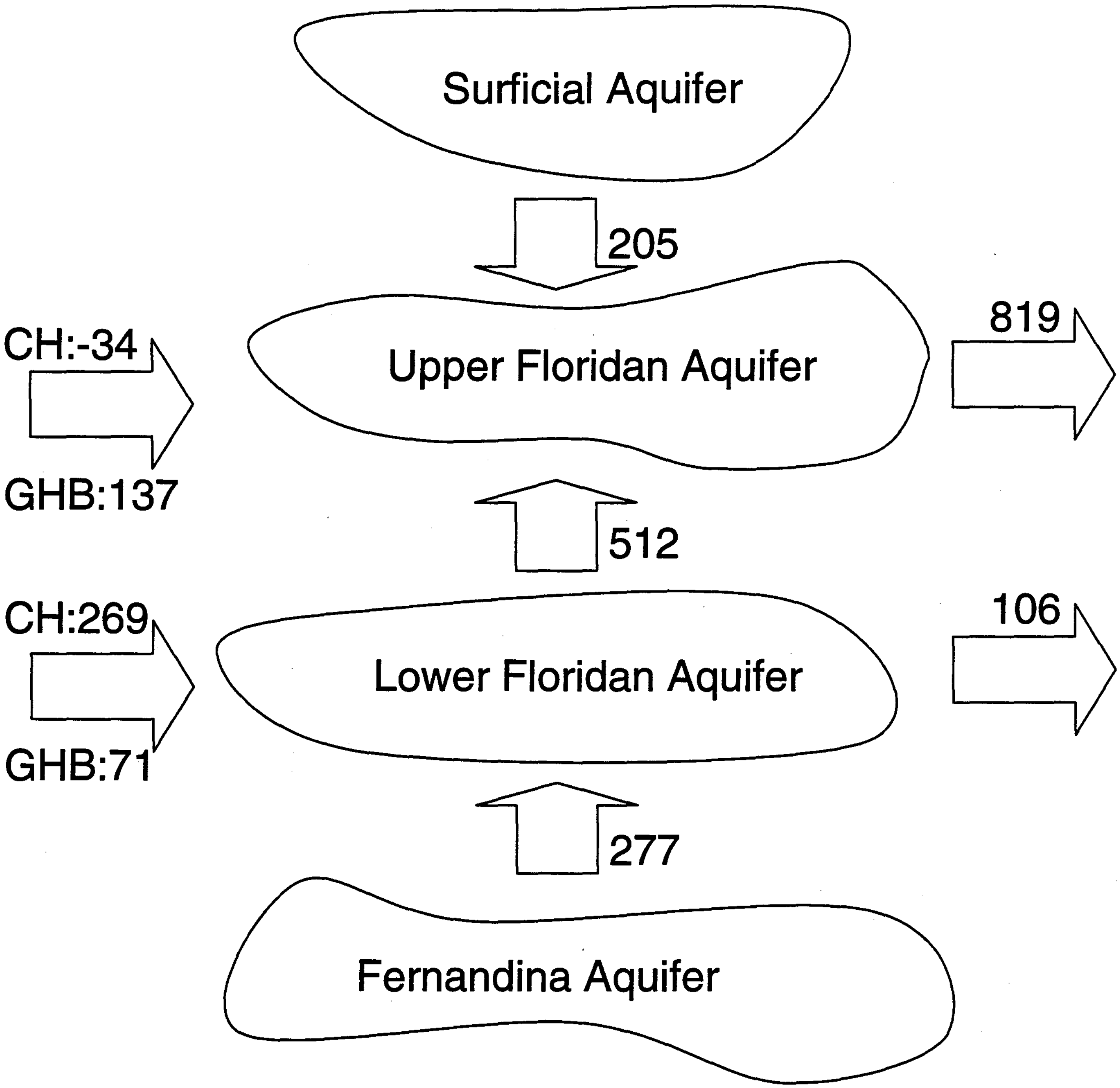
The two contrasting situations indicate that the model is sensitive to its boundaries, and that the balance of water inflow between the three potential sources is an important issue. **Figures 6 and 7** illustrate this point further by making changes to the boundary assumptions. In figure 6, flows from the Fernandina are eliminated and the water balance changes significantly. Much

Simulation: Base Case Undeveloped



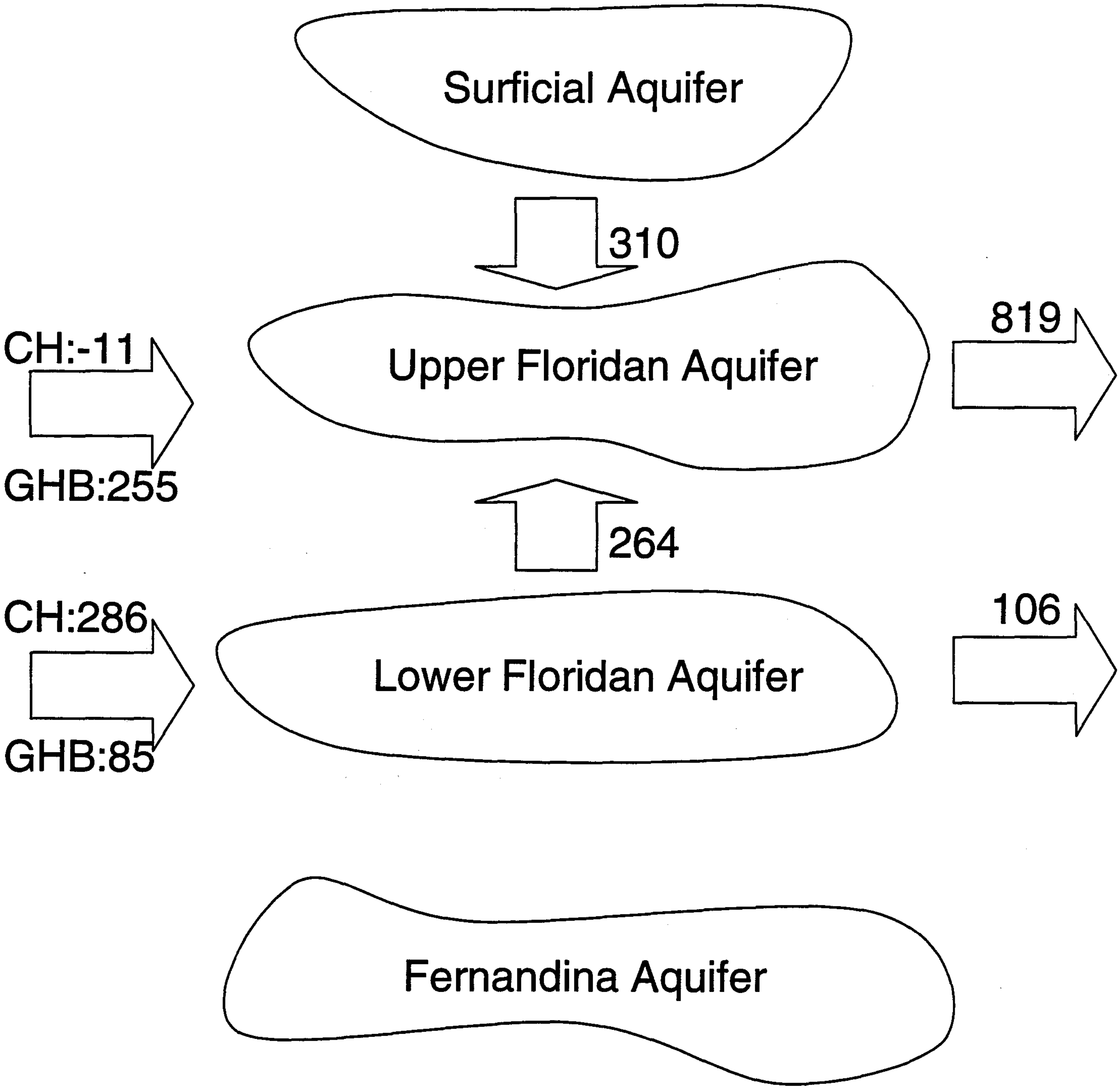
CH - Flux Across Constant Head Boundary

Simulation: Base Case Developed



CH - Flux Across Constant Head Boundary
GHB - Flux Across General Head Boundary

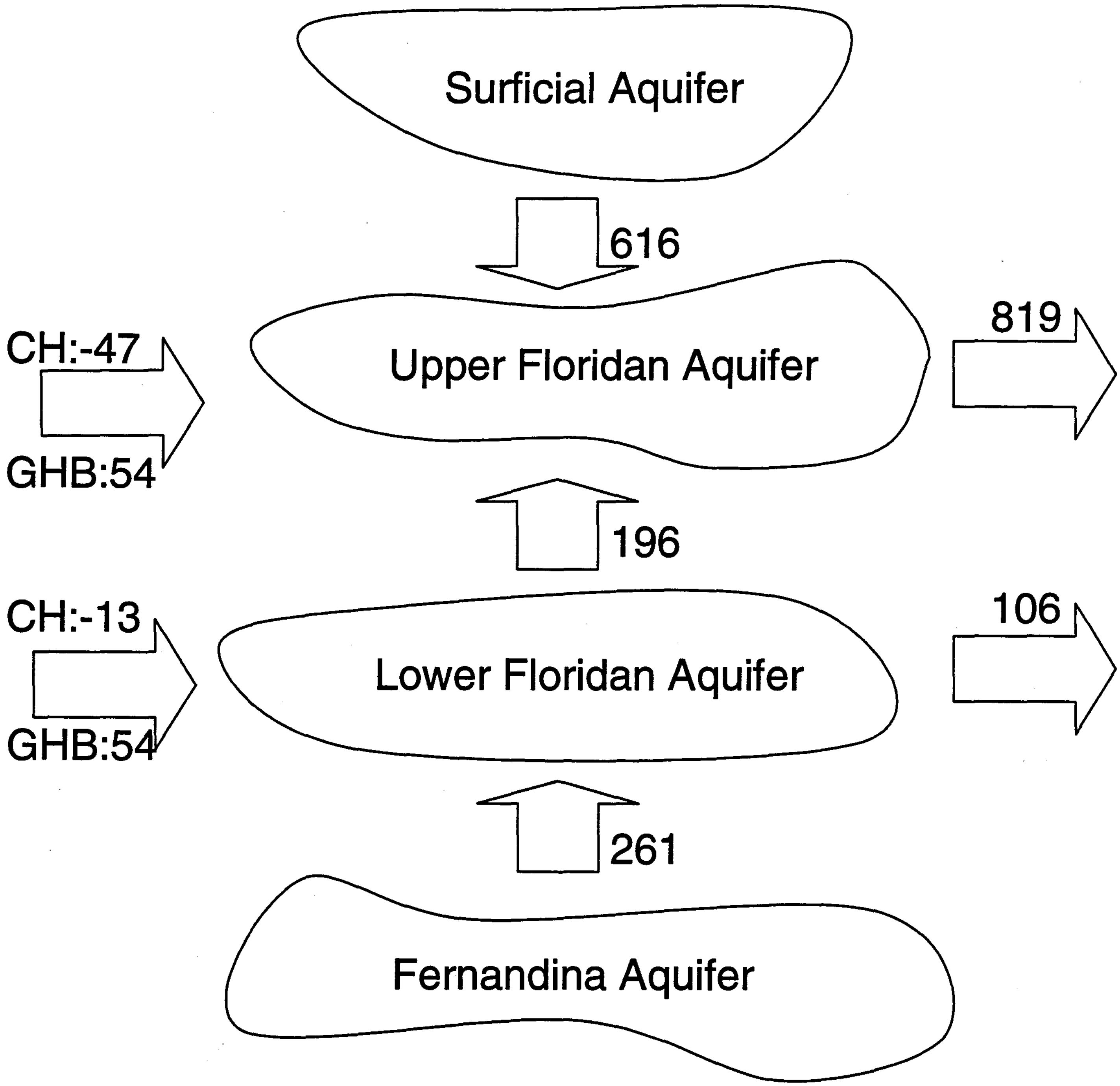
Simulation: The Fernandina aquifer in layer 4 was changed from fixed heads to a no-flow boundary.



CH - Flux Across Constant Head Boundary
GHB - Flux Across General Head Boundary

Figure 6

Simulation: All the fixed heads in layer 1 were raised 20 percent.



