Linking the WAM and GAM Models: Considerations and Recommendations

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Prepared by:

HDR | ONE COMPANY *Many Solutions*℠

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Linking the WAM and GAM Models: Considerations and Recommendations

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Executive Summary

Water Availability Models (WAMs) and Groundwater Availability Models (GAMs) have been developed as tools for use in the development of regional and state water plans in Texas. A WAM is a computer-based simulation program used to evaluate the amount of surface water in a river or stream that would be available to existing and proposed water rights under specified basin operations and hydrologic conditions. A GAM is a computer-based, deterministic model that simulates the flow of groundwater within an aquifer in response to interactions with surface water features such as reservoirs, streams, and springs and a specified set of pumping and recharge conditions.

Currently, the WAMs do not account for stream-aquifer interactions over time or variable hydrologic conditions and predictive simulations using the GAMs do not account for streamflow changes associated with permitted surface-water withdrawals and/or return flows. With a goal of sharing the surface water/groundwater interaction between the two models, HDR Engineering, Inc (HDR) and the Texas Water Development Board (TWDB) entered into a research contract to assess the differences in how WAMs and GAMs consider groundwater and surface water systems and, more importantly, assess the potential for linking them to interactively exchange simulation results. The goal of the linking would be to develop more accurate tools for calculating the availability of surface water and groundwater supplies and estimating the impact of water supply development on streams and aquifers.

The project approach was divided into five primary tasks:

1. Conduct a stakeholder survey to develop an understanding of their needs that cannot be met with the current models, but potentially could be met by WAM-GAM linkage.
2. Formulate two or three conceptual approaches to link the models, analyze pros and cons of each, and select one for development.
3. Compile and present results to the TWDB. Receive feedback from the TWDB regarding mid-course adjustments.
4. Based on TWDB direction, design software to link the two models, writing subroutines or modules in the WAM and/or GAM to facilitate the exchange of simulation results with either a passive or active linkage, testing the software,

developing readily usable tables and graphics of the results, and providing quality control/quality assurance.

5. Prepare report and provide recommendations for implementation.

ES.1 WAMS

There are 15 major and 8 coastal river basins in Texas. WAMs in Texas include a system of individual models with each one representing portions of or multiple river basins. In total, 21 individual WAM models were developed for state-wide coverage, including the Rio Grande, which is a special application. The WAMs are intended to assist the Texas Commission on Environmental Quality (TCEQ) in evaluating potential water right permits and to assess the reliability of existing water rights. With regard to considering interactions between ground and surface water, the majority of the WAMs do not account for channel losses or include assumptions regarding how groundwater development might influence naturalized flows. When included, WAMs currently have two primary means for defining how surface water and groundwater systems influence each other: (1) through application of a channel loss function or (2) a naturalized flow adjustments file.

Channel losses are entered into the WAM as fixed percentages, and reflect the portion of the flow "lost" between sequent upstream and downstream control point locations. These losses reflect not just seepage from stream channels, but also free surface evaporation from the stream and evapotranspiration from vegetation growing along the stream channel.

A few WAMs use a "flow adjustments" file to modify naturalized flows to account for pumping levels (and resulting springflows) that differ from historical levels. A flow change indicated by the flow adjustments file is applied at a specified control point, and adjusts flows at all control points physically downstream at the start of each month of the simulation.

Precise knowledge of the hydraulic connections between stream and aquifer systems is limited. However, changes in stages of different baseflows are unlikely to result in appreciably different levels of computed seepage to the underlying aquifer. Under baseflow conditions (typically small discharges), substantial differences in baseflow discharges result in relatively minor differences in stage, typically much less than one foot. Stage (hydraulic head) is a primary factor controlling the rate of seepage through the streambed, and with all other variables held relatively constant (wetted perimeter, permeability), small changes in stage will not substantially change the rate at which seepage occurs. As long as the stream bed does not completely dry up in the WAM simulation, it can reasonably be assumed that interactions between the stream and aquifer will continue to occur within the accuracy represented in a GAM. The driving force (hydraulic head of the water in the stream channel) is unlikely to vary substantially and knowledge of the relationship between stage and seepage is uncertain enough that any changes in stage are well within the precision limitations of the computational methods.

ES.2 GAMS

GAMs in Texas consist of a system of models representing one or more aquifer systems. Because plans are to develop GAMs for only the major and minor aquifers in Texas, there will not be complete coverage across Texas. When completed, there will be 31 GAMs in Texas, including coverage of 9 major aquifers and 21 minor aquifers. All of the GAMs use the U.S. Geological Survey's MODFLOW groundwater model. A well calibrated model gives confidence that the model will produce reasonable predictions of water levels in the future and is suitable for applications, such as predicting how the aquifer will respond to variable pumping patterns and/or potential drought conditions. A GAM run does not directly produce an estimate of groundwater availability or reliability as with a WAM run. Instead, the determination of groundwater availability is rooted in the acceptability of impacts of assumed or projected pumpage, as determined by an individual or entity. The level of acceptable may be based on allowable drawdowns, rates of springflow, and/or baseflows in streams.

MODFLOW offers four options that can be directly used to simulate groundwater-surface water interactions from a groundwater system perspective, including the stream package, river package, reservoir package, and drain package which makes groundwater-surface water interactions highly subjective to the modeler. In general, the GAM will be much less sensitive to changes in the surface water system because of the dynamic, time-varying nature of surface water systems and the regional, highly buffered characteristics typical of groundwater systems.

ES.3 Technical Considerations for WAM and GAM Linkage

A linkage between the GAM and WAM would be most useful in quantifying the impacts of the aquifer system on surface water rights and water availability, rather than attempting to capture the more subtle effects of surface water rights on the groundwater system.

There are several distinct differences between WAM and GAM structures that need to be considered prior to model linkage, as shown in Table ES-1. The WAM simulates the operation of water rights (diversions and reservoirs) for a repeat of the hydrologic period of record. The GAM, on the other hand, simulates future aquifer conditions for an assumed pumping and recharge scenario. The GAM can be thought of as predictive in nature, i.e., *"What will happen in the future if…,"* whereas the WAM is retrospective, i.e., *"what would have happened if…"*.

Quantification of groundwater-surface water interactions is a complex science, primarily due to complexities caused by geographic, geologic, climatic, and management variations. In addition, limited data exist to describe these interactions precisely. Linking the WAM to the GAM will involve defining not only the hydrologic responses of both the groundwater and surface water systems, but also defining how the two models will interact to pass this information back and forth.

Table ES-1.
WAM and GAM Features and Distinctions

Feature	*WAM*	*GAM*
Primary Use	Determines water availability and reliability for existing and proposed water rights	Evaluate acceptable impacts; does not directly provide groundwater availability and reliability
Scale of Application	Local, specific water rights	Regional system responses
Stream-Aquifer Interactions	Very limited and typically static (or fixed) over time through channel losses or flow adjustment files	General and variable over time; simulates rivers, springs, reservoirs, and evapotranspiration
Model Simulation	Retrospective, based on repeat of historical hydrologic cycles	Predictive, based on assumed pumping and recharge scenarios
Extent of Coverage	By river basin, throughout the state	For major and minor aquifers, non-continuous
Geographic Scales	Site-specific control points	Three-dimensional grid cells no greater than one square mile
Temporal Scales	Responds quickly to wet and drought conditions	Typical GAM response is slow, but response to hydrological climatic conditions varies according to the aquifer system
Model Time-Steps	Typically monthly	Typically annual
Maintained by	TCEQ	TWDB

Two general approaches have been identified to define how the WAM and GAM could exchange results in a practical sense. One is an active linkage, whereby the WAM and GAM share data back and forth at the end of each time-step/stress-period; and, the other is a passive linkage where one model run is completed and information passed to the second model for its run.

ES.4 Active and Passive Linkages

An active linkage would require substantial computer code modifications to both the WRAP model (used by the WAM) and the MODFLOW model (used by the GAM) in order for the two to communicate results on a month-by-month basis. An active linkage is most suitable for changes in an aquifer flux (which would be the difference between baseline (historical) and projected values such as discharges from major springs). In this case, a GAM would be run for a single stress period, the computed springflow would then be passed to the WAM, the WAM flows would be adjusted, and the WAM simulation would commence for the current month. After completion of the WAM simulation for a given month, the WAM could pass data (such as amount of water available for artificial recharge) back to the GAM for the GAM to complete another stress period.

A passive linkage operates under the assumption that data need to be passed in only one direction (i.e., GAM to WAM) because model-to-model feedback on a month-by-month basis is unnecessary. This is believed to be the case with most WAM and GAM situations, where changes in groundwater pumping might reasonably be expected to alter surface water baseflows through long-term changes in springflows or groundwater flux, but changes in surface water rights would not be expected to provide appreciable impacts to groundwater. Such a passive linkage can be facilitated without modification to the code of either the WAM or GAM model by developing a data transfer program. Because of the complexity of developing an active linkage of multiple GAMs to a WAM effectively, a passive linkage from the GAM outputs to the WAM input appears to be the more reasonable approach.

The geography of streams and aquifers in Texas is such that most all of the major streams cross multiple aquifers. Multiple river basins could be affected if a major groundwater development has a drawdown pattern that extends into adjacent stream basins. Similarly, a major surface water project could affect the streamflow losses into multiple aquifers downstream of the project. From these two examples, realistic WAM-GAM linkages may include one GAM and adjacent WAMs or one WAM and multiple GAMs.

ES.5 Stakeholder Survey

At the onset of planning and developing a linkage of the WAM and GAM models, HDR conducted a survey of 50 stakeholders in the water community representing diverse interests to find out their current uses, expectations for new information and uses of the linked models, concerns related to the linked models, and recommendations on future funding. The results of the survey indicate that the water community believes that improving the individual WAMs and GAMs should be given priority over linking the models.

After completion of Tasks 1 and 2, representatives from the TWDB, HDR, Dr. Ralph Wurbs from Texas A&M University, and Michael McDonald from McDonald Morrissey Associates met on May 25, 2006 for a mid-course review (Task 3). On the basis of the discussions, HDR offered four options for moving forward:

Option 1. Document fully the considerations as briefly discussed above in a final report, but *do not pursue a linked model* at this time based upon recognition that: (1) the two models are developed and operated with different paradigms, spatial scales, and temporal scales; (2) information is limited with which to describe groundwater-surface water interactions accurately; and (3) linkage of the two models would provide little additional information that the two models don't already provide separately.

Option 2. Complete the discussion described in Option 1, but also develop a *hypothetical situation using greatly simplified GAM and WAM configurations* by which the mechanisms for linking the two can be demonstrated.

Option 3. Complete the discussion described in Option 1 and *perform a limited case study using the Hill Country GAM and the GSA WAM* to demonstrate the mechanisms by which the models can be linked and the differences in surface water availability that might result.

Option 4. Complete the discussions described in Option 1 and perform a limited case study *using a combination of GAMs and one WAM* that will more fully demonstrate the mechanisms by which the models may be linked, and also better demonstrate the magnitude of effects that incorporating a linked analysis might have on surface water supplies.

On the basis of this information and considering the level of effort and limitations of the four options, the TWDB requested[1] that HDR complete this research contract with Option 1 to fully document the considerations, but not pursue a linked WAM and GAM model.

[1] Email from Yujuin Yang (TWDB) to David Dunn (HDR) on August 28, 2006.

ES.6 Considerations

In the consideration of future revisions and linkages, several levels of effort should be considered, including

- A complete redesign of the models to be suitable for meeting their current applications plus linking for new applications. This would be a major undertaking to develop a consensus on the objectives of the simulations and what is an acceptable format of the results. (Not Recommended)
- Focus on improving the utility, reliability, confidence, and standardization of the current models, especially the GAMs, over the next several years. Then, reconsider the linking of the two models in a structured manner. (Recommended)
- Support dialogue between the two modeling groups in an attempt to understand the information needs of the other, to develop innovative means of extracting results from one model for use in the other model, and restructuring traditional model runs to be more similar in concept. (Recommended)
- On a case-by-case basis, consider the water information needs and look for means of utilizing the results from one model in the other model. (Recommended)

ES.7 Recommendations

To reasonable quantify the surface water- groundwater interaction that would be expected in linking WAMs and GAMs the following recommendations are offered:

ES.7.1 Recommended WAM Improvements

Update Period of Record. Since development of the WAMs, additional streamflow data are available which suggest a new drought of record in many areas of the State. Updating the period of record to include this additional drought information would increase the reliability of WAM results.

Consistent Representation of Streamflow Gains/Losses. With the diversity of stream settings across Texas and a relatively large number of teams developing WAMs in a relatively short period, different approaches were used to represent surface water- groundwater interaction.

Development of consistent representation of streamflow gains and losses by conducting research on potential methods, available data, means of accommodating estimates from GAM simulations, and range of stream-aquifer settings is recommended.

ES.7.2 Recommended GAM Improvements

Consistent Representation of Streams, Springs, Wetlands, and Reservoirs. The computer program (MODFLOW) used in the GAMs allows surface water-groundwater interaction in four packages: River, Stream, Drain, and Reservoir Packages. A guidance document should be developed that provides information regarding which package should be used for a range of stream, reservoir, spring, and wetland settings.

Consistent Representation of Evapotranspiration. The quantification of surface water-groundwater interaction is a considerable challenge because model cells with evapotranspiration (ET) usually overlap cells with streams, rivers, springs, or wetlands and the observed or measured values of ET and baseflow for model calibration are very limited and highly variable. A guidance document is recommended to identify conditions for which the ET Package should be used and to provide guidance in estimating minimum and maximum ET rates and extinction depths.

Consistent Representation of Recharge. In the conceptualization of a GAM, the method and assumptions used to estimate recharge can strongly influence computations of surface water-groundwater interactions. Recharge in GAMs has been simulated as net recharge which represents only the amount of water that reaches the main body of an aquifer, and is often estimated as a fraction of precipitation. Research needs to be conducted and guidelines prepared on the most appropriate means of estimating recharge in the GAMs.