CH - Flux Across Constant Head Boundary
GHB - Flux Across General Head Boundary

Figure 7

more water enters the model through the surficial aquifer and through the general head boundary to make up the loss of water from below. The same is true if the fixed heads are adjusted in the surficial aquifer (figure 7). In this case, the increased flows from the surficial aquifer, due to a 20 percent increase in assumed heads, are offset by reduced flows from the boundaries. Note that the model fluxes must balance within a simulation. Thus in the two sensitivity simulations shown in figures 6 and 7, in order to adjust the fluxes, the distribution of heads simulated in the model changed significantly and no longer matched the data. This usually indicates that the simulated fluxes could be accurate, however, additional investigation is needed to confirm this.

At this time, CDM feels that the actual distribution of water flowing into and out of the Floridan Aquifer is not adequately understood, and that this situation must be improved in order to effectively model salt water intrusion. In areas such as Hilton Head, downward leakage from the surficial aquifer offshore will be salty, and an accurate assessment of this flux is critical. Likewise for the Brunswick area, where flows up from the Fernandina are brackish, a good understanding of the magnitude of these fluxes is critical to accurately assess the threat of salt water upconing in this area.

Because the surficial aquifer, the Fernandina aquifer, and the lateral flows into the model through the horizontal boundaries are all boundary fluxes, the present structure of all five models make it difficult to assess the accuracy of these fluxes. It is conceivable that a different balance of inflows to the model may produce similar calibration results, yet could result in very different assessments of the threat of salt water intrusion. (Note that a comparison of the Smith and Savannah models illustrates this point, see below.) This situation can be improved by updating the models, and explicitly modeling the surficial aquifer and the Fernandina. We believe that this effort would result in a greater understanding of the relative importance of each source of water, and improve (or verify) the present estimates of fluxes along the coast.

5.3 Results of Sensitivity Testing

A summary of the main findings derived from the sensitivity testing is provided here. The details of each simulation are not presented, only the significant results from the various simulations are summarized in bullet form.

- A test run was requested in which 0.5 mgd of water was injected into the RASA and Savannah models. The results showed a head rise of less than 0.05 feet. Since this could not be contoured, the results are not shown in graphic form as originally requested.

- Changes made to the inland fixed head boundary in the RASA model are shielded by the lower transmissivities of the Gulf Trough (with T values of less than 20000 ft^2 per day). A simulated 70 foot drop north of the trough due to changes in the inland boundary makes little difference to results near the coast. The conclusion is that the model is not sensitive to the inland fixed head boundary in the area of interest.

- All the models are very sensitive to T values in the Upper Floridan Aquifer.

- The RASA, Coastal, and Glynn models are very sensitive to the assumptions made in layer 4 regarding the Fernandina Aquifer. A change from fixed head to a no-flow boundary in layer 4 results in a drop of 12 to 14 feet in the Floridan Aquifer. This result leads to the conclusion that the fluxes from the Fernandina into the Floridan are important, and more insight into this boundary is required to improve the models.

- The estimate of the amount of water simulated to flow from the lower Floridan into the upper Floridan in the telescoping models is probably reasonable, because T-values for the upper Floridan are well documented. The source of this water, however, is more difficult to assess. Understanding the relative amounts coming from the inland boundaries and from the Fernandina is critical to understanding the threat of salt water upconing in the Brunswick area.

- The Glynn model is very sensitive to changes in the vertical hydraulic conductivity between the Fernandina and the Lower Floridan Aquifer. Much of the Glynn model simulated heads in the Floridan Aquifer are controlled by water supplied upward from Fernandina. The dynamics of this source of water are poorly understood, and a better understanding of these fluxes is necessary to improve the Glynn model

- The Glynn, RASA, and Coastal models are sensitive to the balance between flow downward from the surficial aquifer and vertical flow upward from the Fernandina.

- Transmissivity of the lower Floridan Aquifer is difficult to assess. CDM's sensitivity runs show that the model is not very sensitive to this factor, and therefore changes to the assumed T-values are possible while maintaining the calibration accuracy.

- The overall leakance of water from the surficial aquifer may be reasonably well calibrated in the models, however, it is unclear if a change in the balance of inflows from below and above could be achieved while still maintaining the water level calibration

- Adjustments to the offshore location of the no-flow boundary have a large effect on coastal heads. More work in defining this boundary will be important in future phases of the modeling effort.

- The Savannah and Smith models depend primarily on flow down from the surface to supply the upper Floridan Aquifer. The Savannah model receives relatively less water from the Lower Floridan, and the Smith model doesn't receive any water from below. The Glynn model and Coastal model reverse this pattern.

5.4 Comparison of Smith and Savannah Models

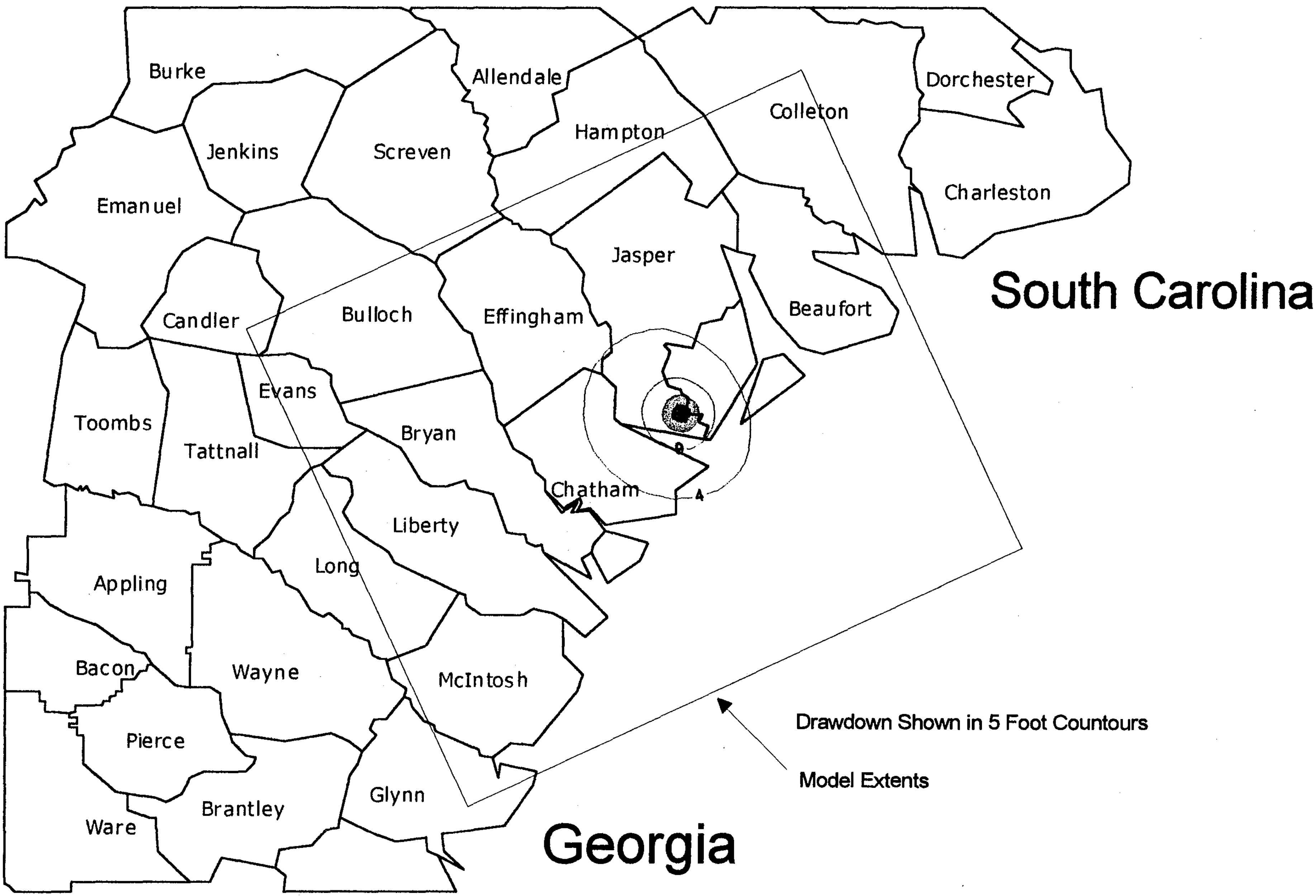
The sensitivity testing done by CDM revealed a great deal about the structure of the models, however, several questions remain. Are the relative amounts of water flowing from the three sources of water (lateral boundaries, the Fernandina, the surficial aquifer) being accurately simulated? Could the models be restructured to produce the same head distribution with a different balance of flows between the model layers and from outside the model boundaries?

To illustrate this point, the Savannah and Smith models, which cover the roughly the same area, were compared. Both models use different assumptions, but seem to come to comparable results in terms of their accuracy in simulating heads in the upper Floridan Aquifer.

The comparison between the Smith and Savannah models was made by simulating a 10 mgd withdrawal of water from the upper Floridan Aquifer near the Savannah River in each of the models. The resulting cone of depression is shown in **Figures 8 and 9** for the Savannah and Smith models respectively. Note that both models simulate similar cones of depression, both in terms of drawdown and in terms of the size of the cone.

The assumptions underlying both models, however, result in different flux balances. This is illustrated in **Table 1**.

Because the Smith model assumes no flow between the lower and upper Floridan Aquifers and the Savannah model assumes fairly significant flows between these aquifers, the relative amounts of flow into and out of the model are different. This suggests that our understanding of fluxes is still incomplete, and future, updated models, must improve on this.



CDM Camp Dresser and McKee Inc.

Figure 8
Drawdown Contours, Savannah Model

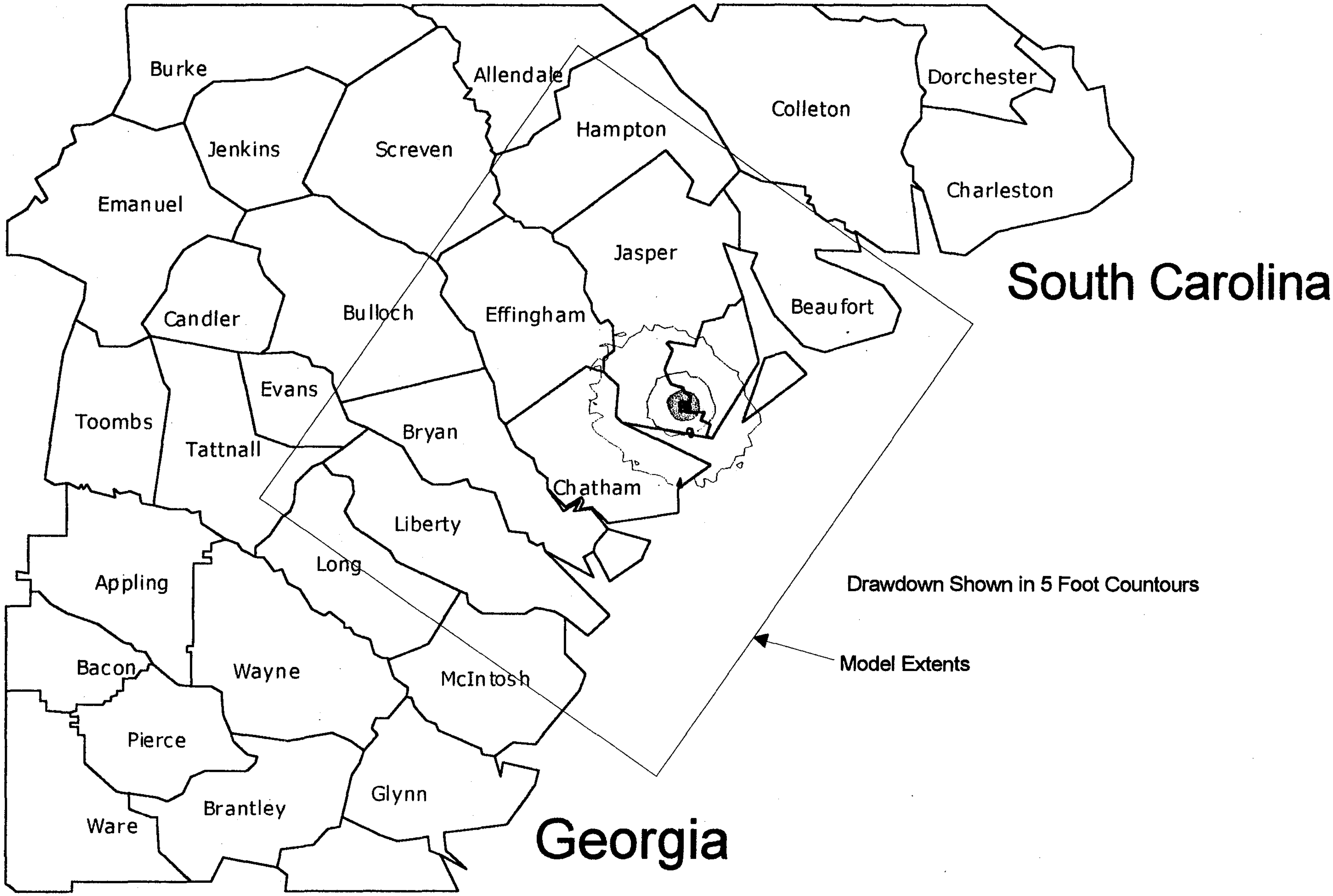


Figure 9
Drawdown Contours, Smith Model

Table 1
Comparison of Savannah and Smith Models

	SAVANNAH MODEL		***SMITH MODEL***
Cone of depression	-95 feet		-100 feet
Cone size	roughly equivalent for both models		
Heads at Hilton Head	-2 to -21 feet		-2 to -19 feet
Port Royal Island Mound	15 feet		15 feet
	1880	***1985***	***1884***
Inflows (cfs)			
Down from surface	24	87	35
Lateral from Boundary	60	93	75
Up from Lower Floridan	23	30	-
Outflows (cfs)			
Up to surface	99	18	63
Lateral to Boundary	3	11	47
Down to Lower Floridan	5	12	-
Pumping	-	169	-
Pump Test 10 mgd			
Drawdown	34 feet		30 feet

Section 6
Significant Findings

The most significant findings of CDM's analysis of the four telescoping models and the Smith model are summarized in this section.

- All five models appear to be well constructed and properly calibrated. The calibration statistics can be considered to be excellent when compared to the range of heads simulated. Selected transmissivities appear to be consistent across all the models.

- The models have been properly applied in past reports and studies.

- The cell size (node spacing) was adequate for the stated purpose of each of the models, with the possible exception of the Savannah and Smith models. Updated models should use variable node spacing and tighter grids.

- Model results are generally sensitive to the vertical hydraulic conductivity of the Upper Confining Unit, and the Transmissivity of the upper Floridan, less sensitive to other parameters. It is likely that the T-values for the upper Floridan are reasonably accurate, however, those for the lower Floridan are more difficult to assess.

- The models are outdated when considered in the light of today's computer capability. The grid spacing could be much tighter, particularly in the areas of concern near Savannah/Hilton Head and in the Brunswick area. The coastal model, with a 2 mile grid, appears to be redundant, and would not be required if the RASA model grid were updated.

- The models, as constructed, can be used to assess large scale injection or withdrawals from the upper Floridan, and can be used to make preliminary assessments of the impacts of pumping on heads near the coast. In general, all the models appear capable of simulating pumping drawdowns in the upper Floridan with sufficient accuracy for regional planning purposes.

- The local models (Savannah, Glynn County, Smith) do not have sufficiently fine grids to be used for well field design or to simulate smaller scale Aquifer Storage and Recovery schemes. They are also too large scale to be used for detailed contaminant transport simulations.

- The accuracy of the simulated fluxes within the models is difficult to assess. Based on the present configuration of the models (fixed heads at the surface, along inland boundaries, and in the Fernandina) and the comparison of results between the Savannah and Smith models, it is apparent that model simulated fluxes should be reexamined in the updated models. The simulated downward fluxes from the surficial and upward fluxes from the Fernandina are critical to the analysis of salt water intrusion. At present too little is understood about the relative magnitude of the various sources of water to the model to feel confident about their accuracy.

Section 7
Primary Concerns

Based on the findings of the model assessment, CDM has a number of concerns about the future use of the models. These can be summarized as follows.

- The present configuration of the models do not allow for simulation of the surficial aquifer. For this reason, impacts of pumping in the Floridan aquifer on the surficial aquifer and associated surface water bodies cannot be assessed. This may not be a concern in many areas, but there is a possibility that pumping in the Floridan aquifer may impact surficial aquifer heads in certain areas, for example in the Hilton Head area. Also, the models should be available for use in evaluating and granting water use permits. This would require that they have the ability to simulate impacts to the water table.

- Fluxes into, within, and out of the model are a critical aspect of modeling in coastal areas. The rate and degree of salt water intrusion is directly associated with fluxes such as the rate of downward leakage of salt water from the ocean and the rate of upward movement of brackish water from the Fernandina. The accuracy of the fluxes in all of the models is difficult to assess, and must be addressed if salt water intrusion modeling is to be attempted.

- The main sources of water to the coastal system are clear: horizontal flows from inland boundaries of the model, recharge of precipitation into the surficial aquifer with subsequent downward leakage into the Floridan aquifer, and upward movement of water from the more permeable units of the lower Floridan aquifer such as the Fernandina. It is the balance between these sources which is still imperfectly understood. At present, both the surficial aquifer and the Fernandina act as unlimited sources of water to the models, and this assumption needs to be reexamined.

- Both the RASA and Savannah models were somewhat unresponsive to changes in pumping and boundary conditions in the Hilton Head area. This can be seen in the matrix provided in appendix 1, where heads at Hilton Head primarily respond to changes in nearby boundary conditions, but are less responsive to changes elsewhere in the model. This could be caused by the relatively thin confining unit beneath the fixed head boundary in the surficial aquifer and the proximity of the northeastern specified head boundary. It appears that these two boundaries are unduly affecting the heads simulated near Hilton Head, and the model results may be less accurate than required.

- The pumping simulated in the model may be incomplete. Additional work on agricultural pumping and inclusion in future modeling work is an important part of improving the model's ability to accurately simulate fluxes.

Section 8
Recommendations

Based upon the findings, a number of specific recommendations have been developed that will help the USGS to address the concerns listed above and to improve the models. The recommendations do not imply past inadequacies in the models, but are designed to bring the models up to date to meet the more extensive demands being placed on them to answer questions on the aquifer system and to support coastal management of the groundwater. Recommendations are first made on improving and updating the flow models. This is followed by some preliminary recommendations on salt water intrusion modeling.

8.1 Flow Model Recommendations

Based on the model evaluation results, CDM recommends the following:

- The present models should be used as the basis for a new set of models, which will include updated grids and a new, more extensive layering scheme.

- Two levels of models are envisioned. The RASA model grid should cover the same general area as the existing RASA model, however, it should employ variable node spacing. Two mile grid spacing would be adequate for inland areas, however, along the coast, the grid should have a spacing of one mile or less. Particularly in areas of concern, such as the Savannah/Hilton Head area or Glynn County, a nodal spacing of 1/4 mile is suggested.

- The coastal model is redundant, and need not be updated. Instead, local models in the Savannah and Glynn County areas could be developed with a grid spacing of less than 1/4 mile, as required. These models should use the same, telescoping approach applied to the present models.

- The models should be redesigned as fully 3-dimensional models. They should contain the eight described in section 4.3 as active layers. Recharge should be explicitly applied to the surficial aquifer, and the Fernandina aquifer should be actively simulated as well.

- It is recognized that there are severe data limitations, particularly in the deeper formations, and that many assumptions will have to be made. Nevertheless, CDM sees great value in explicitly modeling all units because we believe that the model development and calibration process will improve our understanding of the entire system. By modeling the entire system, valuable insight will be gained in the relative importance of each of the sources of water to the model, and with the insight gained, better, more effective data collection programs can be designed and implemented.

- Additional data should be collected on agricultural pumping, and all data on the surficial aquifer should be compiled and organized for use in developing the updated models.

- Although CDM sees no problem in continuing with the use of MODFLOW as the flow model code, consideration should be given to a finite element code. Finite element codes may prove to have better flexibility in designing the grid, and may also be more compatible with the codes selected for use in salt water intrusion modeling.

8.2 Preliminary Recommendations on Salt Water Intrusion Modeling

In selecting a suitable code for salt water intrusion modeling, a number of considerations are important. First and foremost, the model's capability and purpose has to match the problem to which it is applied. Practicality is also a consideration, the model should be relatively easy to use and the results or computed variables should be easily related to the management objectives. The range of applicability of the model code is also important, since there are multiple management objectives involved in the coastal groundwater management effort.

Models can be categorized by the processes simulated. Suitable model categories for coastal management are:

- Flow models: which simulate the movement of one fluid. The models consider the hydraulic system parameters (hydraulic conductivity, aquifer thickness, etc) as independent field information, and the hydraulic head and fluxes as the dependent variables.

- Flow models which simulate the movement of more than one fluid in porous or fractured rock. One fluid is water, the other, if present, can be a DNAPL or LNAPL. In the case of salt water intrusion, a special case of multi fluid flow occurs when layers of water of distinct density are separated by a relatively small transition zone.

- Solute Transport Models, which simulate the displacement of pollutants. They are used to predict movement and concentration of water-soluble constituents, and require groundwater velocities for the calculation of advective transport. They often can calculate spreading by dispersion. A special category of solute transport models couples the solute concentration to the fluid density, which, in turn, affects the hydraulic heads.

Models can also be categorized by spatial dimension, such as one, two or three dimensional models. A survey of literature has indicated that there are several models potentially applicable to salt water intrusion modeling of density dependent flow, including the DYN-system of CDM (groundwater flow, contaminant transport, sharp interface dual density flow in 3-dimensions), SHARP (groundwater flow and sharp interface dual density flow in quasi-three dimensional model), HST3D (groundwater flow and solute transport with density dependent capabilities in three dimensions), MOCDENSE (solute transport and dispersion of up to two constituents with density dependent flow in 2-dimensions), SUTRA (transport of dissolved substances with fluid density dependent flow in 2-dimensions), SWICHA (variable density fluid flow and solute transport for sea water intrusion in 3-dimensions), SWIFT (transport of dissolved substances with fluid density dependent flow in 3-dimensions), and FEMWATER (transport of dissolved substances with fluid density dependent flow in 3-dimensions).

The conditions along the Georgia coast are similar in many ways to those found further south in Florida. Based on our experience there as well as along the Atlantic coast, we have the following preliminary recommendations.

- Effective salt water intrusion modeling of the entire coast, of the Savannah/Hilton Head area, or the Brunswick area may require the use of several approaches and modeling techniques to fully understand the aquifer system response to pumping. All of the approaches, however, will depend on the adequacy of the updated flow models to simulate both horizontal and vertical flow through the system.

- For existing intrusion near Hilton Head and in the Brunswick area, fully three dimensional models are strongly recommended over more simple two dimensional or cross-sectional models. The movement of salt water in these areas is a three dimensional phenomenon, and must be modeled as such.

- The aquifer system and the behavior of salt and fresh water is highly complex. For this reason, practical approaches to modeling rarely attempt to simulate fully three-dimensional density-dependent miscible fluid flow. Rather simplifying assumptions are made to enable reasonable but practical solutions. Considering the nature of intrusion in the Savannah/Hilton Head area, as well as the threat of regional intrusion along much of the coast, a reasonable assumption is that the salt water and the fresh water are immiscible, separated by a sharp interface.

- Three dimensional sharp interface models are well suited to analyze the long term sustainability of coastal wells, provide insight into the horizontal and vertical movement of salt water based on heads and the effects of differing density, give estimates of the rate of advance and upconing of salt water near pumping centers, and help estimate the present location of the salt water wedge offshore where data is lacking.

- More traditional solute transport models can be effectively combined with the results of the sharp interface model to provide additional insight into chloride concentrations on a local scale near pumping centers.

- In selecting the software, consideration should be given to the ability of the codes to use the same basic models to perform a variety of types of simulation (flow, solute transport, density dependent flow etc.). This reduces the overall effort, and makes the extensive calibration and sensitivity testing performed on the flow model directly applicable to the subsequent salt water intrusion models. For example, CDM has developed a set of models called the DYN-series. These are fully three-dimensional finite element models that are integrated around the basic flow model. Once the flow model has been developed and calibrated, the same model can be used to simulate solute transport using random walk particle tracking, or to simulate lateral salt water intrusion using the sharp interface assumption, or to simulate upconing of salt water with or without consideration of density effects.