ES.7.3 Analysis of Available Data and Priority Areas

Historical estimates of streamflow gains and losses are needed for calibration of the GAMs and to refine estimates of naturalized streamflow for the WAMs. A two phased approach is recommended: to develop the methods and guidelines for simulating streamflow gains and losses in both GAMs and WAMs, and to perform the analyses by aquifer system and/or river basin.

Surface water and groundwater interaction should be prioritized for (1) areas where the overall portion of the stream and aquifer water budget related to surface water-groundwater interaction is significant, (2) areas where the overall potential for critical in-stream flow conditions depends largely on baseflow, and (3) areas with the greatest likelihood of new and substantial groundwater development in the near future.

ES.7.4 Collection of Additional Data

Systematic Baseflow Surveys. To get to a scale needed by a GAM to simulate streams crossing aquifer outcrops, localized baseflow surveys along stream reaches a few miles or tens of miles in length are needed to account for tributary inflows, streamflow diversions, and wastewater effluent discharges in addition to measured streamflow at given intervals.

Localized Measurements of Groundwater Levels and Stream Stages. Collect local data to define surface water and groundwater interactions in GAMs, which are calculated on the basis of the stage level in the surface water body and groundwater levels in the underlying aquifer.

Springflow and Baseflow Measurements in Small Tributaries. Local springs and baseflows in small tributaries are very important and probably will be the first to be noticeably affected by groundwater development.

Improve Estimation of ET Extinction Depths. With a goal of improving the accuracy of partitioning the aquifer's discharge along a stream between baseflow and ET, the parameter with the poorest definition is the extinction depth which is equivalent to plant rooting depths. HDR recommends the simpler ET Package in MODFLOW, which requires definition of only the extinction and maximum ET depths. HDR also recommends research using existing data to select representative test plots for field scale research.

ES.8 Conclusions

While the basic concept of linking the WAMs and GAMs to facilitate a "handshaking" of surface water and groundwater interactions appears advantageous in principle, logistical issues, vastly different model structures, and limited data availability make WAM-GAM linkage a challenging and time-intensive task. In addition, data necessary to accurately estimate and define the interactions between surface and groundwater are too limited to provide meaningful information. The available computational mechanisms are likely sufficient, but the data to provide accurate parameterizations on a basin-wide scale are lacking. Results would have limited reliability. Significant improvements to the WAMs and GAMs are necessary in order to develop a suitable linkage in the future. Consistent approaches and procedures are needed to represent streamflow gains and losses in the WAMs and GAMs. Overall, for successful linkages of WAMs and GAMs to be maintained over time, the TCEQ and TWDB would need to coordinate model updates and maintenance activities, and determine a funding mechanism for such updates and model improvements.

Section 1
Introduction

Texas law mandates the development of regional and state water plans every 5 years to address future water supply needs and provide adequate supplies of water for the citizens of Texas through a 50-year planning horizon. Water Availability Models (WAMs) and Groundwater Availability Models (GAMs) have been developed as tools that can be used in the development of regional and state water plans. A WAM is a computer-based simulation program used to evaluate the amount of water in a river or stream that would be available to existing and proposed water rights under specified, basin operations and hydrologic conditions. A GAM is a computer-based, deterministic model that simulates the flow of groundwater within an aquifer in response to interactions with surface water features such as reservoirs, streams, and springs and a specified set of pumping and climate conditions.

The WAMs are developed, maintained and used by the Texas Commission on Environmental Quality (TCEQ) for evaluating proposed water right permits. They are also used extensively by regional water planning groups, the Texas Water Development Board (TWDB), river authorities, and others for water supply planning.

The GAMs are developed and maintained by the TWDB, and are used extensively by groundwater conservation districts, regional water planning groups, the TWDB, and others for planning. Since 2005, House Bill 1763 requires joint planning among groundwater conservation districts within groundwater management areas to develop estimates of “managed available groundwater” based on “desired future conditions” for their groundwater resources, which can be evaluated with GAMs.

Currently, the WAMs do not account for stream-aquifer interactions over time or variable hydrologic conditions and predictive simulations using the GAMs do not account for streamflow changes associated with permitted surface-water withdrawals and/or return flows. With a goal of sharing the surface water/groundwater interaction between the two models, HDR Engineering, Inc (HDR), assisted by McDonald Morrissey, Associates, Dr. Ralph Wurbs, and the TWDB entered into a research contract to assess the differences in how WAMs and GAMs consider interaction between groundwater and surface water systems and, more importantly, assess the potential for linking them to interactively exchange simulation results at appropriate modeling time steps. The goal of the linking would be to develop more accurate tools for calculating the availability of surface water and groundwater supplies and estimating the impact of water supply development on streams and aquifers.

The HDR team's approach in developing the linkage of the WAM and the GAM included five primary tasks. The first task included contacting about 50 stakeholders in the water industry from a wide array of interests and responsibilities to develop an understanding of their needs that cannot be met with the current models, but potentially could be met with a linkage of the two models. During these interviews, each stakeholder discussed the level of interest and need for linked WAMs and GAMs to increase coverage and accuracy. The second task was to formulate two or three conceptual approaches in linking the models, analyzing the pros and cons of each, and selecting one for further development. During this task, the team reviewed the benefits of a passive linkage which may be computationally more efficient and an active linkage where the models exchange parameter values during each time step. Under the third task, HDR compiled and synthesized the results of the first two tasks including a presentation to and discussion with TWDB officials regarding these findings. This provided the TWDB an opportunity to reevaluate the approach and provide direction on mid-course adjustments such as deciding to document the findings and terminate the pilot linkage at an interim stage of the project. The fourth task was to focus on designing the software that links the two models, writing subroutines or modules in the WAM and/or GAM to facilitate the exchange of simulation results testing the software, developing readily usable tables and graphics of the results, and providing quality control/quality assurance. The fifth task addressed the need for ongoing communication with the TWDB and TCEQ, preparing presentations and report(s) and manual(s), and providing recommendations for implementation.

The purposes of this report are (1) to summarize the results of the stakeholder survey, (2) to describe the potential avenues for WAM and GAM linkage, and (3) to provide recommendations to the TWDB regarding linking the WAM and GAM models and for improving the models.

Section 2
Description of the WAMs and GAMs

The WAM system in Texas is a group of individual models, each one representing one, sometimes two, river basins. In total, 21 individual WAM models were developed for state-wide coverage, including the Rio Grande which is a special application, for the 23 river basins shown in Figure 2-1. Three models include two basins each, and one basin, the Nueces-Rio Grande Coastal Basin, is divided between two WAM models.

GAMs in Texas consist of a system of models representing one or more aquifer systems that may be subdivided for logistical purposes. When completed, there will be 31 GAMs in Texas, including coverage of 9 major aquifers and 21 minor aquifers. Because plans are to develop GAMs for only the major and minor aquifers in Texas, there will not be complete coverage of all Texas groundwater resources. Also, because of the layering of major and minor aquifers, multiple GAMs may exist in some areas. Figure 2-1 shows the locations of WAM coverage by river basin and minor and major aquifers included in GAMs.

2.1 WAMs

2.1.1 History

In 1997, Senate Bill 1 of the 75th Texas Legislature directed the TCEQ (then the Texas Natural Resource Conservation Commission, TNRCC) to develop new Water Availability Models (WAMs) for 22 river basins in the State, excluding the Rio Grande. Later legislation directed the agency to develop a model for the Rio Grande River Basin, under a special application. The models are intended to assist the agency in evaluating potential water right permits and to assess the reliability of existing water rights. All WAMs were completed by 2003. The WAMs undergo regular updates by agency staff to reflect new permitted water rights, refine techniques to model specific rights, and account for updates to the Water Rights Analysis Package (WRAP),[1,2] the generalized package of computer programs developed by Texas A&M

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[1] Wurbs, R.A., Water Rights Analysis Package (WRAP) Modeling System Reference Manual, TR-255, Third Edition, Texas Water Resources Institute, The Texas A&M University System, College Station, Texas 77843-2118, September 2006.
[2] Wurbs, R.A., Water Rights Analysis Package (WRAP) Modeling System Users Manual, TR-256, Third Edition, Texas Water Resources Institute, The Texas A&M University System, College Station, Texas 77843-2118, September 2006.

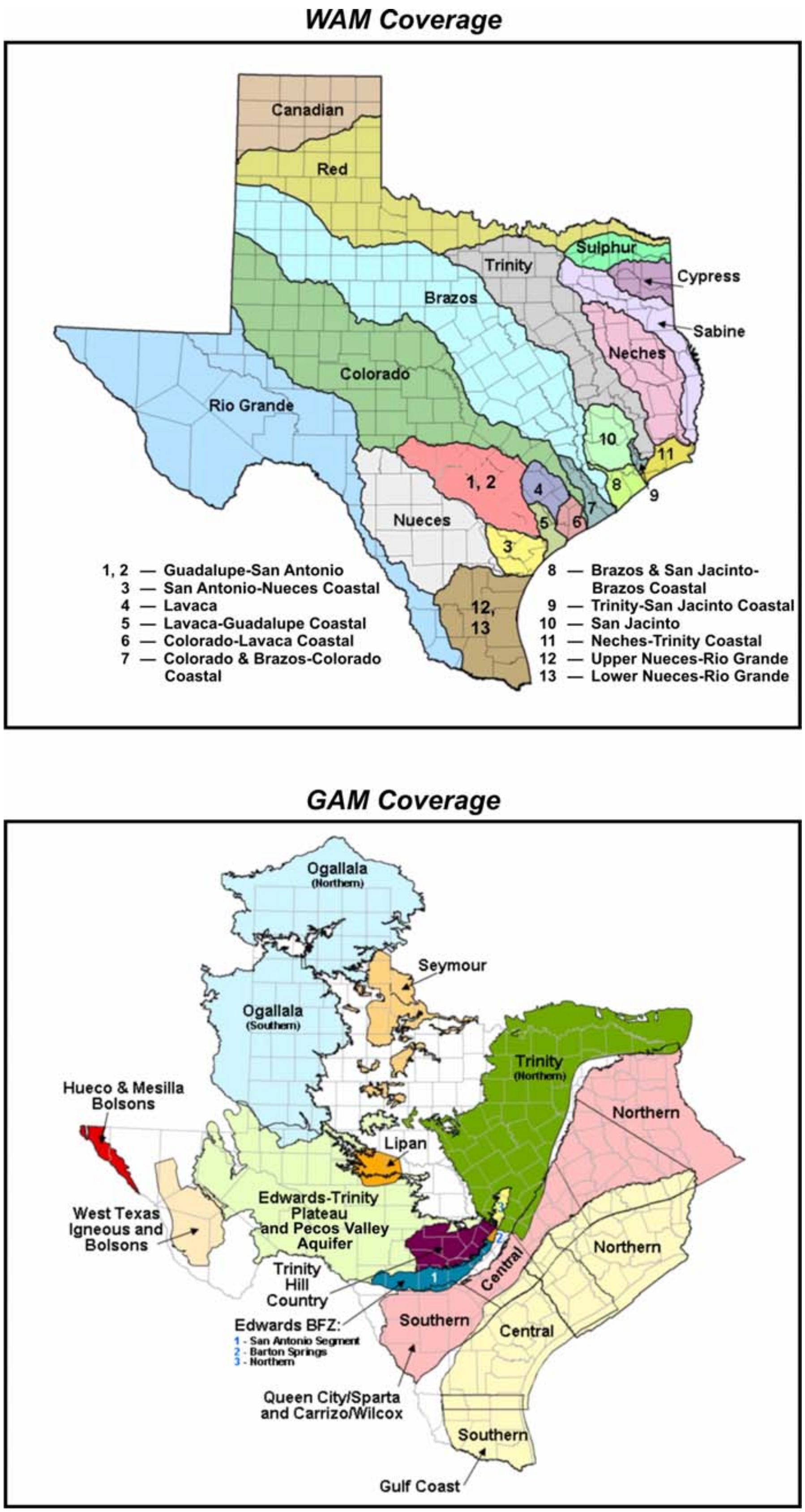


Figure 2-1. Location of WAMs and GAMs in Texas

University to simulate management of surface water resources and water rights and the prior appropriation doctrine.

With regard to considering interactions between groundwater and surface water, the majority of the WAMs do not account for channel losses or include assumptions regarding how groundwater development might influence naturalized flows. Several WAMs explicitly include channel losses throughout the model, distributed between primary control points, or in a few isolated reaches as described in more detail in Section 2.1.2. The Guadalupe-San Antonio WAM includes a “flow adjustments” file, which is used by the model to modify naturalized flows to reflect pumping levels (and resulting springflows) that differ from historical levels.

Since completion, the WAMs have been used by the TCEQ for water rights permitting, and extensively by the Texas Water Development Board, regional water planning groups, and others for water supply planning.

2.1.2 Operational Concepts

A WAM model consists of several input data sets that are read by the primary WRAP computer program, SIM. These input files contain data describing naturalized flows, reservoir evaporation rates, and water rights (locations, priority dates, authorized diversions, monthly diversion patterns based on type of use, reservoir storage, and return flows).

Basic data for a WAM model are associated with control points, which are locations in the river basin at which naturalized streamflows have been developed. Naturalized streamflows are those flows that would have occurred naturally in the stream without human influence. Typically, naturalized streamflows are based on historical gaged streamflows that have been adjusted to remove the effects of upstream diversions, reservoir operations, and discharges of treated wastewater effluent. Increases in runoff due to urbanization and changes due to groundwater development typically are not accounted for in the naturalization process.

Primary control points are locations for which naturalized streamflows have been developed through analyses of streamflow gage data and records of upstream diversions, upstream discharges (wastewater effluent), and upstream reservoir operations. Naturalized streamflows at primary control points are computed outside the WRAP model to be used as input. Historical streamgage data are adjusted to account for these upstream water management activities. Some primary control points are located at major reservoirs, and naturalized streamflows are computed through analyses of reservoir operational data (end-of-month storage, diversions, spills, evaporation). The periods of record at some streamflow gages are less than the period of record for the overall WAM, and data for some time periods for some primary control points are estimated (filled in) using regression analyses with nearby gaged locations.

Secondary control points in the WAM represent water rights, instream flow requirements locations, or other locations for which model output is desired. Naturalized streamflows for secondary control points are computed within the WAM, based on the naturalized streamflow input at nearby primary control points. The naturalized flows from the applicable primary control points are distributed within the WRAP model using drainage area ratios, often accounting for channel losses, differences in runoff curve numbers, and differences in long-term annual precipitation. A typical WAM includes a substantially greater number of secondary control points than primary control points.

Reservoir evaporation data are input for control points at which reservoirs are located. Evaporation data are typically based on quadrangle-averaged data developed by the TWDB, or on local reservoir evaporation pan data. Evaporation data are entered as “net” evaporation, which is the arithmetic difference between evaporation and precipitation falling on the reservoir surface. Negative net evaporation depths represent months where rainfall exceeded evaporation for a given reservoir. Net evaporation data are then adjusted to account for runoff that would have occurred from the land area inundated by the reservoir (effective net reservoir evaporation). When a reservoir’s surface area is small compared to a watershed’s drainage area, the adjustment is minor. However, when the reservoir surface area represents a significant portion of the watershed’s drainage area, the adjustment can be significant. The net evaporation adjustments typically are computed within the WAM on a month-by-month basis during the simulation, but for some WAMs are computed outside the model and included in the basic evaporation data input to the WAM.

Changes to the naturalized flows for both primary and secondary control points can be specified using sets of “constant inflows” or a “flow adjustments” file. A flow change using either option is applied at a specified control point, and adjusts flows at all control points physically downstream at the start of each month of the simulation. Using the constant inflows option, flow changes are input as 12 monthly values that are applied for every year of the simulation. The constant inflows capability has been used typically to represent assumed levels of discharged wastewater effluent (return flows), which would not vary from year to year during the simulation.

The flow adjustments file is used to input a time series of flow adjustments that vary from month-to-month and year-to-year. The option has been applied in the Guadalupe-San Antonio WAM, and Colorado and Brazos-Colorado Coastal WAM to reflect changes to flows discharging from major Edwards Aquifer springs; and the Rio Grande WAM to reflect changes to San Solomon and Griffin springs For the Guadalupe-San Antonio WAM, the naturalized streamflows in the model reflect historical discharges from the Edwards springs, which themselves reflect historical pumping levels from the Edwards Aquifer. The flow adjustments file option is used to model pumping scenarios from the Edwards Aquifer that are different from that which has occurred historically, and would therefore result in different springflows. There are numerous challenges to be overcome when linking groundwater data to WAM (in this case the Guadalupe-San Antonio WAM) such as determining and applying springflow adjustments to replicate the frequency of no-flow occurrences at Edwards springs during drought conditions. These limitations and other technical considerations are discussed in more detail in Section 3.4.

The South Central Texas (Region L) Regional Water Planning Group for their 2006 Regional Water Plan utilized a flow adjustments file to simulate groundwater and surface water interaction in a modified version of the Guadalupe-San Antonio WAM to evaluate cumulative effects of implementing recommended future water supply projects, as shown in Figure 2-2. In addition to analyzing the effects of varying levels of Edwards pumping on baseflows, changes in streamflow are used to account for increased levels of pumping from the Carrizo-Wilcox and Gulf Coast Aquifer systems. For the Carrizo-Wilcox and Gulf Coast Aquifers, these changes are applied as constant changes in streamflow representation of a future point in time after groundwater development was projected to occur. Channel losses occur when flows passing a specific location do not reach a point downstream. Channel losses result from evaporation from the stream water surface, seepage through the stream bed to underlying alluvium, evapotranspiration from riparian vegetation, and flood plain storage of overbank flows. The WRAP model utilizes constant channel loss factors, which do not vary with discharge or time, expressed as the decimal fraction of discharge that is lost in the reach between two adjacent control points. Naturally-occurring channel losses are inherently included in the streamgage data

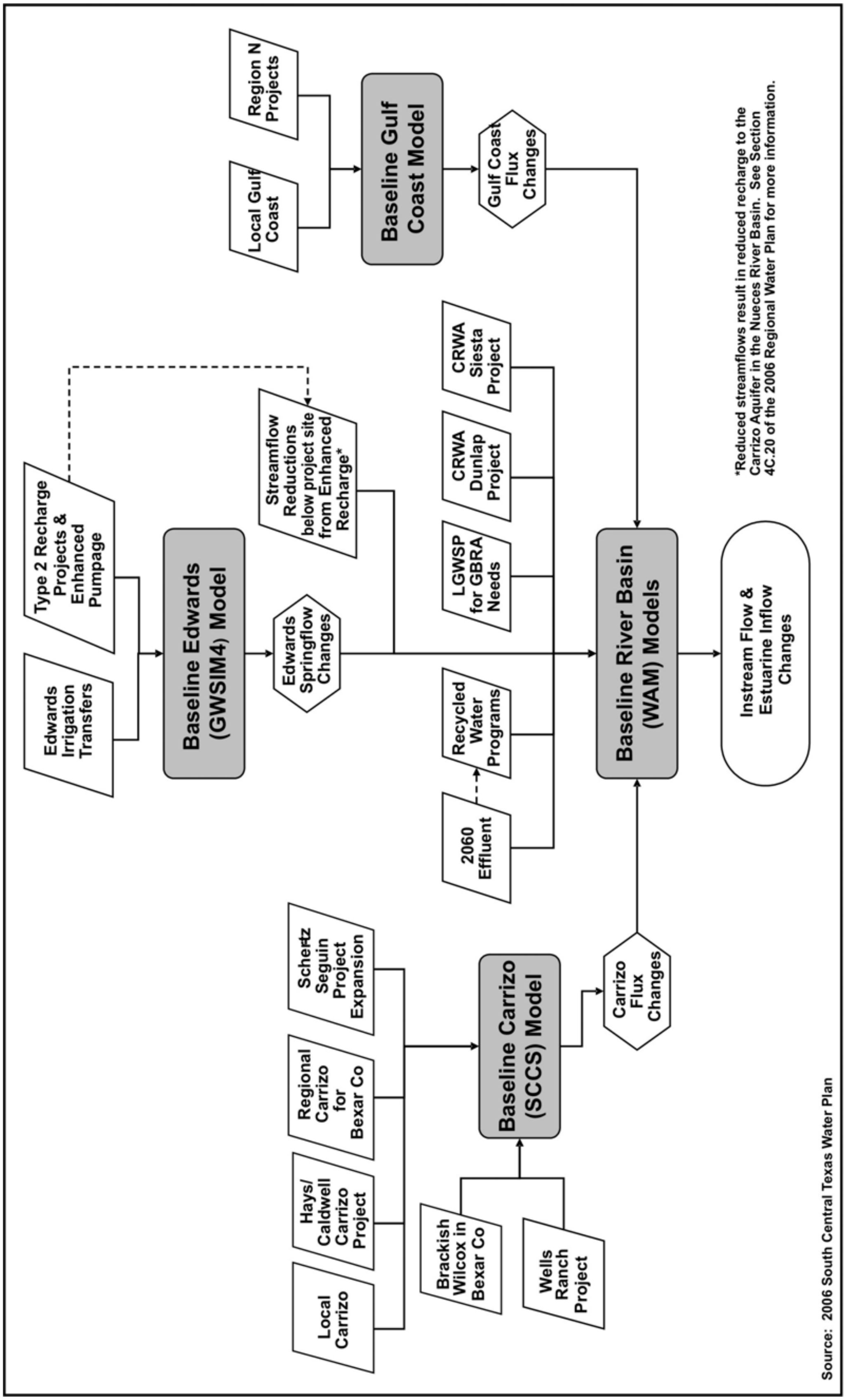


Figure 2-2. Flowchart for Surface Water-Groundwater Interaction between WAMs and GAMs Used to Assess Cumulative Effects of Implementation of Water Projects on Surface Water and Groundwater Resources for the 2006 Region L Water Plan

used to compute naturalized streamflows, and are therefore reflected in the naturalized flows. Channel losses are applied only to changes in streamflow (diversions, storage, and return flows), rather than to total flows, for this reason.

Typically, channel loss rate factors are developed for median or lower flow conditions in order to capture critical low flow or drought conditions as accurately as possible. During normal or wet conditions, channel losses are often smaller (on a percentage basis), but are less critical in determining water availability.

Channel losses are not always apparent from inspection of streamflow data from adjacent gages. Most streams increase in discharge in the downstream direction as contributions from tributary streams, baseflow contributions, and small springs add to total discharge. Often, these lateral contributions mask any channel losses that might be occurring from free surface evaporation or evapotranspiration, or from isolated locations with significant seepage. For this reason, the majority of the WAM models do not explicitly include channel losses. So long as the resulting regulated flows (i.e., flows remaining in the stream after satisfying water rights requirements) do not differ greatly from the magnitudes of the gaged streamflows upon which the naturalized flows are based, neglect of channel losses in the WAM models should not impact results dramatically because naturally-occurring losses are already reflected in the gaged records.

Table 2-1 includes a summary of selected features for each WAM including the number of water rights and control points, and a listing of WAMS that explicitly include groundwater/surface water interactions through channel losses or flow adjustment files.

Information concerning water rights and how specific rights operate are entered into the model using a variety of information. Basic information for a water right includes annual diversion authorization, reservoir storage authorization, date of priority, return flow requirements, and seasonal demand pattern upon which to disaggregate the annual diversion authorization. Additional information can be added concerning instream flow requirements, alternative diversion locations, and a variety of other information describing how a specific water right should operate. A single water right might be divided into multiple separate water rights in an input file.

The WRAP model simulation proceeds on a monthly basis, examining each water right in priority order under a strict application of the doctrine of prior appropriation, (i.e., "first in time

Table 2-1.
Listing of WAMs and Selected Features

River Basin(s)	Period of Record	Number of Water Rights: Regular Water Rights	Number of Water Rights: Instream Flow Rights/ Requirements	Number of Control Points	Number of Primary Control Points	Channel Losses Included?	Flow Adjustment File Used to Represent Groundwater Interaction?
Guadalupe and San Antonio	1934-89	860	184	1,349	46	Yes, throughout	Yes, Edwards Aquifer springflows
Brazos and San Jacinto-Brazos Coastal	1940-97	1623	118	3,829	77	Yes, throughout	No
Nueces	1934-96	376	30	544	41	Yes, throughout	No
Canadian	1948-98	56	0	85	12	Yes, throughout	No
Red	1948-98	447	111	443	50	Yes, in limited reaches	No[1]
Sulphur	1940-96	85	5	83	8	No	No
Cypress	1948-98	150	1	169	10	No	No
Sabine	1940-98	310	21	376	27	No	No
Neches	1940-96	333	17	318	20	No	No
Neches-Trinity Coastal	1940-96	138	9	245	4	No	No
Trinity	1940-96	1169	23	1,334	40	Yes, in limited reaches	No
Trinity-San Jacinto Coastal	1940-96	24	0	94	2	No	No
San Jacinto	1940-96	150	14	410	16	No	No
Colorado and Brazos-Colorado Coastal	1940-98	1591	75	2,263	45	Yes, in limited reaches	Yes, Edwards Aquifer and Edwards-Trinity Springs
Colorado-Lavaca Coastal	1940-96	27	4	111	1	No	No
Lavaca	1940-96	71	30	185	7	No	No
Lavaca-Guadalupe Coastal	1940-96	10	0	68	2	No	No
San Antonio-Nueces Coastal	1948-98	12	2	49	9	Yes, throughout	No
Lower Nueces-Rio Grande	1948-98	70	6	119	16	Yes, throughout	No
Upper Nueces-Rio Grande	1948-98	34	2	81	13	Yes, throughout	No
Rio Grande	1940-00	2610	4	957	55	Yes, throughout	Yes, San Solomon and Griffin Springs

[1]Use to simulate Oklahoma flows, not groundwater related.

is first in right"). The most senior water right is allowed first opportunity to divert and/or store available streamflow, and changes in streamflow caused by that water right are routed downstream. Computations proceed with each water right in priority order, with each water right causing changes in flow that are translated to all locations downstream. Water available to any specific right is constrained by flow at the water right location, as well as water appropriated by other senior water rights downstream. In this fashion, a junior water right is not allowed by the model framework to impact the appropriation by a senior right. Each senior right is operated as if no other rights junior to it exist.

Output from the WRAP model can be very detailed, and includes all pertinent monthly data for each water right, reservoir, instream flow requirement, and control point. From this output, the reliability (frequency statistics) of specific water rights, time series of flows at control points, and time series of reservoir storage can be obtained. Figure 2-3 shows a typical process and concept of a WAM run. The WRAP system can be used to tabulate output data and perform statistical analyses of the time series data, or the data can be input into spreadsheets or statistical analysis programs for further summary and analysis.

2.1.3 Common Uses

The WAMs provide the ability to perform a wide variety of water resources-related analyses. Originally developed primarily as a water rights modeling tool, information regarding the reliability and performance of specific or groups of water rights can be obtained. In additional to determining reliability of water rights, the output from WAM runs can be used to determine the firm yield of reservoir systems as shown in Figure 2-4. Specific modeling assumptions can be modified to evaluate the effects on reservoir yields of reduced reservoir storage due to sedimentation, the effects of water supply agreements, the effects of differing levels of return flows discharged to streams, and the effects of instream flow requirements. The TCEQ utilizes the various WAMs to evaluate applications for new or amended water rights. Water supply entities use the various WAM models to evaluate firm and safe yields of reservoirs, and to evaluate potential new sources of supply. Regional water planning groups formed under Senate Bill 1 utilize the various WAM models to evaluate water supplies available to existing rights under current conditions and those projected to occur through the planning horizon, and to evaluate water supplies that might be available from water management strategies currently being considered to meet future water needs.