Appendix A
Matrix of Model Response to Sensitivity Simulations

Table A-1
Matrix of Model Response to Sensitivity Simulations

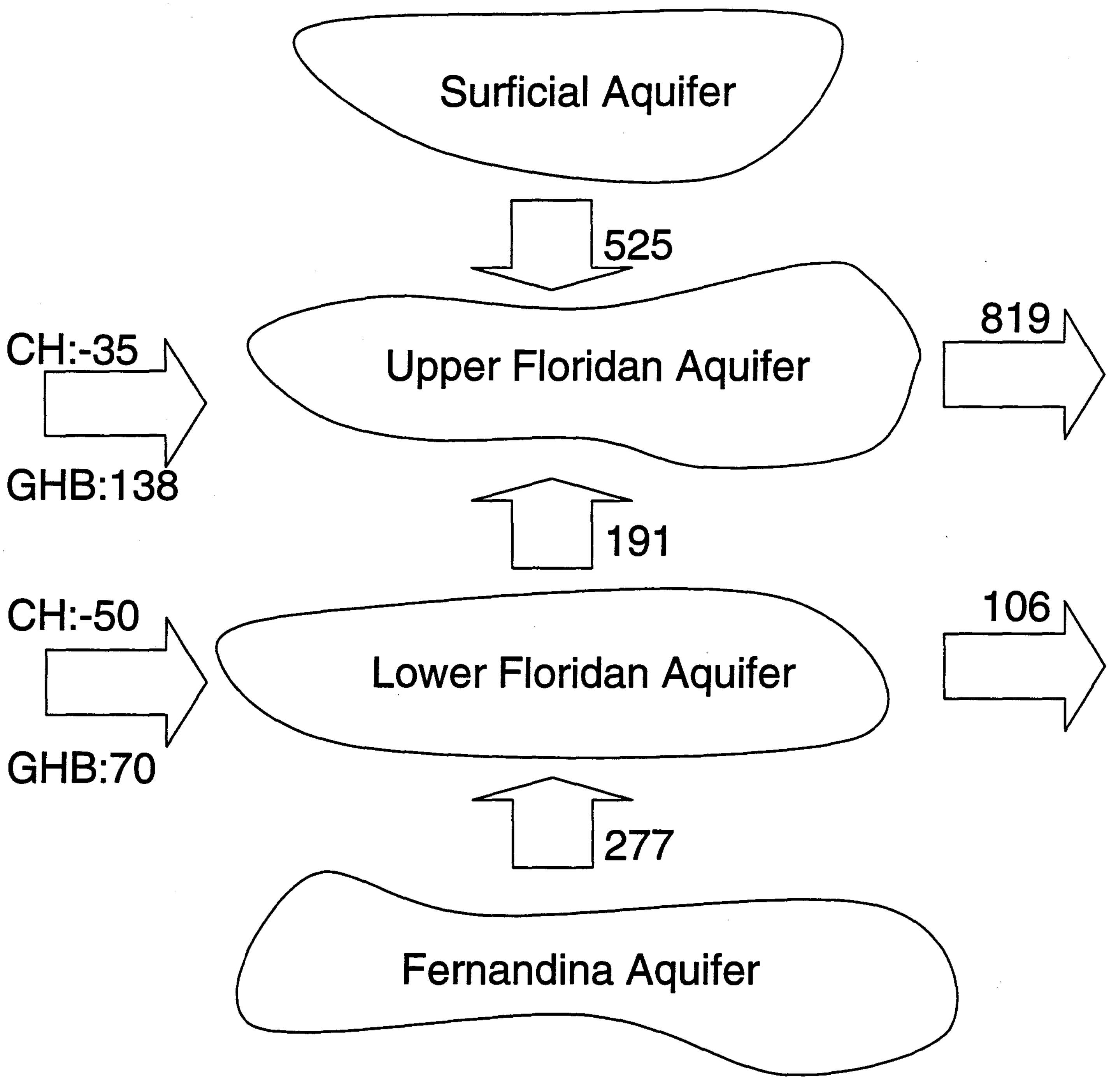
Head (feet) in Layer 2 - Upper Floridan Aquifer

	ras	raslay3	raslay32	raslow	l1head	l3head	l3head_2	gulft	moveocn	moveocn2	moveocn3	moveocn4	noghb
N Hilton Head	-5	-5	-5	-5.7	-3.9	-5	-4.9	-5.5	-3.2	-3.1	-5.9	-6.3	-5.3
Savannah	-67.1	-67.3	-67.2	-73.7	-62.6	-62.6	-62.6	-62.6	-62.6	-62.6	-62.6	-62.6	-70.8
Brunswick	7.8	7.6	7.7	-17.2	10.4	7.7	7.7	6.2	3.8	3.6	8.4	7	0
Well Inj Node	9.5	8.8	8.9	-7.3	12.7	8.9	8.9	6.4	9.9	9.8	8.3	6.6	1.8
Fernandina Beach	-34.2	-34.3	-34.3	-61.6	-32.2	-34.2	-34.2	-34.8	-41.8	-41.8	-33.7	-37.8	-40.6
Appling County - Central GA	49.2	48.9	49.2	40.7	56.5	49.2	49.2	44	48.7	48.6	49.1	48.4	36.3
Pulaski County - NW GA	235.7	227.8	235.7	235.7	271.8	235.7	235.7	235.8	235.7	235.7	235.7	235.7	235.7
Allendale - Northern SC	116.8	112.3	116.8	116.8	138.1	116.8	116.8	118	116.8	116.8	116.8	112.3	116.8
Offshore - Hilton Head	0.7	0.7	0.5	0.4	1	0.7	1	0.4	CH	CH	-0.2	-0.5	0.6
Offshore - Brunswick	17	17	17	-2.8	18.4	17	17	16.3	9999	9999	9999	9999	14.1
Offshore - Jacksonville Beach	24.6	24.5	24.6	8.6	25.6	24.6	24.6	24.4	9999	9999	9999	9999	22.2

CH - Constant Head Boundary
9999 represents no flow in grid block

Appendix B
Flux Diagrams of Base Simulations and Sensitivity Simulations

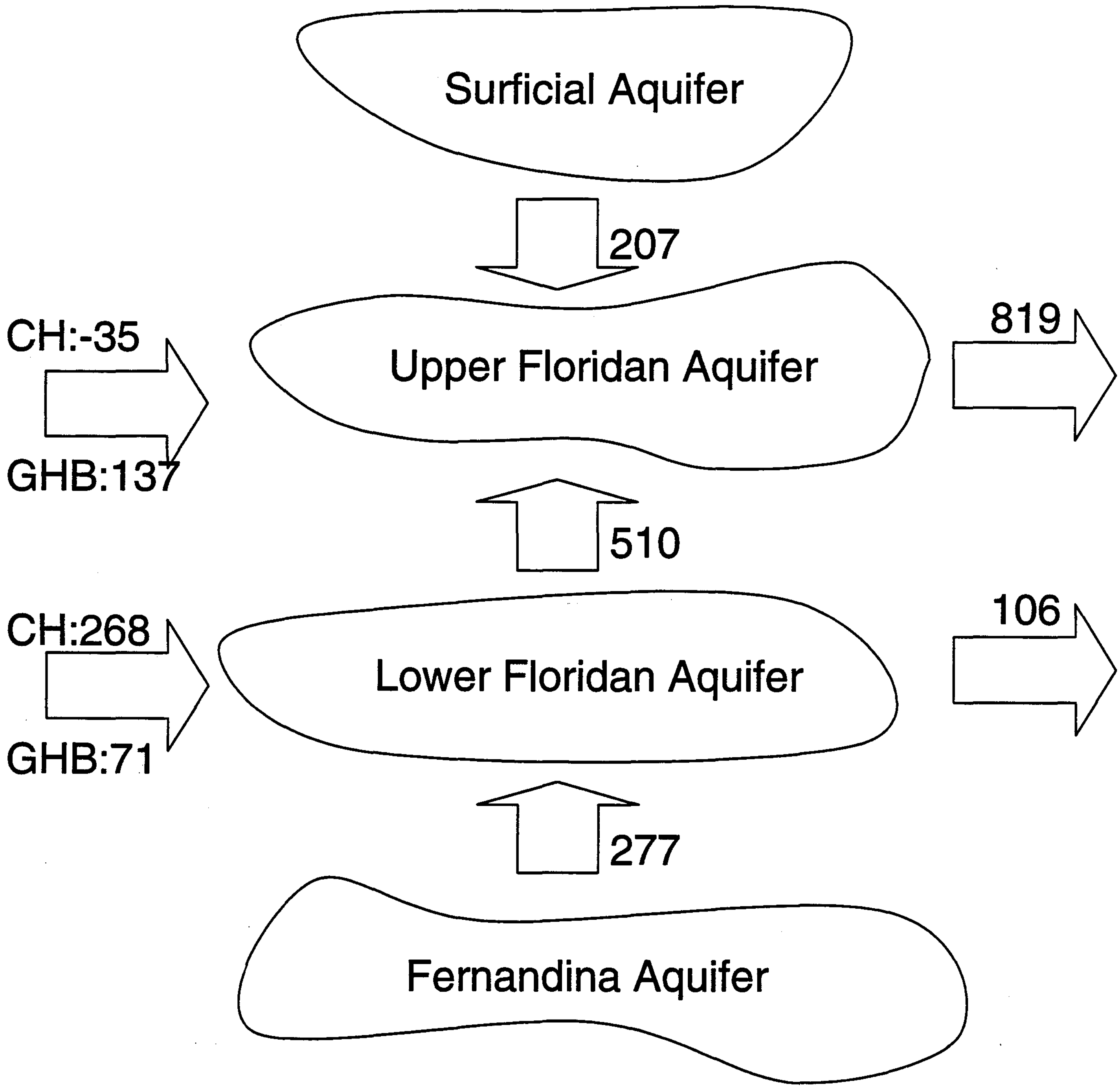
Simulation: The fixed head boundaries to the west and north were changed to no-flow boundaries in layer 3.



CH - Flux Across Constant Head Boundary
GHB - Flux Across General Head Boundary

Figure B-1

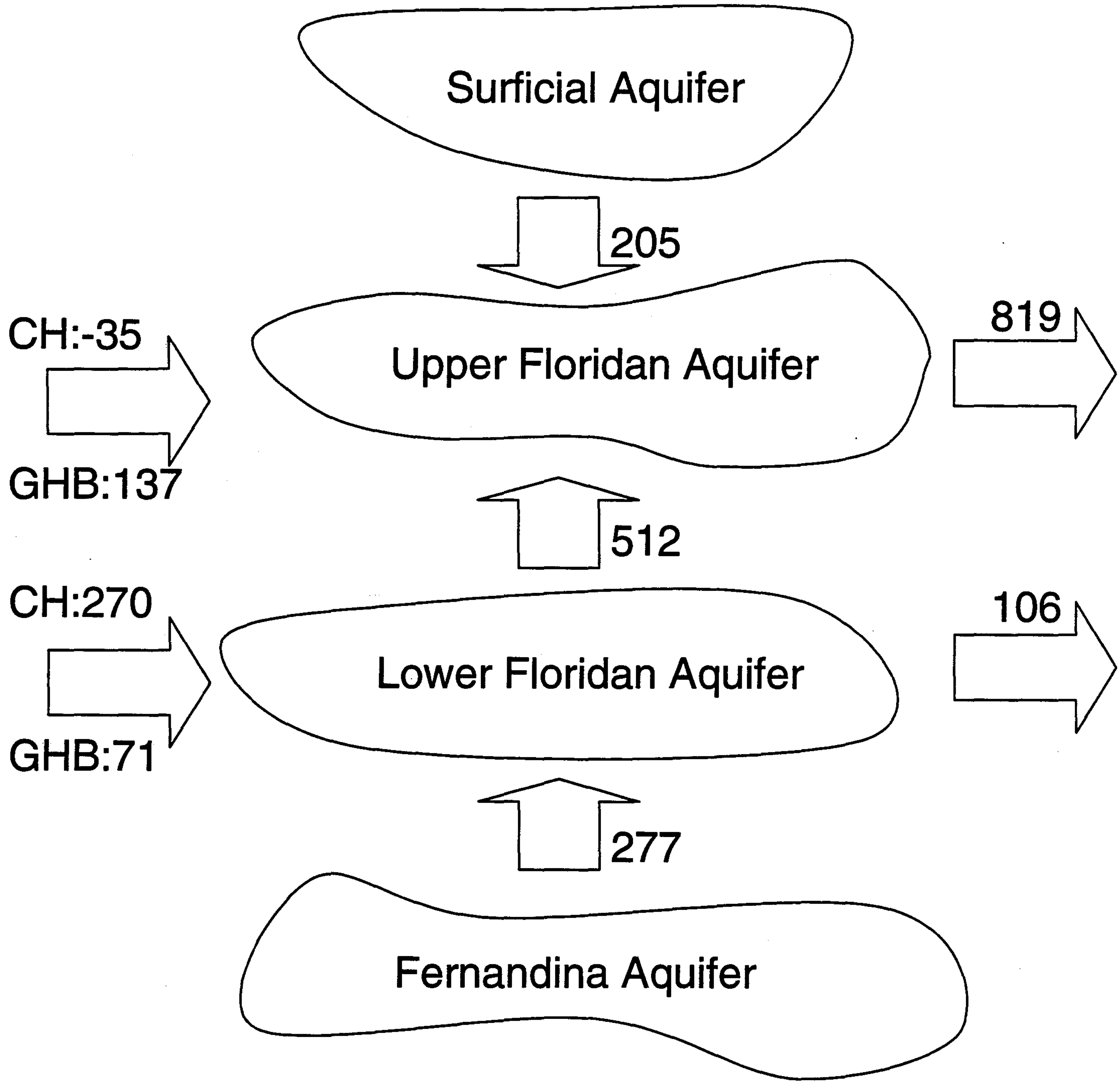
Simulation: The constant head boundary in the Lower Floridan layer offshore to the east was changed to no-flow in both layer 2 and layer 3.