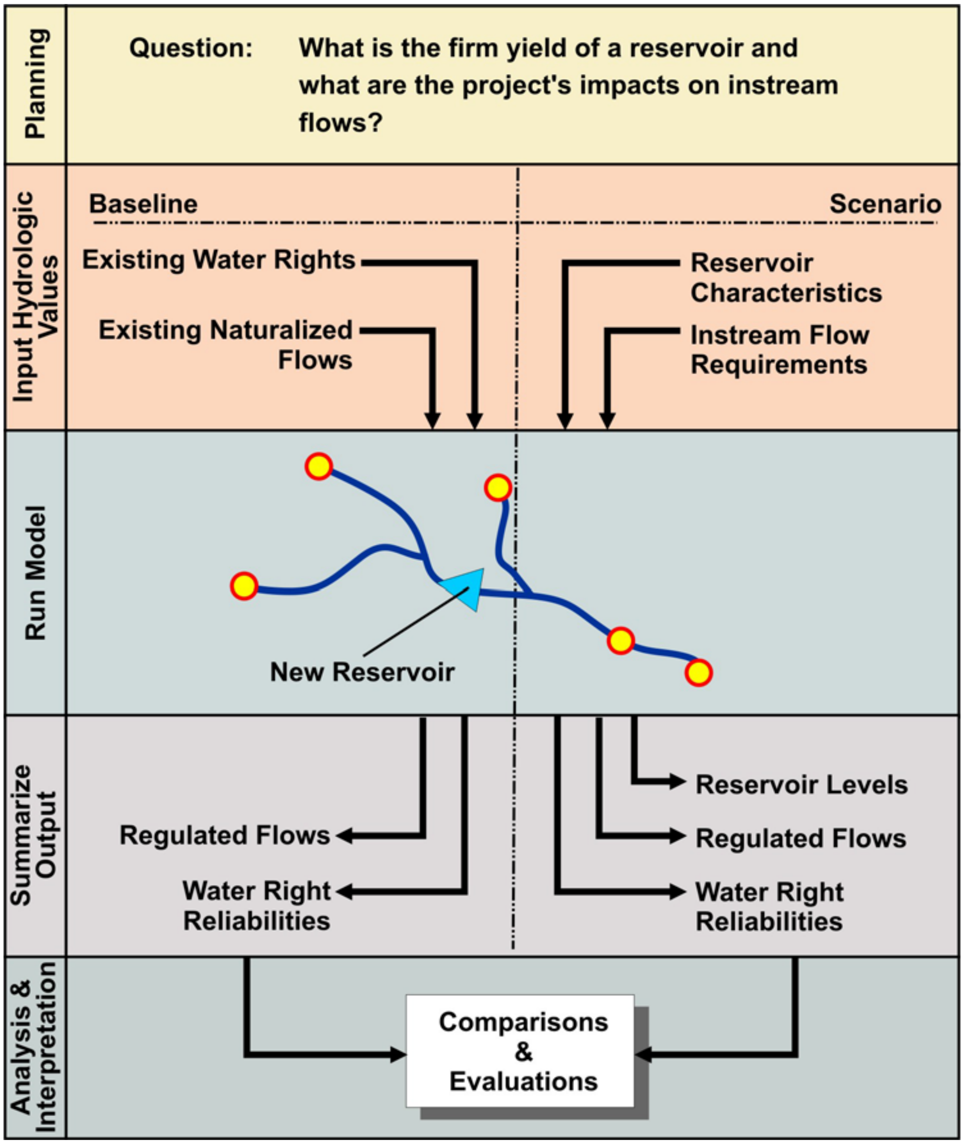
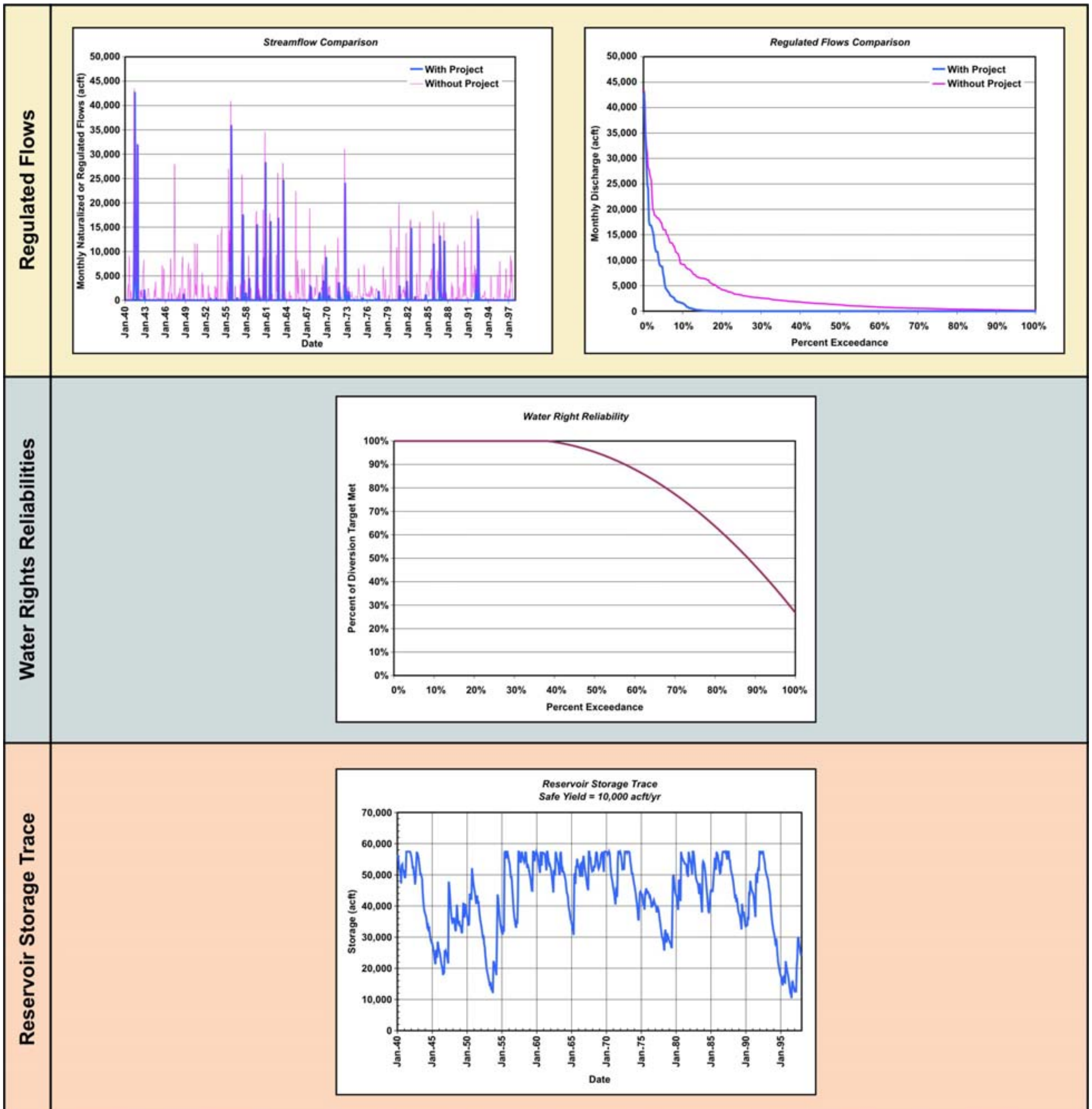


Figure 2-3. Schematic Showing Concept of a WAM Run



Future Water Supply

Reservoir Storage	Firm Yield (acft/yr) 2010	Firm Yield (acft/yr) 2060
58,000	10,000	9,800

Reservoir Storage	Safe Yield (acft/yr) 2010	Safe Yield (acft/yr) 2060
58,000	9,200	9,015

*Sedimentation reduces supply by 2% by 2060.

Figure 2-4. Typical Results of a WAM Run

2.2 GAMs

The TWDB Groundwater Availability Model (GAM) program was initiated in response to a need for a uniform and fully documented tool to evaluate the effect of pumping and droughts on regional aquifer systems. Because of the complexity of groundwater flows within, into, and out of an aquifer system, the interaction between streams and aquifers, and the variability of aquifer properties, a computer program (MODFLOW) is coded to mathematically represent an aquifer system and to simulate an aquifer's response to future stresses such as groundwater pumping or reduced rainfall which in turn affects aquifer recharge. MODFLOW was developed by the U.S. Geological Survey (USGS) (McDonald and Harbaugh, 1988), has been updated several times, tested and applied world-wide, and is widely accepted.

2.2.1 History

The 76th Texas Legislature, recognizing the importance of accurate groundwater availability estimates, approved initial funding for the GAM program. The goal of the GAM program is to provide useful and timely information for determining groundwater availability utilizing standardized, thoroughly documented, and publicly available groundwater models. These models are important tools for Groundwater Conservation Districts and Regional Water Planning Groups to evaluate water management strategies and to assess trends and limits in groundwater availability.

The nine major aquifers in Texas require 17 different models (completed) to provide full coverage. The 14 additional models needed to cover the minor aquifers are either completed, in progress, or planned. The GAMs are maintained by the TWDB, which conducts model runs at the request of representatives from groundwater conservation districts, regional water planning groups, water management areas, and the Texas Legislature. Typical results of a GAM run include projected future water levels, drawdowns, baseflow in streams, springflow, and water budgets in response to aquifer stress.

2.2.2 Operational Concepts

For standardization, all of the GAMs use the USGS MODFLOW groundwater model, which is a product of about three decades of use and refinement and is, by far, the most commonly used groundwater flow model.

MODFLOW is a generic computer program that uses a finite-difference mathematical formulation of groundwater flow equations for representing and simulating common features of aquifer systems. Conceptually, a MODFLOW model has two parts. The first part is a mathematical representation of the physical and hydraulic aspects of an aquifer system. This representation transforms a conceptual model of an aquifer system into a three-dimensional grid consisting of many model cells. Each cell is assigned physical dimensions and properties such as x, y, and z length dimensions and hydraulic properties such as horizontal and vertical hydraulic conductivity and storage coefficients. The second part is defining the hydrologic aspects which include recharge, well discharge, stages of streams, and initial groundwater levels. A simulation combines these two parts and runs the model. The results of the simulation are groundwater levels, groundwater movement (flux), and water budgets at selected time intervals.

Before a GAM can be used for its intended purpose, it must be developed and validated through a calibration process. These steps include:

(1) Developing a simplified, yet realistic, hydrogeologic concept of the aquifer system;
(2) Layering and gridding the aquifer into a rectangular, finite-difference format;
(3) Estimating aquifer hydraulic properties;
(4) Estimating recharge and pumpage;
(5) Coding the values to each model cell;
(6) Compiling historical water level measurements for wells, baseflow, streams and springflows; and
(7) Running and rerunning the model with incremental changes in aquifer properties, recharge, and/or pumping until calculated values (water levels, baseflows and springflows) until simulated values reasonably match measured values. At this point, a model is considered "calibrated."

Once calibrated, the model is considered to be suitable for applications, such as predicting how the aquifer will respond to variable pumping patterns and/or potential drought conditions. A well calibrated model gives confidence that the model will produce reasonable predictions of water levels baseflows and springflows in the future. The model can assimilate variable future pumping patterns for a range of hydrologic conditions, including prolonged wet or dry periods, to predict how water levels will change over time. A common future GAM scenario may include assessing the impact of a future drought under conditions of increased pumping and decreased recharge.

Table 2-2 includes a summary of selected GAM parameters including how each GAM simulates historical transient and predictive periods.

Table 2-2.
Summary of Selected GAM Parameters

GAM	Steady-State	Historical Transient		Predictive		Drought of Record
		Years	Stress Period	Years	Stress Period	
Carrizo-Wilcox/QCSP (Central)	Pre-development[1]	1975-2000[2]	Annual	2000-2050	Assume Annual	1954-1956
Carrizo-Wilcox/QCSP (Northern)	Pre-development[1]	1975-2000[2]	Annual	2000-2050	Assume Annual	1954-1956
Carrizo-Wilcox/QCSP (Southern)	Pre-development[1]	1975-2000[2]	Annual	2000-2050	Assume Annual	1954-1956
Edwards (Barton Springs Segment)	1979-1998	1989-1998	Monthly with 12 timesteps per stress period	2000-2050	Assume Monthly	1950-1956
Edwards (Northern)	1980 Conditions	1980-2000	Monthly	2000-2050	Monthly	1954-1956
Edwards (San Antonio Segment)	1939-1946	1947-2000	Monthly	No Predictive Model	-	1956
Edwards-Trinity Plateau	1980 Conditions	1980-2000	Annual	2000-2050	Assume Annual	1951-1957
Gulf Coast (Central)	1910-1940	1980-1999	Annual stress periods except monthly for 1987-1989, 1995-1997.[3]	Not available	-	1951-1956
Gulf Coast (Northern)	Pre-1891	1981-2000	Annual except monthly in 1980, 1982, & 1988.	2000-2050	Annual	1980, 1982, & 1988
Gulf Coast (Southern)	1930-1980	1980-2000	Annual except monthly for 1988, 1989, 1990, 1994, 1995, & 1996.	2000-2050	Assume Annual	1950-1956
Hueco Bolson	No timeframe is mentioned in text.	1903-1996	Annual	No Predictive Model	-	No mention in text.
Lipan	1980	1981-1999	Annual	2000-2050	Assume Annual	1950-1956
Ogallala (Northern)	1950 Conditions[4]	1950-1998	Annual	2000-2050	Assume Annual	1952-1956
Ogallala (Southern)	1940 Conditions	1940-2000	Monthly stress period in 1982-1984 & 1992-1994. Assume annual for others.	2000-2050	Annual stress periods were used[5]	1952-1956
Seymour & Blaine	1960's-1970's (Varies for individual 'pods')	1980-2000	Monthly	2000-2050	Annual stress periods were used[5]	1988
Trinity (Northern) & Woodbine	1880-1980 Conditions	1980-2000	Annual	2000-2050	Assume Annual	1954-1956
Trinity (Hill Country)	Winter of 1975-1976	1996-1997	Monthly	1997-2050	Assume Annual	1950-1956
West Texas Bolsons and Igneous	Pre-1950	1950-2000	Annual	2000-2050	Assume Annual	1951-1957

[1] No specific year(s) were noted in the text.
[2] 1975-1980 was 'ramp-up' period and was not used for calibration.
[3] The first stress period in the transient run spans 40-years (1940-1980).
[4] Steady-state was run as a transient model with 6000 timesteps.
[5] Monthly stress periods were used for the final 10-year period of each predictive simulation.
Note: Mesilla Bolson GAM, completed September 2004, is not included on the list due to the localized conditions of the model.