CH - Flux Across Constant Head Boundary
GHB - Flux Across General Head Boundary

Figure B-2

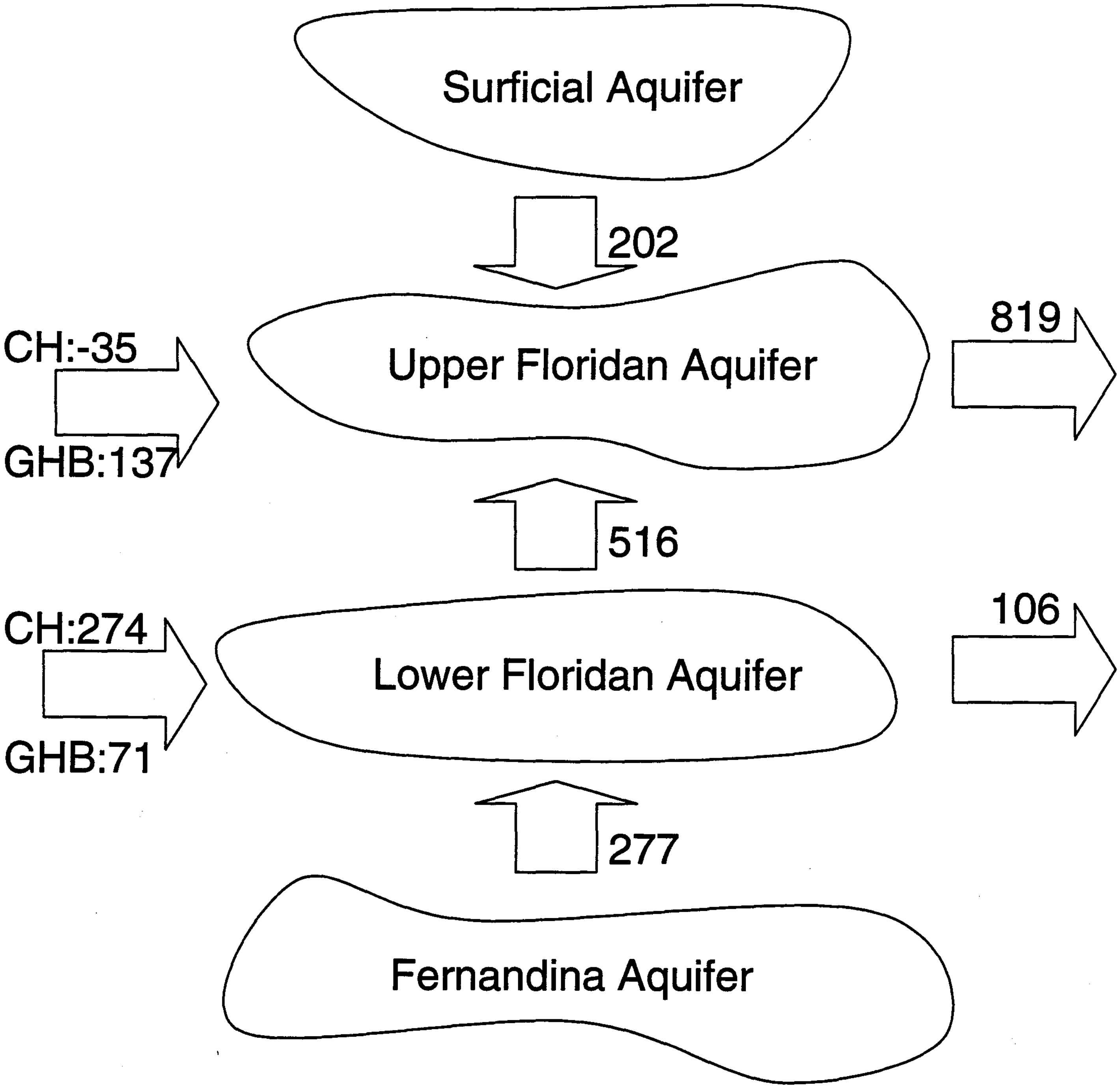
Simulation: All the heads in the offshore layer 3 fixed head boundary were raised by 10 feet.



CH - Flux Across Constant Head Boundary
GHB - Flux Across General Head Boundary

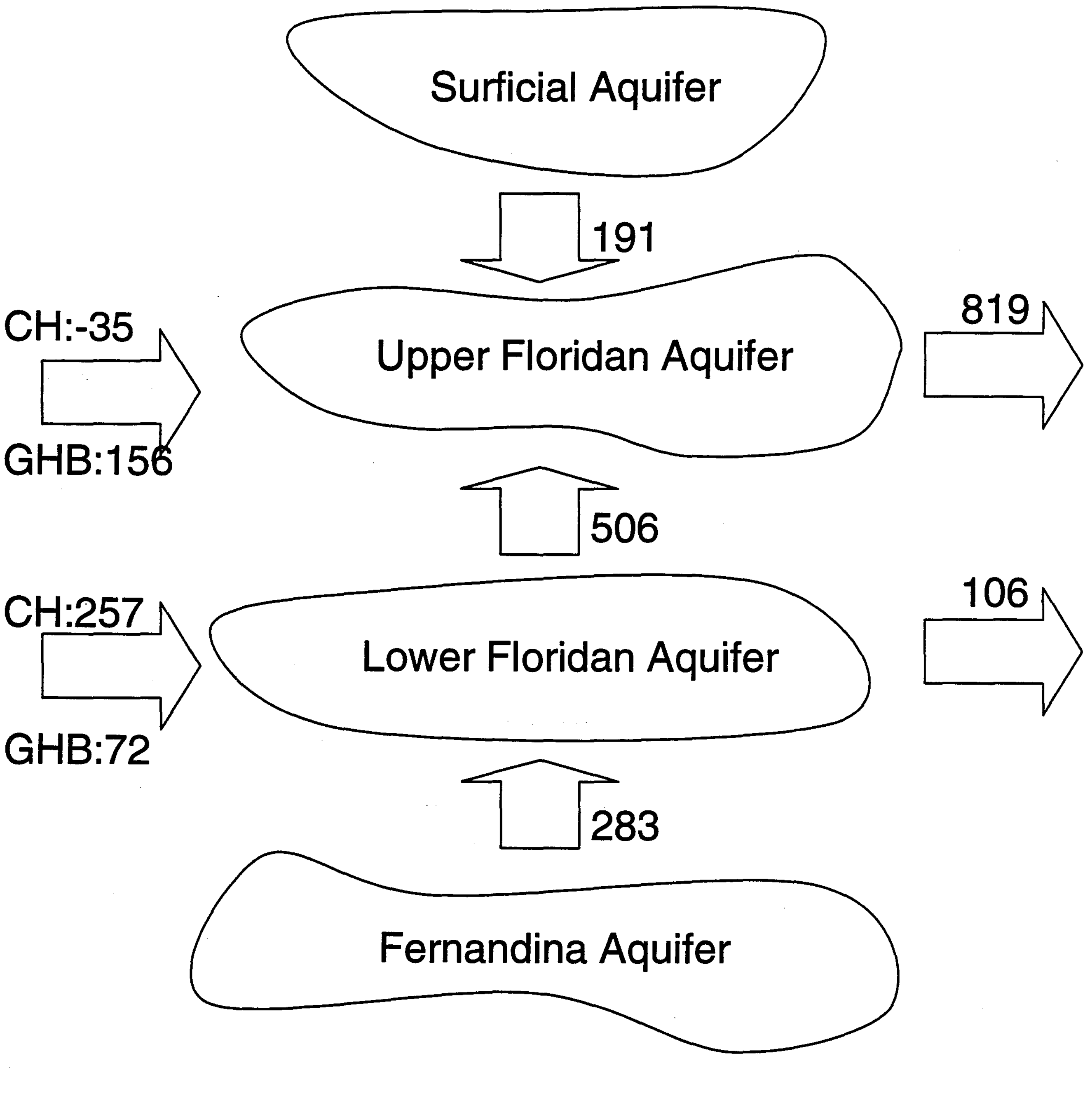
Figure B-3

Simulation: Offshore fixed heads in layers 2 and 3 were raised by 10 feet.



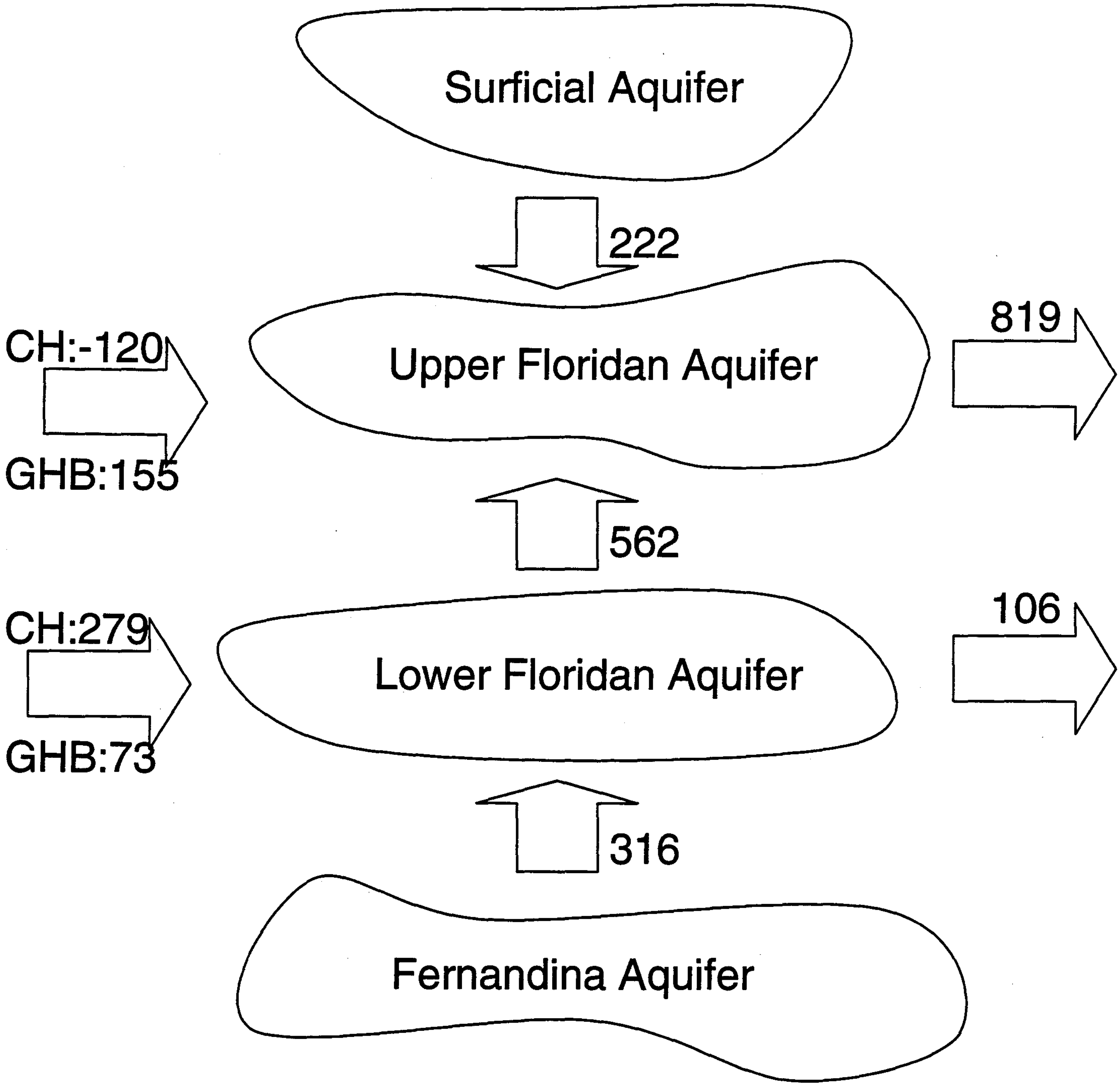
CH - Flux Across Constant Head Boundary
GHB - Flux Across General Head Boundary

Simulation: The transmissivity of the gulf trough was decreased by 50 percent.