A GAM run does not directly produce an estimate of groundwater availability or reliability as with a WAM run. Instead, the determination of groundwater availability is rooted in the acceptability of impacts of assumed or projected pumpage, as determined by an individual or entity. The level of acceptability may be based on allowable drawdowns, rates of springflow, and/or baseflows in streams. Often, a model run is formulated to answer *"What if…..?"* questions, such as, *"What if we pump 10 million gallons per day from this well field for 10 years, how much drawdown will there be?"*. Figure 2-5 shows the typical process and concept of a GAM run.

2.2.3 Common Uses

For groundwater conservation districts and regional water planning groups, the GAMs have been used to:

- Calculate drawdown and, in a few cases, springflow and baseflow that would result from regional water management strategies;
- Calculate the amount of pumpage that would cause a given amount of drawdown;
- Estimate recharge;
- Estimate the amount of water in storage;
- Calculate water budgets; and
- Determine allowable pumpage within future desired conditions, as established by groundwater conservation districts within each groundwater management area (ongoing H.B.1763 process).

A summary of typical results from a GAM run is shown in Figure 2-6.

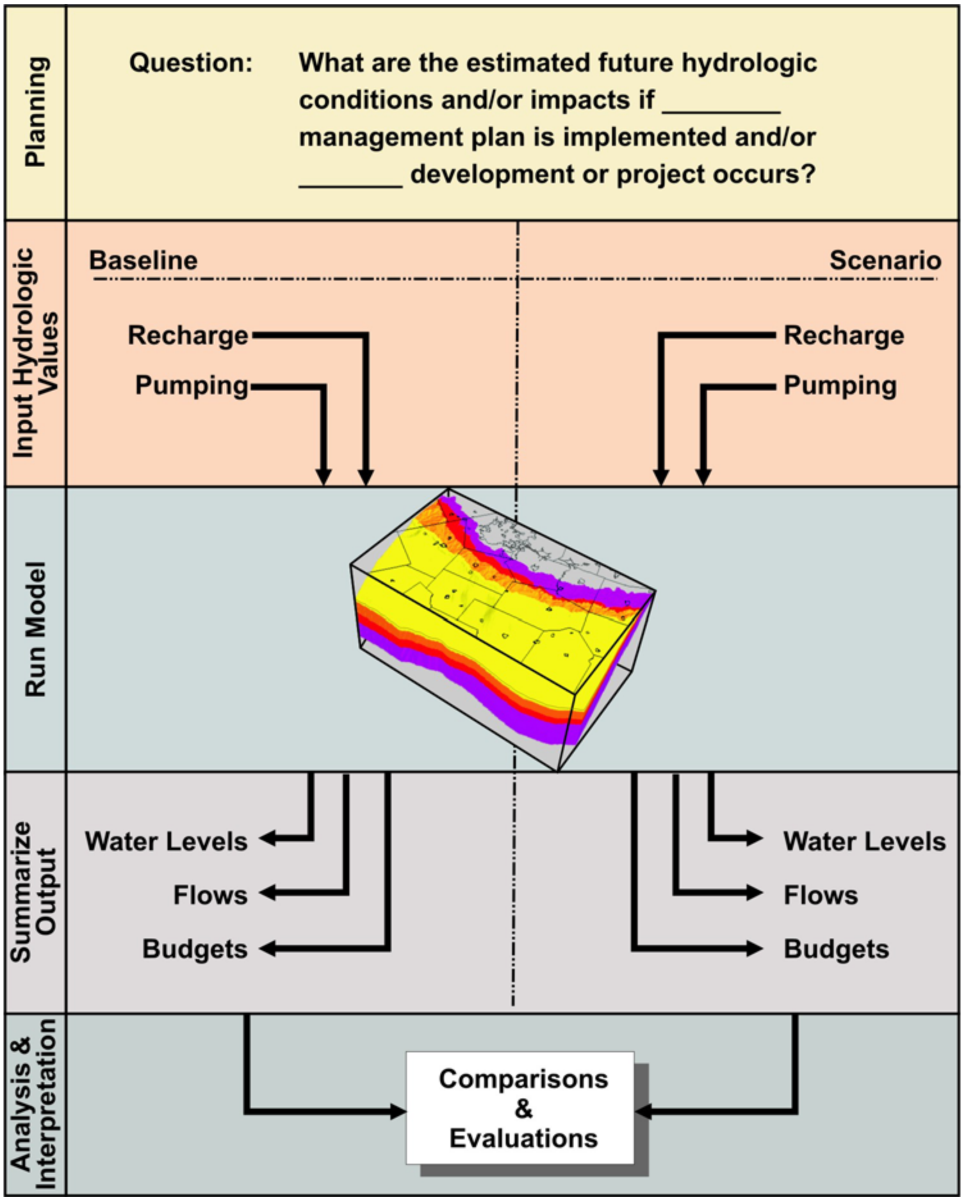
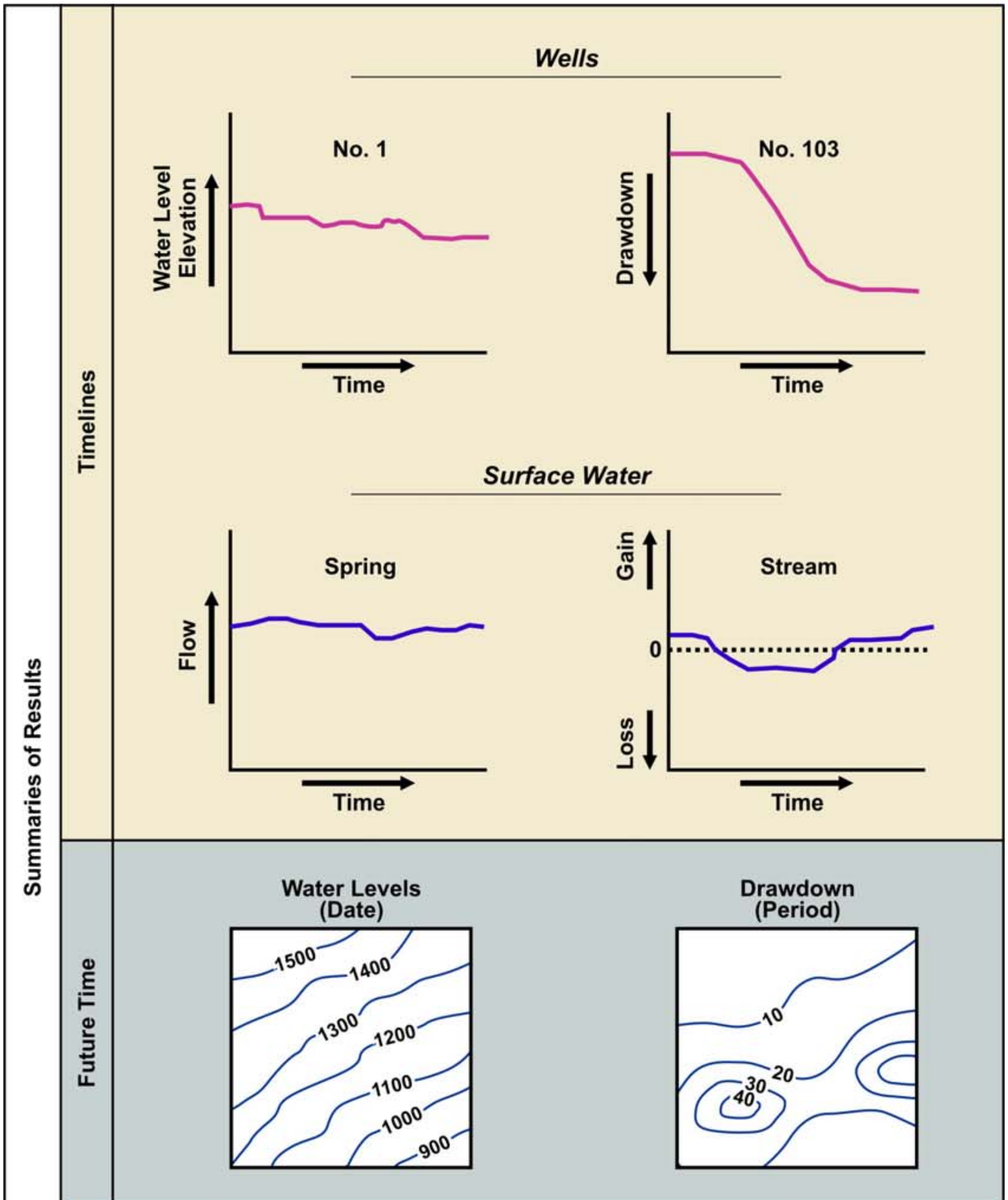


Figure 2-5. Schematic Showing Concept of a GAM Run



Water Budget

Component	*Inflow (acft/yr)*	*Outflow (acft/yr)*
Recharge	42,000	0
Pumping	0	15,000
ET	0	2,000
Leakance	3,000	1,000
Surface Features	4,000	28,000
Storage	0	3,000
Total	49,000	49,000

Figure 2-6. Typical Results of a GAM Run

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Section 3
Technical Considerations for Linkage

3.1 Paradigms of Models

The WAM simulates the performance of water rights (diversions and reservoirs) over a repeat of the hydrologic period of record, generally about 1940 through 1997. The GAM, on the other hand, simulates future aquifer conditions for an assumed pumping and recharge scenario. A common GAM modeling scenario is to simulate recharge at long-term average rates except during periods representative of the "drought of record", which typically is inserted at the end of the simulation period. This drought stress period utilizes below average annual recharge values based on recharge estimated during the drought of record. An exception is the Edwards Aquifer (San Antonio Segment) GAM, which includes a historical sequence of monthly recharge estimates. This sequence captures the "drought of record." The GAM can be thought of as predictive in nature (i.e., "*What will happen in the future if…,"*) whereas the WAM is retrospective (i.e., "*what would have happened if…"*). GAM results are typically analyzed by considering future water levels, while WAM results are usually analyzed by looking at time series data and statistical measures of reliability.

3.2 Geographic Scales

A typical GAM is defined by a three-dimensional grid of one square mile grid cells, within which aquifer properties are averaged. The WAM is defined by site-specific control points or nodes that reference streamflow passing these locations. These geographic distinctions for a typical WAM and GAM are shown in Figure 3-1. The GAM spatial resolution makes it strongly applicable for defining and estimating regional aquifer responses to regional stresses (pumping), but not well suited for defining the effects of regional or localized pumping on a local scale. The WAM focuses on the behavior of local, specific water rights and their interactions with other rights, while the GAM focuses on responses within a regional system.

3.3 Temporal Scales

Typically, aquifer systems respond relatively slowly to stresses such as prolonged droughts or increasing withdrawals, simply due to the scale of the systems and the physics of groundwater flow. River systems, however, are sensitive to short-term stresses such as changes in hydrologic conditions and increased diversions or returns. For these reasons, the GAMs typically simulate a series of annual stress periods, while the WAM utilizes a monthly simulation time step, as shown in Figure 3-2.

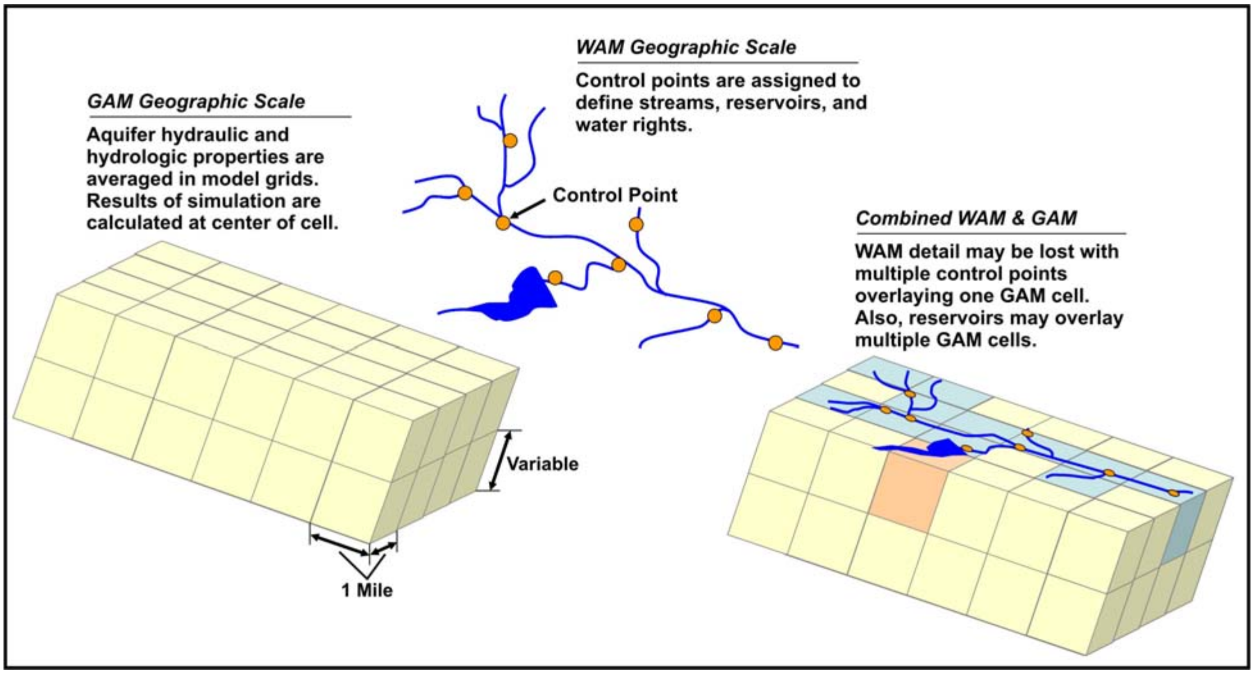

Figure 3-1. Geographical Representation of a Typical WAM and GAM

3.4 Calculation and Characterization of Water Movement between Streams and Aquifers (SW/GW Interaction)

Stream and aquifer systems interact primarily where surface water features (streams, springs, and reservoirs) intersect aquifer outcrop areas. Streamflow and water impounded in reservoirs can percolate into an underlying aquifer formation through stream beds and banks. Groundwater can enter the surface water system through well-defined springs, as well as by a general flux (seeps) from an aquifer to a stream along a length of channel, or diffuse wetlands. Often, these fluxes from a groundwater system constitute a substantial portion of the baseflow of a stream. As aquifer water levels vary, baseflow in a stream can increase, decrease, or change direction (from gaining to losing). Along a channel, baseflow can be positive in some reaches and negative in other reaches. To complicate matters, the baseflow patterns and rates can change with seasons and hydrologic conditions.