CH - Flux Across Constant Head Boundary
GHB - Flux Across General Head Boundary

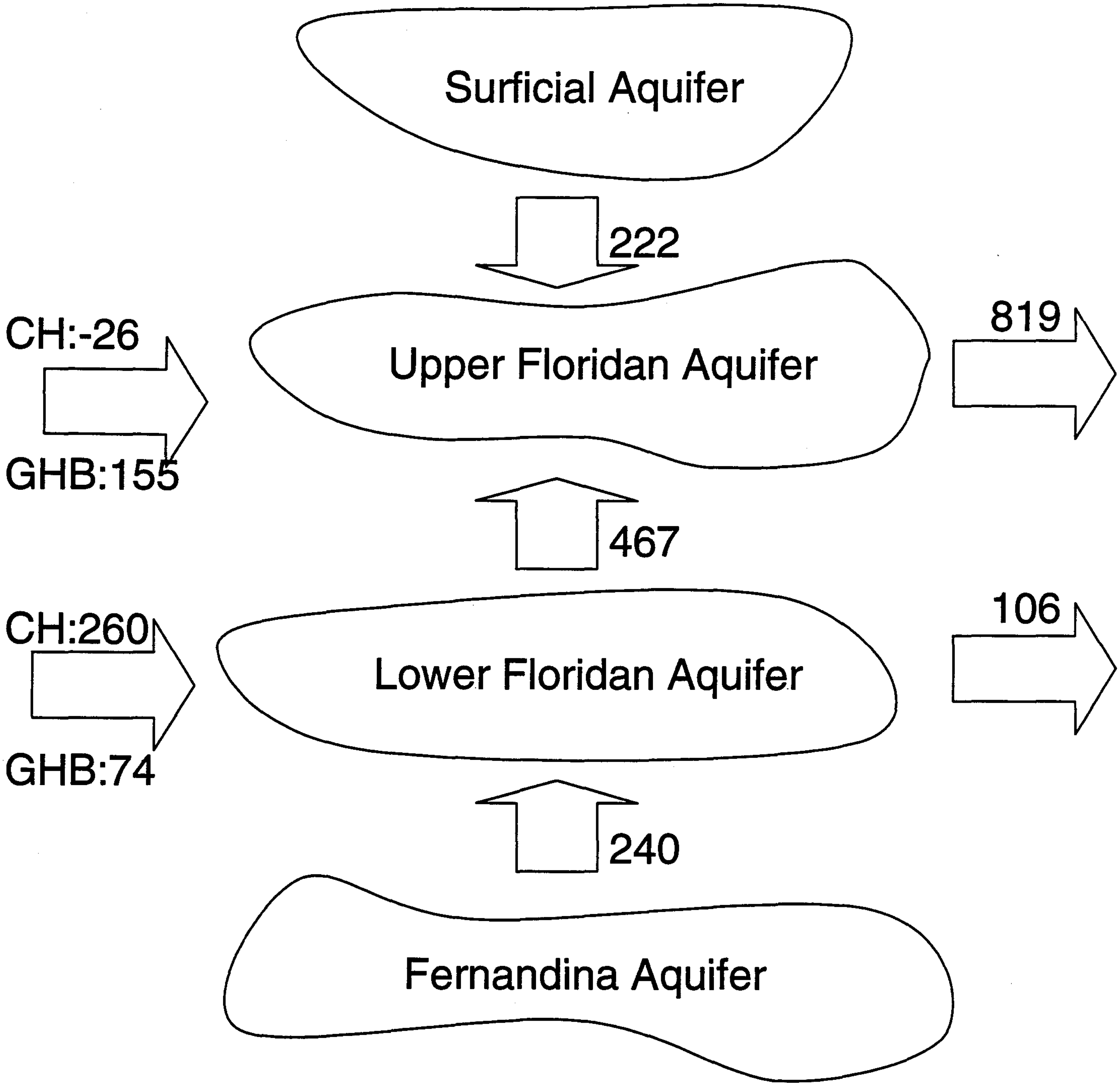
Simulation: The constant head boundary of layer 2 (Upper Floridan) was moved from far offshore to just offshore.



CH - Flux Across Constant Head Boundary
GHB - Flux Across General Head Boundary

Figure B-6

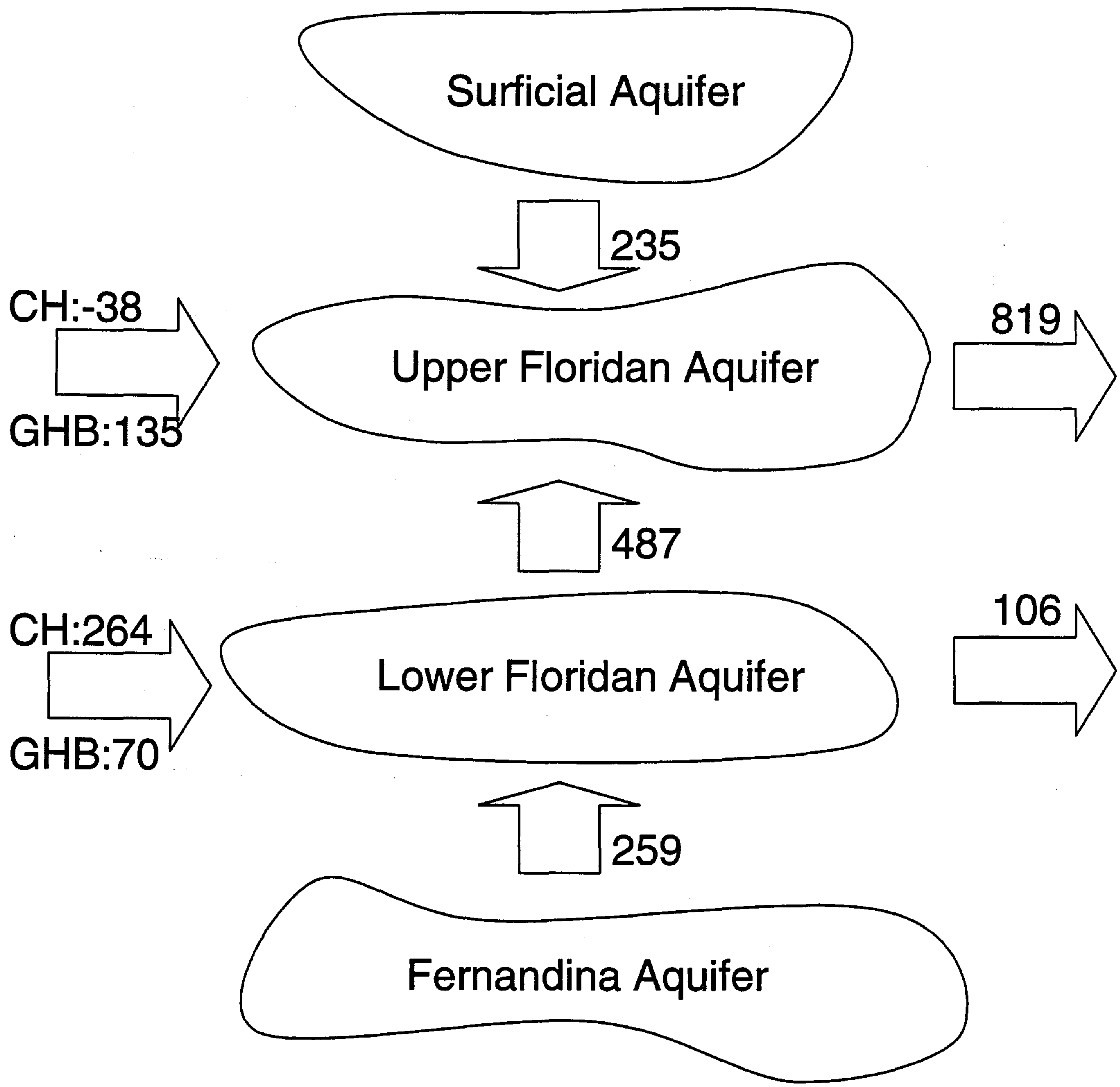
Simulation: Both Upper and Lower Floridan fixed head boundaries were moved to just offshore.



CH - Flux Across Constant Head Boundary
GHB - Flux Across General Head Boundary

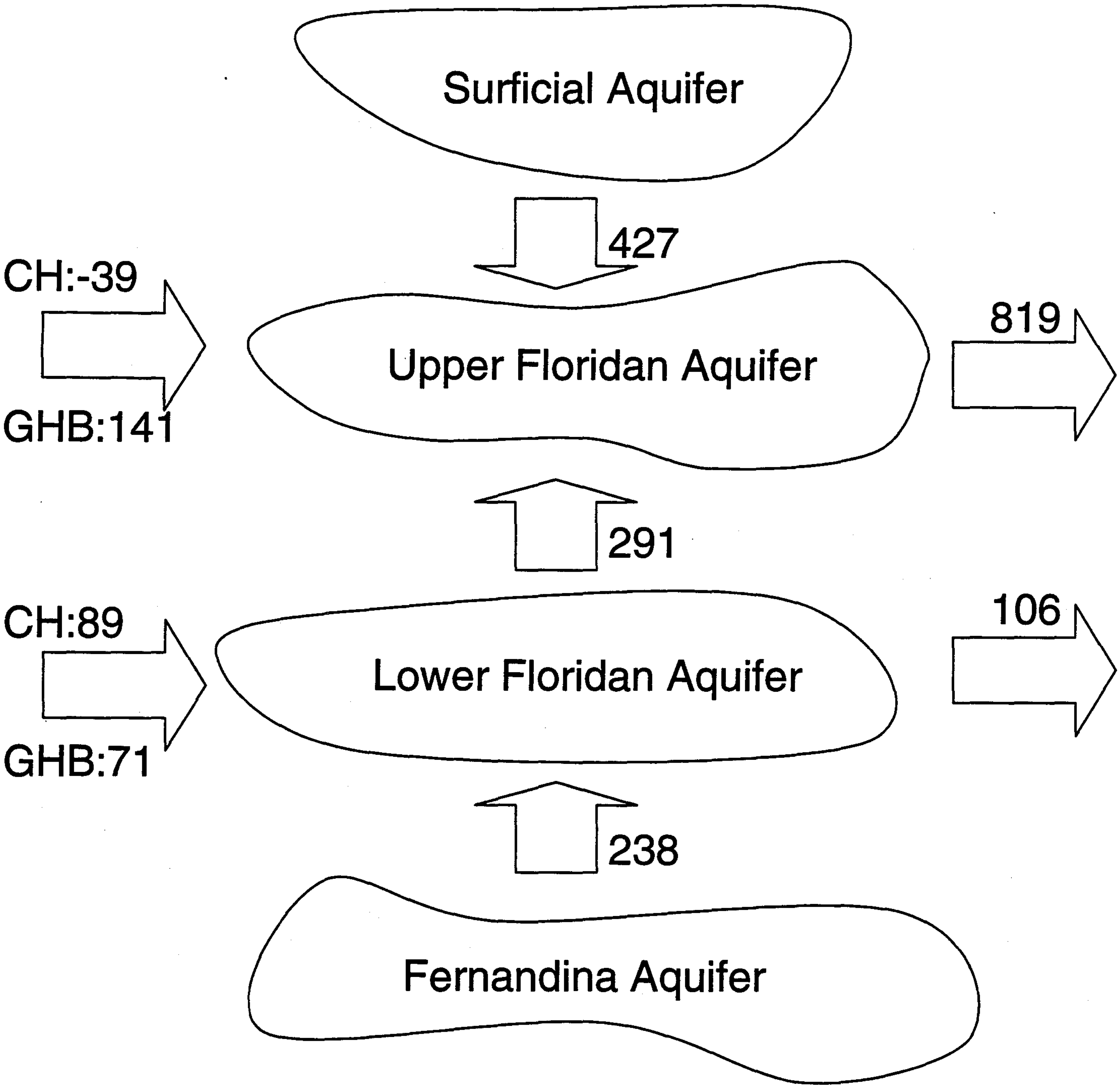
Figure B-7

Simulation: The entire coast was converted to a no-flow boundary located just offshore in layer 3 (lower Floridan)