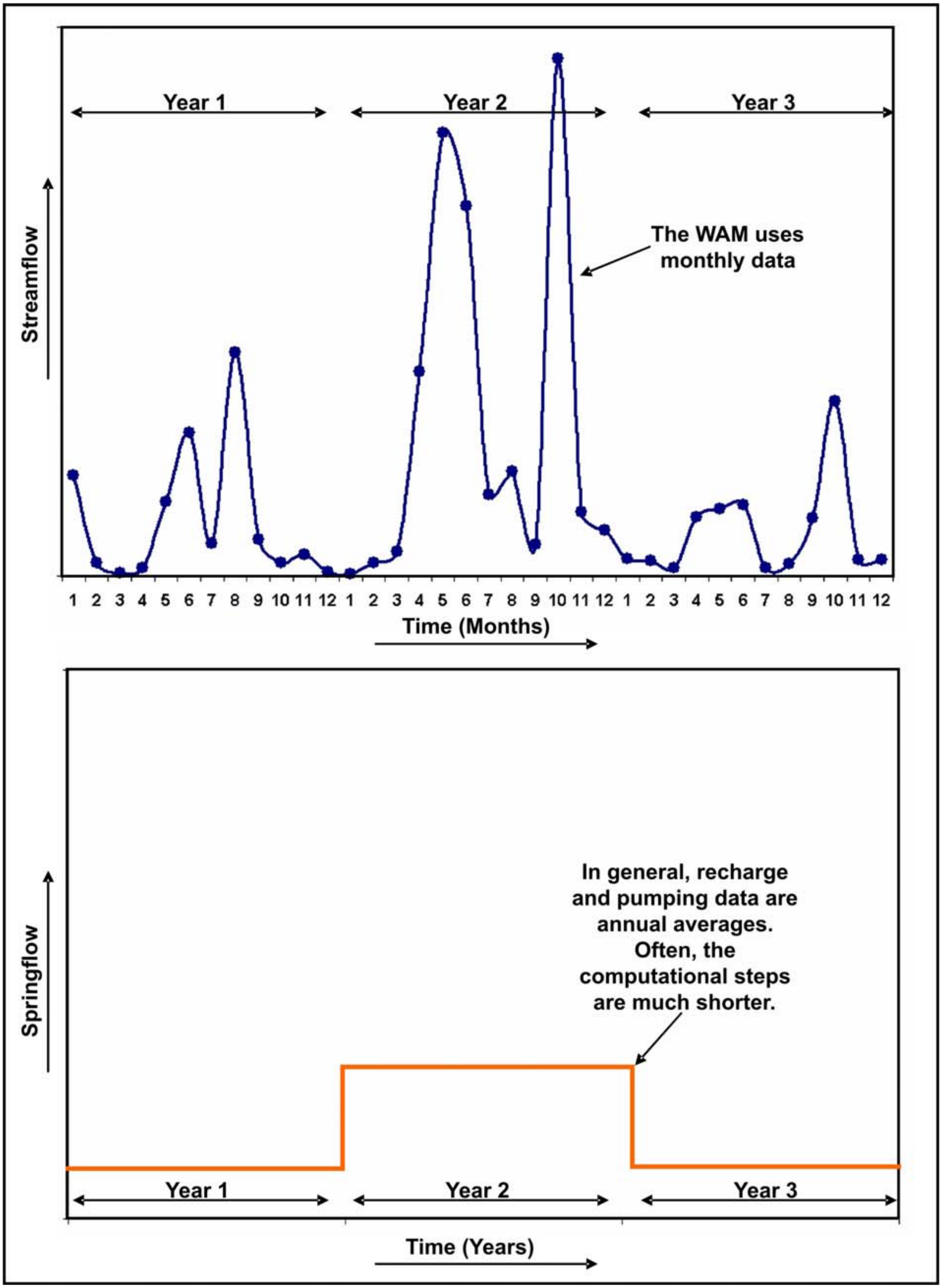

Figure 3-2. Temporal Representation of a Typical WAM and GAM

Quantification of groundwater-surface water interactions is a complex science, primarily due to complexities caused by geographic, geologic, climatic, and management variations. In addition, limited data exist to describe these interactions precisely. Linking the WAM to the GAM will involve defining not only the hydrologic responses of both the groundwater and surface water systems, but also defining how the two models will interact to pass this information back and forth.

3.4.1 How WAMs Represent Streamflow Losses/Gains and ET

The WAM currently includes two primary means for defining how groundwater systems might influence streamflow and evapotranspiration (ET), which is the loss of water from soil by evaporation or plant transpiration. The first is through a naturalized flow adjustments file, whereby changes to the naturalized flows used in the WAM are modified to account for changes in spring flows or in the flux from an aquifer to a stream channel and ET. The WAM naturalized flows are based upon gaged streamflow records and inherently reflect historical interactions with aquifer systems. Hence, most WAM naturalized flows reflect historical groundwater development and patterns of riparian vegetation.

In order to move to some defined future "managed" groundwater development condition that may have greater pumping than that which occurred in the early part of the simulation period, but less than recent pumping, flows in earlier years might be decreased while flows in later years might be increased. This is the case in the Guadalupe-San Antonio River Basin WAM (GSA WAM), which includes a flow adjustments file used to adjust naturalized flows to reflect a regulated pumping level from the Edwards Aquifer of 400,000 acre-feet per year. These adjustments are applied to the major springs discharging from the Edwards Aquifer (San Marcos, Comal, Hueco, San Antonio, and San Pedro), and are translated through control point locations downstream of the spring locations. The adjustments are actually the differences between two aquifer simulations.[1] The first simulation reflects springflows occurring during historical pumping conditions; the second simulation accounts for calculated springflows occurring under assumed aquifer pumping conditions. The difference in monthly springflows between the two model simulations forms the basis for the flow adjustments applied in the GSA WAM. Additional adjustments are applied to correct for model calibration, thereby allowing the

[1] The TWDB GWSIM4 model of the Edwards was used. The GWSIM4 model for the Edwards Aquifer and the MODFLOW model are approved.

magnitudes of the simulated historical springflows to more closely agree with observed historical springflows.

The WAM includes a second methodology that partially reflects groundwater-surface water interactions through the application of a channel loss function. Channel losses are entered into the WAM as a fixed percentage, and reflect the portion of the flow “lost” between sequent upstream and downstream control point locations. These losses reflect not just seepage from stream channels, but also free surface evaporation from the stream and ET from vegetation growing along the stream channel. Because the naturalized flows already reflect naturally occurring channel losses, the channel loss factors are applied only to changes in flow caused by diversions, wastewater effluent discharges (return flows), and reservoir operations. Channel losses are also applied to the flow changes input into the flow adjustment file. As shown in Table 2-1, channel losses are used widely in eight of the WAMs: the Nueces, Guadalupe-San Antonio, Brazos and San Jacinto-Brazos Coastal, Canadian, San Antonio-Nueces Coastal, Lower Nueces- Rio Grande, Upper Nueces- Rio Grande, and Rio Grande. The Trinity, Colorado and Brazos-Colorado Coastal, and Red River WAMs utilize channel losses to a limited extent, but they are not applied basin-wide.

The WAM is able to model recharge to an aquifer system and discharge from an aquifer using one or more “water rights” that remove or add water to the surface water system, keyed to specific output parameters from the GAM. For water rights that remove water from the surface water system (and are assumed to input water to the groundwater system), the relationship of these flows to naturally occurring recharge must be well defined and incorporated into the recharge calculations in the GAM. Since most GAM models use average annual and drought-averaged annual recharge, additional statistical inference would have to be made from the monthly water right output in order to adjust the annual recharge values. One situation where this might be used is in the case of a reservoir constructed over an aquifer recharge zone (i.e., Lake Corpus Christi over the Gulf Coast Aquifer). While the WAM does not contain specific capabilities for defining leakage from a reservoir, relationships could be input whereby water would leave the WAM as a function of reservoir level. These surface water losses could then be combined with natural recharge estimates in the appropriate GAM.

However, in very few cases will alterations to the surface water system result in noticeable changes in aquifer recharge. New water rights granted by the TCEQ are unlikely to completely dry up a stream because they will be subject to instream flow requirements and will be required to pass inflows to downstream senior rights. While precise knowledge of the hydraulic connections between stream and aquifer systems is limited, differences in stages due to changes in baseflows are unlikely to result in appreciably different levels of computed seepage to the underlying aquifer. Under baseflow conditions (typically small discharges), substantial differences in baseflow discharges result in relatively minor differences in stage, typically much less than 1 foot. Stage (hydraulic head) is a primary factor controlling the rate of seepage through the streambed, and with all other variables held relatively constant (wetted perimeter, permeability), small changes in stage will not substantially change the rate at which seepage occurs. As long as the stream does not completely dry up in the WAM simulation, one can reasonably assume that interactions between the stream and the aquifer will continue to occur within the accuracy represented in a GAM. The driving force (hydraulic head of the water in the stream channel) is unlikely to vary substantially and knowledge of the relationship between stage and seepage is uncertain enough that any changes in stage are well within the precision limitations of the computational methods. Exceptions include in the case of structures built and permitted specifically to enhance recharge to an aquifer, or to water rights located upstream of highly permeable recharge zones where little of the water entering a stream reach remains as streamflow and a substantial fraction is "lost" to the underlying aquifer. These situations are primarily associated with the outcrop of the Edwards Aquifer and should be treated as special cases.

3.4.2 How GAMs Represent Aquifer Losses/Gains and ET

MODFLOW offers four options that can be directly used to simulate groundwater-surface water interactions from a groundwater system perspective, including the stream package, river package, reservoir package, and drain package. These packages have different capabilities and applications and their use varies among individual GAMs. Regardless of what model package is used to simulate groundwater-surface water interactions, estimates of the amount of water lost from the aquifer to evapotranspiration and water lost as leakage from the aquifer to a stream are highly subjective and are based on professional judgment and parameters identified by the model developer. All of these packages are based in part on computed aquifer levels to quantify water lost to a stream or gained from a stream. As discussed earlier, quantities can be computed in an execution of the GAM that can then be input to the WAM stream or gained from a stream, as shown in Figure 3-3.

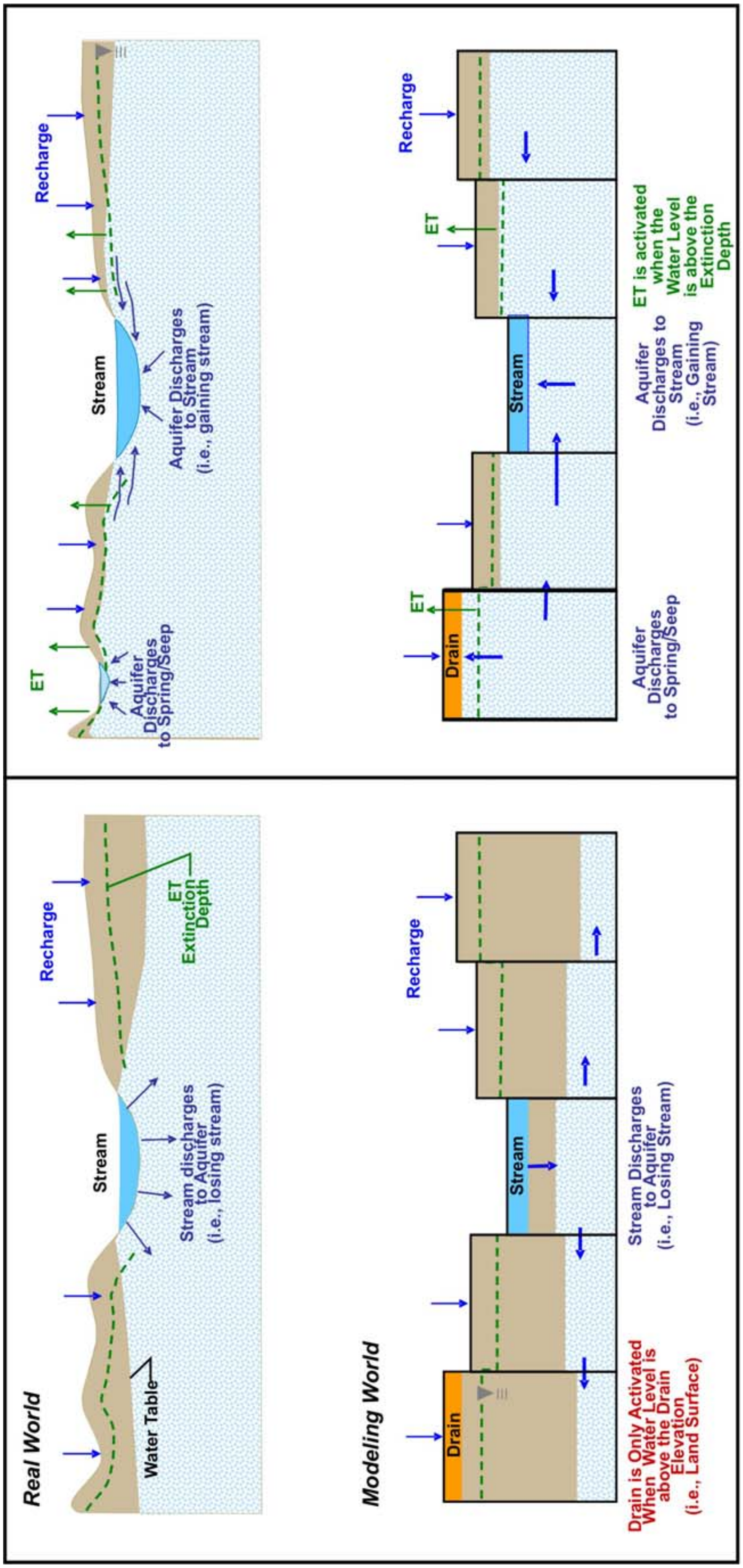

Figure 3-3. Schematic Showing Representation of SW/GW Interaction in GAM

As discussed earlier, flux from an aquifer to a stream channel or springflows can be computed in an execution of the GAM and included in a WAM by changing naturalized flows through use of a WAM flow adjustments file. These adjustments would need to be processed for two GAM simulations, a baseline simulation reflecting historical conditions and a projected simulation that reflects conditions after future groundwater development. These two GAM simulations would then be used to evaluate the difference between historical and projected groundwater- surface water interactions after future groundwater projects are in place.

For a given scenario, a GAM run calculates baseflow for each model cell at each future time step. A future point in time must be selected at which the cumulative effects of groundwater development on streamflow would be introduced into the WAM. This would normally be a constant change in flow at each defined point of interaction that would not vary temporally throughout the WAM simulation period. For example, a planner might want to assess the effects of increased groundwater pumpage on water rights in a specific river basin based on aquifer levels at the end of a 50-year GAM projection. In this case, the GAM would provide a single change in baseflow value at each applicable WAM control point that would be applied at all WAM time steps.

One of the difficulties in using MODFLOW for calculating surface water/groundwater interaction along a stream is partitioning the aquifer's discharge between evapotranspiration and baseflow for a single model cell along a stream where both conditions occur. This difficulty is exacerbated because: (1) there is a length scaling issue with a model cell being one square mile and the stream and riparian vegetation corridor being significantly narrower, (2) there is a time scaling issue in that actual ET and baseflow can be quite variable during the year, but the model time steps are commonly annual timesteps, and (3) ET fluxes and baseflows in streams are difficult to estimate.

In general, the GAM will be much less sensitive to changes in the surface water system because of the dynamic, time-varying nature of surface water hydrology and the regional, highly buffered characteristics typical of groundwater systems. In simple terms, aquifer systems typically have much more mass (storage) and inertia and are not "driven" in the short-term by stream or reservoir conditions. A linkage between the GAM and WAM would be most useful in quantifying the impacts of the aquifer system on surface water rights and water availability, rather than attempting to capture the more subtle effects of surface water rights on the groundwater system. Overall, groundwater-surface water interactions are not well-quantified statewide and little data or research results exist upon which to base an entire GAM or WAM linkage. In some locations and times, site-specific studies may have been performed, but the spatial and temporal scale of the GAM precludes direct application of results on a regional basis without first acknowledging this limitation.

3.5 Two Mechanisms for Linking

Two general approaches have been identified to define how the WAM and GAM could exchange results in a practical sense. One is an active linkage, whereby the WAM and GAM share data back and forth at the end of each time-step/stress-period; and, the other is a passive linkage where one model run is completed and information passed to the second model for its run.

Regardless of whether an active or a passive link is used, specific knowledge of the hydrology, geology, and geography of the river basins and aquifer systems to be studied is required, in addition to familiarity with both the GAMs and WAMs to be linked. Professional judgment is required to determine how best to accumulate flow and water budget changes from the MODFLOW package (stream, river, reservoir, or drain) used by a specific GAM, and where to assign these flow changes within the WAM depiction of a river basin. Basin-specific WAM knowledge is required that includes familiarity with the methodology for distributing naturalized flows from gaged to ungaged control point locations and knowledge of which stream reaches could be affected by changes in springflows or groundwater flux. It is unlikely that any simple, generic methodology can be developed that would apply to all GAMs and WAMs. However, once the "homework" has been completed related to defining the linkages between specific WAMs and GAMs, the same data that define the linkage framework for specific WAMs and GAMs can continue to be employed so long as the base model data sets are not altered (official WAM and GAM data sets are periodically updated by the TCEQ and the TWDB, respectively). Geographic Information Systems can be useful in developing much of the base linkage information required, as with several of the proprietary MODFLOW interface packages such as Groundwater Vistas™.[2]

[2] Scientific Software Group, Sandy, Utah, www.groundwater-vistas.com. Trade names are mentioned here for identification purposes only and do not reflect endorsement by the TWDB or the State of Texas.

3.5.1 Active Linkage

An active linkage would require substantial computer code modifications to both the WRAP model (used by the WAM) and the MODFLOW model (used by the GAM) in order for the two to communicate results on a month-by-month basis. To complicate matters, the generalized computer programs (WRAP and MODFLOW) and data files are periodically updated with additional capabilities and data to reflect improved information or changed conditions. Thus, any hard-coded "handshake" linking the two would need to be ported to the updated models and tested. This issue might be minor if the "handshake" capability were to utilize standard features incorporated into both models specifically for this purpose.

An active linkage is most suitable for changes in an aquifer flux (which would be the difference between baseline (historical) and projected values, such as springflows from major springs). In this case, a GAM would be run for a single stress period, the computed changes in springflows would then be passed to the WAM, the WAM flows would be adjusted, and the WAM simulation would commence for the current month. After completion of the WAM simulation for a given month, the WAM could pass data (such as amount of water available for artificial recharge) back to the GAM, and the GAM would complete another stress period. A schematic illustrating a procedure that could be used to actively link a GAM and WAM is shown in Figure 3-4. This sequence of "handshakes" would continue with GAM and WAM output providing "real-time" feedback to the other model until the entire simulation is completed.

This process was used by the South Central Texas Regional Water Planning Group (Region L) to assess a potential water management strategy know as "Recharge and Recirculation."[3] In this process, recharge was enhanced by defined recharge projects using the GWSIM4 Edwards Aquifer Model maintained by the TWDB. The enhanced recharge increased springflows in the GSA WAM, and the increased springflows were made available to further recharge enhancement in the GAM by being pumped back to the recharge zone of the aquifer. In this particular application, the WAM and GAM provided feedback to one another on a month-by-month basis.

[3] South Central Texas Regional Water Planning Group, 2001 Regional Water Plan, January 2001.

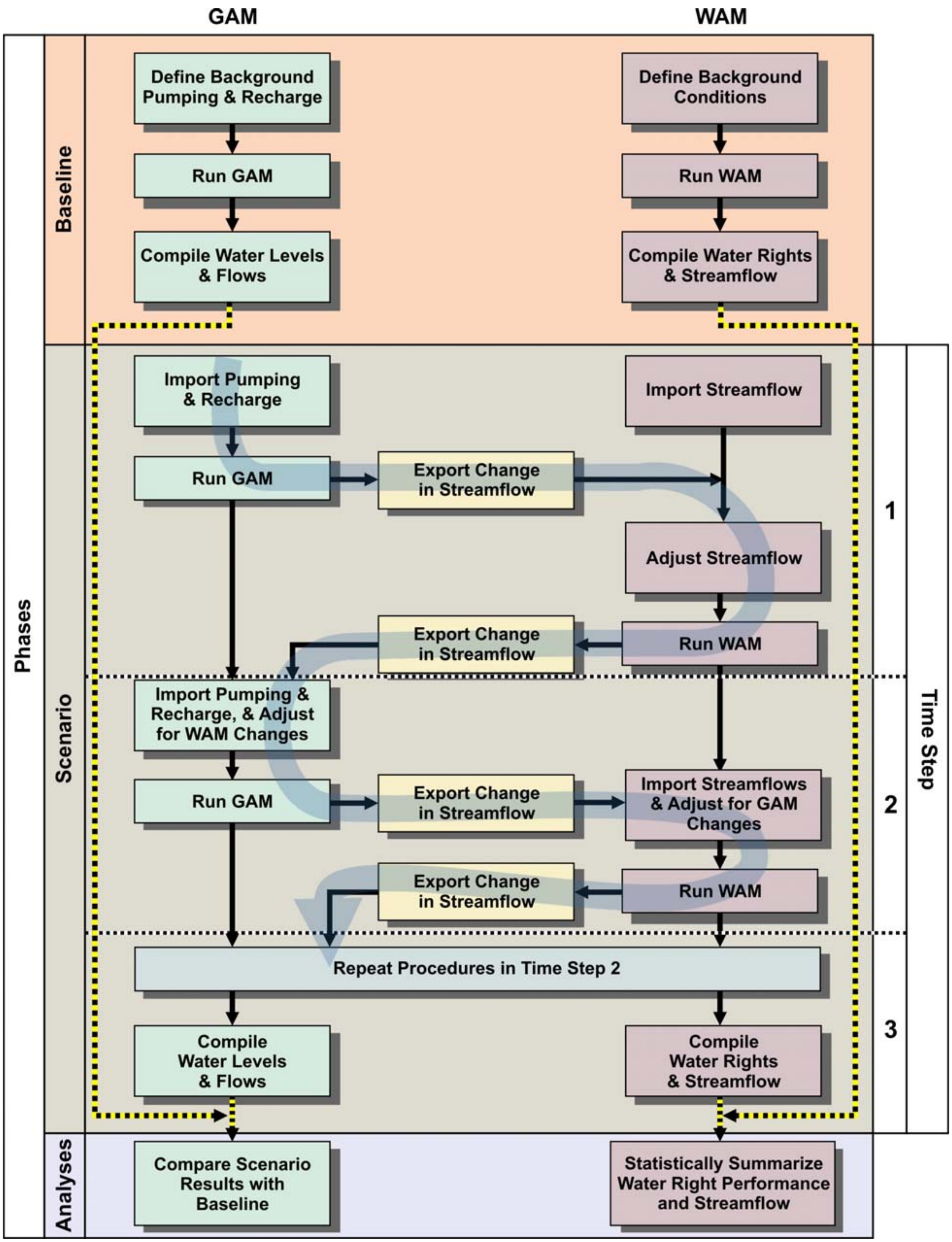

Figure 3-4. Schematic Illustrating Active Linkage of GAM and WAM

3.5.2 Passive Linkage

A passive linkage operates under the assumption that data needs to be passed in only one direction (i.e., GAM to WAM) because model-to-model feedback on a month-by-month basis is unnecessary. A passive linkage schematic of how GAM data can be used in WAM models is shown in Figure 3-5. This is believed to be the case with most WAM and GAM situations, where changes in groundwater pumping might reasonably be expected to alter surface water baseflows through long-term changes in springflows or groundwater flux, but changes in surface water rights would not be expected to provide appreciable impacts to groundwater. Output from the GAM is post-processed to identify potential changes in streamflow expected to occur at a selected point within the future timeframe. Such a passive linkage can be facilitated without modification to the code of either the WAM or GAM model by developing a data transfer program. This program would be written expressly for that purpose and may use a programming language, spreadsheet analysis tools, or a combination of the two.

Because of the complexity of developing an active linkage of multiple GAMs to a WAM effectively, a passive linkage from the GAM outputs to the WAM input appears to be the more reasonable approach.

3.6 Multiple or Chain Linkages

The geography of streams and aquifers in Texas is such that most all of the major streams cross multiple aquifers. Likewise, most all of the major and minor aquifers extend laterally across multiple river basins. Multiple basins could be affected if a major groundwater development has a drawdown pattern that extends into adjacent stream basins. This condition could easily occur if the well field is along a divide between two basins, which would cause a regional drawdown pattern that has the potential of reducing streamflow gains and/or increasing streamflow losses in two or more WAMs. Another example is a major surface water project that may reduce or greatly alter the streamflows in upper or middle reaches and could affect the streamflow losses into multiple aquifers downstream of the project. From these two examples, realistic WAM-GAM linkages may include one GAM and adjacent WAMs or one WAM and multiple GAMs. Figure 3-6 shows how a surface water project can result in less streamflow losses to an aquifer. Figure 3-7, shows a more likely scenario, where groundwater development simulated in a GAM crossing can extend laterally to multiple WAMs. Table 3-1 identifies GAMS which cross multiple river basins.