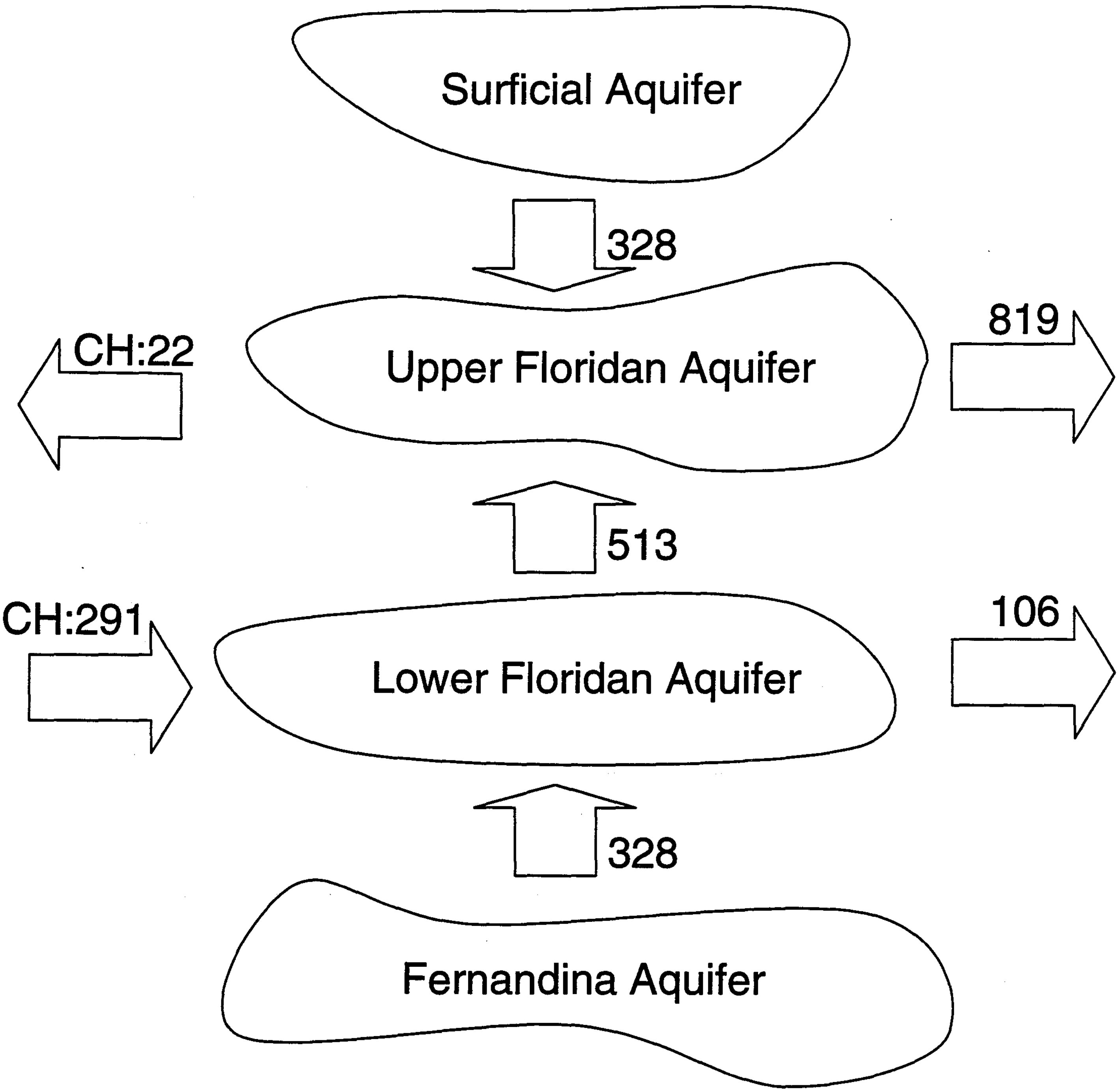
CH - Flux Across Constant Head Boundary
GHB - Flux Across General Head Boundary

Simulation: The entire coast was converted to a no-flow boundary located just offshore in layers 2 and 3 (upper and lower Floridan)



CH - Flux Across Constant Head Boundary
GHB - Flux Across General Head Boundary

Simulation: All general head boundaries in south west part of model were converted to a no-flow boundary.



CH - Flux Across Constant Head Boundary

GEORGIA SOUND SCIENCE INITIATIVE

REVIEW OF GROUND-WATER FLOW MODELS

Prepared for

Georgia Environmental Protection Division

Prepared by

Law Engineering and Environmental Services, Inc.

March 9, 1999

REVIEW OF USGS GROUND-WATER MODELS FOR FLORIDAN AQUIFER IN COASTAL GEORGIA AND ADJACENT PARTS OF SOUTH CAROLINA AND FLORIDA

(The Smith 1988 Flow Model, The EPD-USGS 1991 Coastal Model, The Garza and Krause 1992 Savannah Vicinity Model, The 1989 RASA Model)

Law Engineering and Environmental Services, Inc., (LAW) has evaluated the subject ground-water flow models consistent with the scope of work outlined in LAW's contract with the Georgia Environmental Protection Division (EPD). This report presents the results of that evaluation. LAW's findings are presented throughout this report in bold type. The final section of the report contains LAW's recommendations.

Appropriateness of USGS QA Procedures

According to information obtained from John S. Clarke of USGS's Atlanta office (e-mail dated 11/23/98), datasets for each of the models were reviewed by the USGS project staff during model development and calibration. In addition, these datasets were reviewed as part of the USGS review process for their model reports. Such report reviews include, at a minimum, one inhouse review, one out-of-office review, and Director's approval. In the case of the three Georgia models, the USGS actually conducted several additional colleague reviews of the papers. Their reviews looked at boundary conditions, hydraulic properties, and model results. In addition, the ground-water-level data that were used to generate potentiometric maps (used for boundaries) and hydrographs were reviewed as part of the District's quality-assurance plan. More information on the USGS quality-assurance plan can be obtained at web site http//wwwga.usgs.gov/gwqa. **The review process appears, in general, to be appropriate.**

Appropriateness of USGS Grid Discretization and Cell Size

The larger regional model (RASA model) has a uniform cell size of four miles x four miles. **This is an appropriate size considering the area covered by the model and the limited amount of available data for some fairly large portions of the modeled area.**

The Coastal Model has a uniform cell size of two miles x two miles. **This can be considered appropriate because this model is also of a regional nature (large area covered) and because there are limited data available for certain portions of the modeled area.**

The Glynn County model has a non-uniform grid with the smallest cells (1/4 mi. x 1/4 mi.) around the pumping centers associated with the City of Brunswick. The cell size gradually increases by a factor 1.3 to 1.5 away from the Brunswick area. The largest cell size in the four corners of the model is four miles x four miles. **The refined portion of the model around Brunswick seems appropriate for modeling steeper hydraulic gradients around pumping centers and areas with more data on aquifer characteristics.**

The Savannah and Smith Models have a uniform grid with cell size of one mile x one mile. **This cell size may not be adequate to provide accurate analyses of changes in hydraulic heads/gradients for areas of highest interest (which also have the most field data available) such as Hilton Head Island and Savannah city area.** Refining the model in these areas, by adopting an approach similar to that taken in the Glynn County model, would potentially offer significant improvements in the model's applicability for aquifer management and engineering control.

The regional RASA model and all three derived telescopic models (Savannah, Glynn County, and Coastal models) are quasi three-dimensional models with two active layers (Upper and Lower Floridan Aquifers). **This model setup does not allow a direct simulation of vertical flow components and flowpaths between different hydrostratigraphic units. A real 3D model, where both aquifers and aquitards are modeled with their respective thickness and**

hydraulic conductivity (horizontal and vertical), would enable analysis of direct hydraulic interconnections between the two Floridan Aquifers and overlying (Miocene and Surficial) and underlying (Fernandina) aquifers. A particle tracking code based on Modflow (e.g., USGS Modpath) would also clearly show capture zones and recharge areas for various pumping centers, as well as particle travel times. **A 3D model with particle tracking capability would increase the value of the models for aquifer management and possible engineering controls, including injection and aquifer storage.**

The Smith model has only two layers with layer 1 (active) being simulated as the constant head source/sink (through assigned leakance) for layer 2 (inactive) which represents the Upper Floridan aquifer. **The comments in the preceding paragraph on the advantages of a truly 3D model apply as well to the Smith model.**

Appropriateness of Hydrogeologic Boundaries

The salt water-fresh water interface in the ocean is appropriately modeled as a no-flow boundary in the regional RASA model (e.g., see USGS PP 1403-D, page D60) over a portion of the interface area. However, this interface in the area of Hilton Head Island and Port Royal Sound is not modeled as a no-flow boundary (i.e., it is not represented as a no-flow boundary in either the RASA or Savannah models; this is the case with the Smith model as well). Rather, a constant head boundary is placed northeast and east of the interface and extends southeast far into the ocean. The use of this boundary condition is inconsistent with the statement in PP 1403-D, page D5: "The eastern boundary is the easternmost limit of the aquifer system in South Carolina or the freshwater-saltwater interface offshore in Georgia and part of South Carolina." **In other words, it appears that the freshwater-saltwater interface is sometimes modeled as a no-flow boundary and sometimes as a constant head boundary.**

It would be useful for the USGS to present field evidence or assumptions for selection of the constant head boundary (or general head boundary in the case of the Smith model). In addition, the rationale for the treatment of the interface in the Hilton Head Island/Port Royal Sound areas should be presented. It also appears, based on the shape of

potentiometric head contours, that application of the constant head boundary influences the head-discharge relationship at Savannah and Hilton Head Island (e.g., such boundaries are important inexhaustible sources of water for the model).

All four boundaries of the Savannah Model are modeled as constant flux boundaries as represented by injection wells. It is not clear why the eastern boundary is modeled this way since it is aligned with the RASA Model's constant head boundary.

In the USGS report, it is stated that the southwestern boundary of the RASA Model is simulated with a constant-flux boundary using Darcy's Law (USGS PP 1403-D, p. D61). However, in the provided computer model files this boundary is simulated with the general-head package that does not maintain constant flux; as hydraulic head inside the active model area decreases (e.g., due to pumpage), the inflow from the boundary increases. **In other words, the general head boundary is an inexhaustible source of water for the model. This inconsistency should be rectified.**

In the case of the Smith model, two constant head boundaries (over the land area) and one head-dependent boundary (in the ocean, no field evidence available) are placed along three model edges. These artificial boundaries were placed away from the study area to minimize potential errors in boundary flow calculated by the model for hypothetical pumping scenarios (USGS WRIR 87-4285, page 21). **However, there is no "quantitative discussion" on the effects of the three artificial boundaries that act as inexhaustible sources of water for the model. The authors only mention that constant-flux boundaries, used to test the boundary flows calculated by the model from the constant heads, are much more sensitive.**

The RASA/Savannah model is sensitive to changes in the constant head boundary in layer 1 (Surficial Aquifer), particularly in the flat terrain around Savannah. For example, reducing this constant head in layer 1 by 10% of its original value (i.e., with the new value being 90% of the original value) results in a 3.2 feet head decrease in cell 36,39 (layer 2, RASA model) and 0.5 feet decrease in cell 45,37 (Hilton Head island).

Layer 1 (Surficial Aquifer) in the RASA/Savannah model is a constant source/sink in the entire model domain for all models including large portions over the ocean. The leakance term is assigned to all cells in layer 1 providing for an unlimited recharge (by terms of leakance) of the Upper Floridan aquifer from the Surficial Aquifer including the ocean area. This concept is not discussed in the available report nor is the field evidence. **If, in fact, there were recharge of the Upper Floridan over the ocean area, this would mean that the sea (salt) water is entering the aquifer and the whole premise of fresh ground-water flow budget, gradients, velocity, travel times, etc. would be highly questionable.**

It should be noted that the "Smith" model (USGS WRIR 87-4285) is based on the assumption that there is no vertical leakance through confining layers separating the Lower and Upper Floridan aquifers, i.e., the base of the Upper Floridan aquifer is considered impermeable. "The aquifer is confined below by a thick sequence of low-permeability limestone, sand, and clayey sand deposists of middle Eocene age. The confining deposists below the aquifer in South Carolina are generally equivalent to the middle confining unit, a regional confining layer (Miller, 1986, p. B56). Late Eocene limestones and sediments of low permeability immediately below the aquifer also confine the aquifer locally" (USGS WRIR 87-4285, page 9). This assumption for the Smith model is in conflict with the counterpart assumption for the RASA/Savannah Glynn County Models. **The two conflicting views regarding hydraulic interconnection between the Upper and Lower Floridan aquifers (Smith versus RASA/Savannah/Glynn County models) should be resolved based on field evidence (recorded vertical hydraulic gradients and vertical hydraulic conductivity at cluster wells).**

Several large surface streams (rivers) flowing across the northwestern portion of the model area (RASA model above Gulf Through) are shown as discharge zones for the Upper Floridan aquifer (e.g., Ocmulgee River, Oconee River, Savannah River). On the other hand, the Ogeechee River is not a discharge area. **The field evidence for this hydraulic relationship between the Upper Floridan aquifer and the rivers is not presented.**

Documentation of Model Input Parameters

This documentation is generally appropriate. However, except for aquifer pumping test locations for the Upper Floridan aquifer, no information on actual data points used for interpolation of model parameters is provided. This is particularly important in case of leakance since this parameter, together with the transmissivity, was used for model calibration (almost exclusively as indicated in the RASA Report). **It is not clear how many actual field measurements of the vertical hydraulic conductivity (used for calculating leakance) were available. Also, it is not clear what interpolation/extrapolation method was used for the initial contouring of model input parameters (transmissivity, leakance, constant head).**

There is a significant discrepancy between field data for the transmissivity (T) and its model calibrated values for the Upper Floridan, particularly in Ware, Pierce, Atkinson, and Bacon counties; the model calibrated value of >250,000 ft^2/day for this large area is, on the average, one order of magnitude higher than the individual aquifer test-derived values.

The basis for the estimated transmissivity of the Lower Floridan aquifer is not documented. In addition, if any "splitting" of the field-derived values for the combined transmissivity of the two aquifers was done, it is not documented. In general, the Lower Floridan has similar (same order of magnitude) transmissivities in the model as those of the Upper Floridan aquifer. However, in the published report for the "Smith" model (USGS WRIR 87-4285, page 9) it is stated that:

> "A deeper aquifer called the Lower Floridan aquifer by Miller (1986, p. B10 and B63) and the lower permeable zone by Hayes (1979, p. 31 and 32) may occur in places, in the study area, however, the Upper Floridan aquifer is *much less permeable* and not as extensive as the Upper Floridan."

The inconsistency between the Smith model and the telescopic set of models regarding the transmissivity estimates of the Lower Floridan should be resolved based on actual field data.

Geographic/spatial density of input parameters

Except for the field pumping test locations for the Upper Floridan, there is no information (e.g., maps or tables) showing actual field points used to estimate (determine) model input parameters (T, leakance/vertical hydraulic conductivity, hydraulic heads in the Lower and Upper Floridan, Fernandina, and Surficial aquifers). **It is, therefore, not possible to comment on the appropriateness of the spatial density of input parameters.**

Input parameters assigned to appropriate grid cell

Based on the published model documentation (USGS and EPD reports), there are several discrepancies between the narrative/graphics and the actual model files provided by USGS:

- Constant head conditions are not assigned to 6 cells along the northern boundary of the RASA model in layer 3 (this constant head boundary is thus not continuous, i.e., it has 6 breaks).
- There is also one break (one cell without assigned boundary condition) at the southwestern General Head Boundary in layer 3 in the RASA model.
- There are seven high-yielding wells (cells) placed at the southern constant head boundary in layer 2, RASA model. The effect of these 7 well cells is, therefore, cancelled by the boundary condition.

Minor discrepancies between reported input parameters and actual values assigned to appropriate grid cells should be corrected and the results of the new model run should then be compared with the previously reported results.

Model Calibration

Model calibration was achieved by adjusting transmissivity and leakance values for all models. It appears that relatively higher "local" values of these two parameters, within larger uniform areas (as presented in the available documentation), are associated with important pumping centers. **If field data on aquifer transmissivity for important pumping centers are available, these data should be compared with the model-calibrated values.**

Actual locations of field water level measurements used for comparison with the model-calculated hydraulic heads are not documented for any of the models. It is also not clear if well losses were considered when hydraulic heads were measured in pumping wells. It should be clarified if all the extraction wells used for water level measurements are completed as "open borehole" (i.e., without screen) within Upper and/or Lower Floridan aquifers.

According to available published documentation, during development of the Savannah Model notable changes/refinements were made in the transmissivity array of the RASA model. It is not clear if any adjustments were then made in the regional RASA model. Such changes were made in the Glynn County model. **The impact of the transmissivity changes in the Savannah model on the results generated by the RASA model is not discussed.**

The model-calculated (calibrated) hydraulic head in the Upper Floridan aquifer, RASA model (plate 18 in the USGS PP 1403-D) do not entirely match results obtained by running the program input files provided by USGS. For example, contour +50 is shown to be continuous from Pierce Co. through Brantley, Charlton, Duval and St. Johns counties. However, the model run generates +50 contour that extends from Pierce Co. towards Okefenokee swamp and ends at the General Head Boundary in the middle of the swamp. In other words, +50 contour is reported to be 20-30 miles shifted toward east compared to the model run results. Similar inconsistencies are found elsewhere in the presented results. **If, as indicated by USGS, the discrepancy**

between the reported and the model-generated hydraulic heads is caused by the fact that the updated telescopic models use well pumpage for 1985 instead of 1980, a discussion summarizing the effects of this new pumpage on models predictive capabilities should be provided.

<u>Appropriateness of prior-to-development data points</u>

There is no documentation included in the modeling reports that show how estimates of pre-development hydraulic heads in the four model layers were made.

<u>Results of the Requested Model Run (Injection Well at Cell 32,29, Layer 2, Savannah Model)</u>

Model runs for the RASA model and the Savannah telescoping model were performed with the original input files provided by USGS for the following two cases:

- "As is", i.e., without the requested injection well

- With an injection well located in layer 2 of the Savannah model, cell 32 (row), 29 (column). The injection rate is 500,000 GPD or 0.775 cubic feet per second (model units). Cell (32,29) corresponds to cell (36,39) in the RASA model (note that this conversion is not straight forward since the coordinate beginnings for the two models differ, i.e., rows in the RASA model correspond to columns in the Savannah model; also, one RASA cell contains 16 Savannah cells).

Table 1 presents a summary of the hydraulic heads (in feet above sea level) or several cells (areas) of interest - Savannah, Hilton Head island, the "requested cell", and a cell adjacent to the constant head boundary in the RASA model placed in the ocean (50,37):

The injection well raises the hydraulic head for about one foot in cell 32,29 in the Savannah model (from -8.171 to -6.877). This effect in the corresponding RASA cell (36,39) is also about one foot (from -8.985 to -7.951). However there is a general difference of about one foot or more between the cells in the two models, both in terms of the average hydraulic head for the corresponding 16 Savannah model cells and the individual cell values.

A general difference in the hydraulic head of about one foot between the two models is also noticeable in the Hilton Head Island area. The impact of the injection well is minimal (in the order of 0.001 feet) in this area.

It appears that the RASA model "favors" extreme parameter values from the corresponding 16 Savannah model cells — cell (39,37) has the hydraulic head of -111.573 (injection well active) which is very similar to the hydraulic head of -111.715 at the Savannah model cell (37,42). On the other hand, the average value for the 16 Savannah model cells is -95.496 or about 14 feet higher than for the corresponding RASA cell (39,37). **It appears that this discrepancy might be the result of not adjusting the transmissivity array of the RASA model to reflect changes/refinements made in the Savannah model.**

Recommendations

To more accurately simulate horizontal and vertical flow components within the coastal aquifer systems, develop a reliable and defensible tool for aquifer management at various scales, eliminate apparent redundancy of the existing set of telescoping models, and take advantage of new modeling techniques, we recommend the following:

- Develop a true 3D ground-water flow model that will simulate flows within and between the surficial, Miocene, Upper and Lower Floridan, and underlying aquifers (e.g., Fernandina Permeable Zone).

- Collect additional data in strategic locations in support of true 3D modeling of all important hydrostratigraphic units. These data include horizontal and vertical hydraulic gradients and transmissive properties of the aquifers. More emphasis should be placed on those units that were previously not modeled as active layers (surficial and Miocene aquifers) as well as on the Lower Floridan aquifer. Because of cost restrictions, the Fernandina Zone will less likely be subject to detailed investigations. However, the hydrogeologic role of this zone could be more accurately assessed (than at present) during model calibration based on actual data collected for other hydrostratigraphic units.

- Merge telescopic models into one model with fine cell discretization for areas of most interest (e.g., Glynn County, Savannah/Hilton Head).

- Utilize transient modeling to enable simulations of seasonal ground-water pumpage and time effects of possible aquifer management alternatives (storage and recovery, engineering control, etc.).

- To fully utilize transient capabilities of the model and more accurately simulate effects of all ground-water withdrawal in the model area, develop and maintain a GIS data base (containing information on well locations, construction details, pumping rates, and water levels) for various users — agricultural, industrial, municipal, and others.

- Analyze in more detail geologic, hydrogeologic, and hydraulic conditions along Gulf Trough and the salt water-fresh water interface off shore. This analysis may indicate a reduction of the model size (for example, the Gulf Trough may greatly attenuate influence of the inland model boundaries west and northwest of the Trough and the Trough may act as a new model boundary).

Finally, we recommend that an option of developing one ground-water model for both flow and variable density transport be analyzed. Several such models have lately been developed, verified, and lately used throughout world. They provide a powerful tool for ground-water management in coastal areas subject to salt-water intrusion.

Table 1: Calculated Potentiometric Heads (fee NGVD)

No Injection Well ("As Is")				
Area of Interest	RASA model		SAVANNAH model	
Savannah	Cell 39,37	-111.573	Average (16 cells)	-95.630
			Minimum (37,42)	-111.867
			Maximum (40,41)	-80.405
Requested	Cell 36,39	-8.985	Average (16 cells)	-9.978
			Minimum (32,32)	-17.663
			Maximum (29,29)	-3.049
			Cell 32,29	-8.171
Hilton Head	Cell 45,37	-5.000	Average (16 cells)	-6.054
			Minimum (40,65)	-9.061
			Maximum (37,68)	-2.862
Adjacent to Constant Head Boundary	Cell 50,37	0.288	Average (16 cells)	0.385
			Minimum (38,86)	0.110
			Maximum (40,88)	0.839

Injection Well at the Savannah Model Cell 32,29 (RASA cell 36,39)				
Area of Interest	RASA model		SAVANNAH model	
Savannah	Cell 39,37	-111.351	Average (16 cells)	-95.496
			Minimum (37,42)	-111.715
			Maximum (40,41)	-80.274
Requested	Cell 36,39	-7.951	Average (16 cells)	-9.330
			Minimum (32,32)	-17.128
			Maximum (29,29)	-2.509
			Cell 32,29	-6.877
Hilton Head	Cell 45,37	-4.985	Average (16 cells)	-6.047
			Minimum (40,65)	-9.052
			Maximum (37,68)	-2.857
Adjacent to Constant Head Boundary	Cell 50,37	0.288	Average (16 cells)	0.385
			Minimum (38,86)	0.110
			Maximum (40,88)	0.839

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