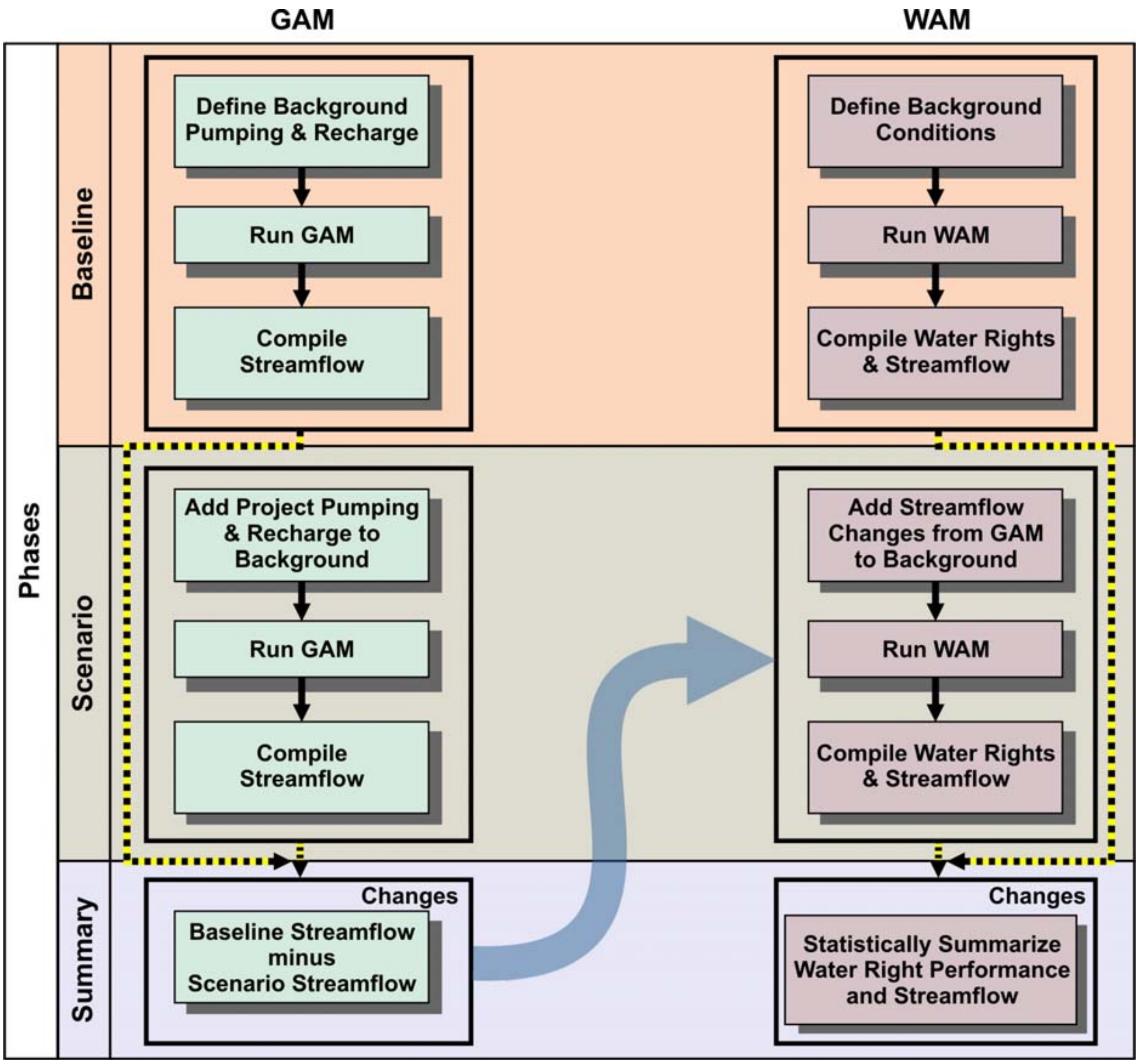

Figure 3-5. Schematic Illustrating Passive Linkage of GAM and WAM

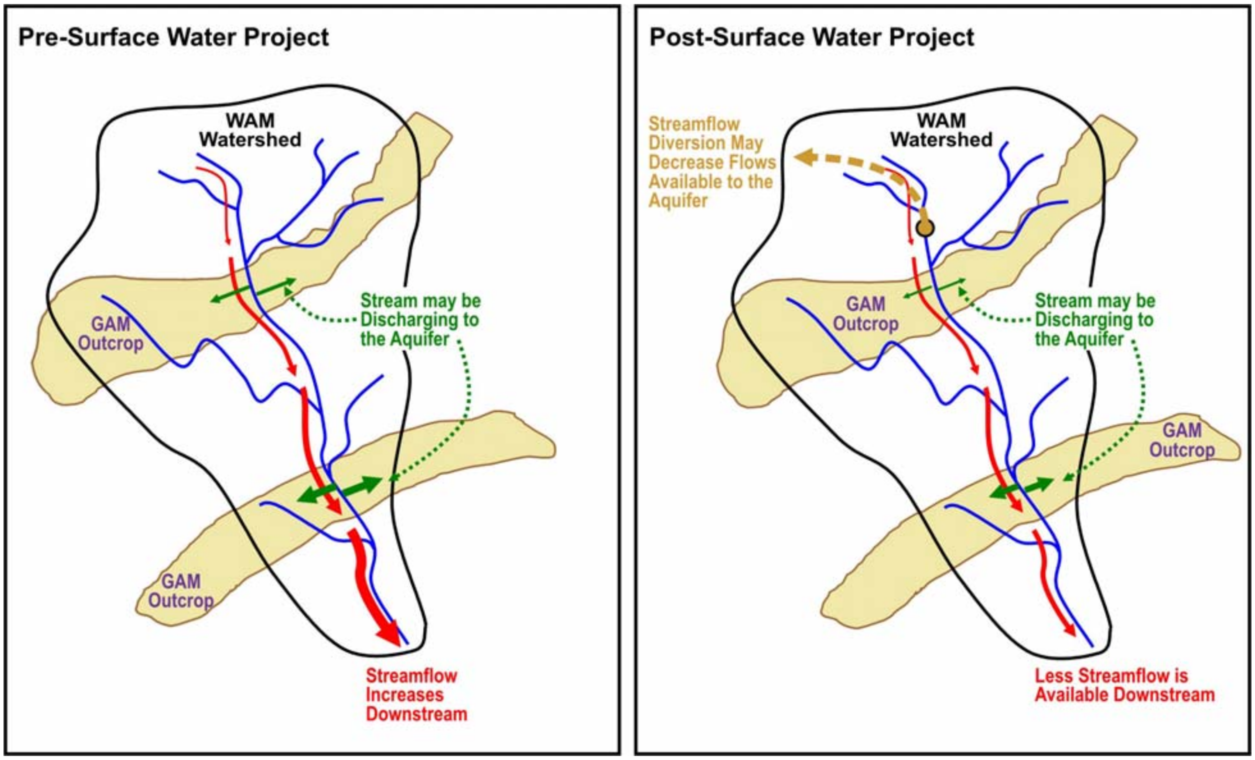

Figure 3-6. Schematic Showing Impact of Surface Water Project from WAM and Possible Impacts to Multiple Aquifers

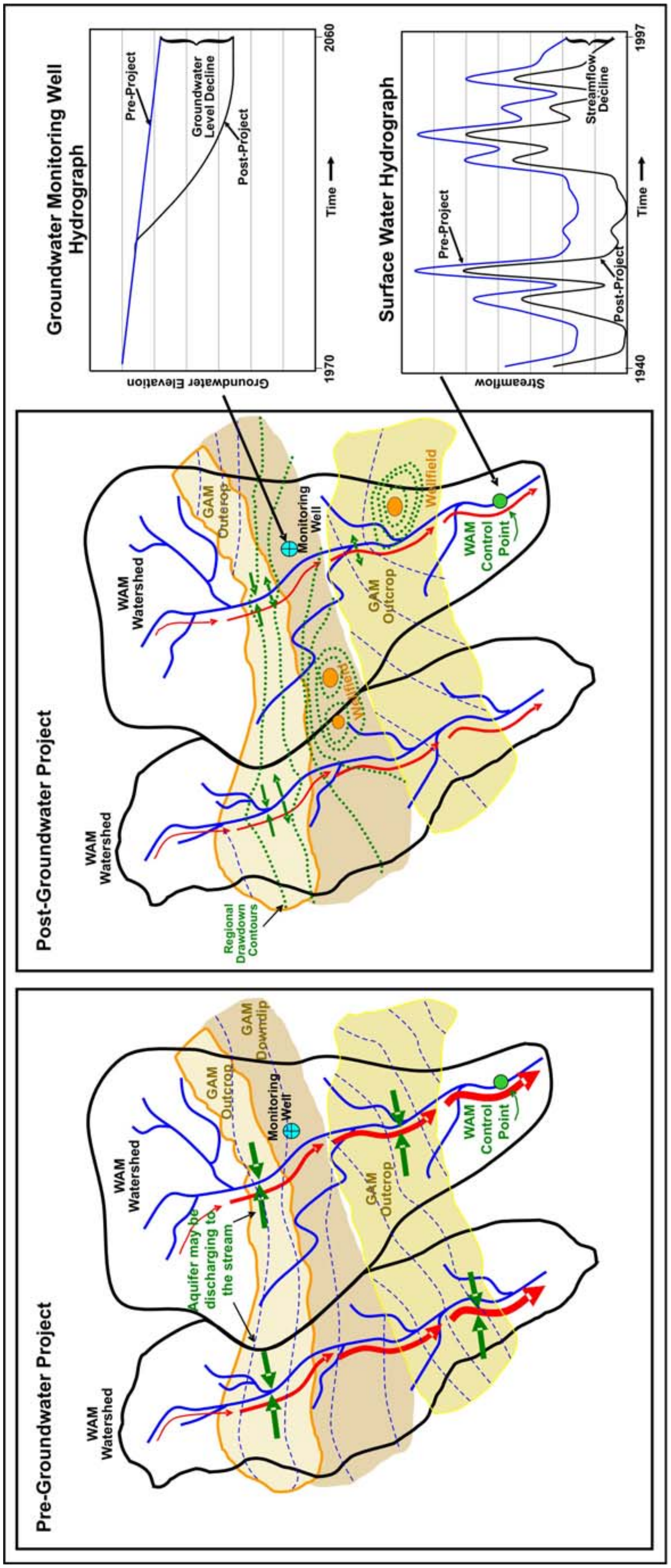

Figure 3-7. Schematic Showing Impact of Groundwater Project to Streamflow in Multiple WAMs

Table 3-1.
River Basins Crossed by GAMs

GAM	River Basins Crossed
Carrizo-Wilcox/QCSP (Central)	Neches, Trinity, San Jacinto, Brazos, Colorado, Lavaca, Guadalupe, San Antonio, Neches-Trinity, Trinity-San Jacinto, San Jacinto-Brazos, Lavaca-Guadalupe, Colorado-Guadalupe, Brazos-Colorado
Carrizo-Wilcox/QCSP (Northern)	Brazos, Trinity, Neches, Sabine, Red, San Jacinto
Carrizo-Wilcox/QCSP (Southern)	Rio Grande, Nueces, San Antonio, Guadalupe, Colorado, Lavaca
Edwards (Barton Springs Segment)	Colorado
Edwards (Northern)	Colorado, Brazos
Edwards (San Antonio Segment)	Nueces, San Antonio, Guadalupe, Colorado
Edwards-Trinity Plateau	Rio Grande, Colorado, Nueces, San Antonio, Guadalupe
Gulf Coast (Central)	Nueces, San Antonio, Colorado, Lavaca, Rio Grande, Nueces-Rio Grande, San Antonio-Nueces, Guadalupe, Lavaca-Guadalupe, Colorado-Lavaca, Brazos-Colorado
Gulf Coast (Northern)	Guadalupe, Lavaca, Lavaca-Guadalupe, Colorado-Lavaca, Colorado, Brazos-Colorado, Brazos, San Jacinto, San Jacinto-Brazos, Trinity, Neches-Trinity, Neches, Sabine
Gulf Coast (Southern)	Rio Grande, Nueces-Rio Grande, Nueces, San Antonio-Nueces
Hueco Bolson	Rio Grande
Lipan	Brazos
Ogallala (Northern)	Cimarron, Canadian, Red
Ogallala (Southern)	Colorado, Canadian, Red, Brazos
Seymour & Blaine	Brazos, Red
Trinity (Northern) & Woodbine	Colorado, Brazos, Trinity, Sulphur
Trinity (Hill Country)	San Antonio, Guadalupe, Colorado
West Texas Bolsons and Igneous	Rio Grande

In most all major water supply projects, there is a wide-spread interest in the effects on the freshwater inflows into bays and estuaries and the cumulative effects of multiple projects. Thus, a reasonable expectation for a water availability analysis would include multiple or chain linkages of WAMs and GAMs. A cumulative effects analysis of both surface water and groundwater development could necessitate the use of multiple WAMs and GAMs.

3.7 Ownership of WAMs and GAMs

The WAM and GAM systems are maintained by separate State agencies, and are used by these agencies for entirely different purposes. The TCEQ uses the WAM to analyze water available to existing surface water rights and evaluate applications for new appropriations. TCEQ staff routinely updates the various WAM data sets to reflect new and amended water rights. These WAM updates frequently include new control point locations and updated methodologies used to model specific water rights. Furthermore, the WRAP model capabilities are continually being updated by Texas A&M University to allow the model to simulate new or more complex surface water right situations. The WAM system is in a continual state of change, with both data sets and model codes being updated on a frequent basis. The TWDB uses the WAM models for water supply planning (reservoir firm yield estimates, surface water supply from run-of-the-river diversions, and evaluation of the effects of new water supply systems on instream flows and freshwater inflows to bays and estuaries). Certain TCEQ assumptions required for permitting perpetual water rights are not necessarily applicable to the water supply planning activities of the TWDB, just as some of the assumptions used by the TWDB are not necessarily appropriate for surface water rights permitting.

The TWDB uses the GAM for water supply planning, and to assist groundwater conservation districts in managing regional groundwater supplies. With the exception of the GWSIM4 Edwards Model, the TCEQ appears to be an infrequent user of GAMs in the course of its activities. A linked approach could be used by the TCEQ to assess the long-term effects of groundwater development on streamflows and the reliability of surface water rights, which could be used to assess potential surface water appropriations. However, additional detail may be necessary in State law and/or TCEQ rules in order to more fully integrate consideration of groundwater/surface water interactions into the regulatory process concerning surface water rights.

Overall, for successful linkages of WAMs and GAMs to be maintained over time, the TCEQ and TWDB would need to closely coordinate model updates and maintenance activities.

3.8 Other Approaches in Linking Surface Water and Groundwater Models

Linking surface water and groundwater models is generally approached from three concepts based on a deterministic groundwater flow model with variation in the modeling framework of the surface water model. These variations[4] include (1) fully dynamic hydraulic models such as the USGS' BRANCH[5] and watershed models such U.S. Department of

[4] Referencing various models and software does not constitute and endorsement by HDR Engineering, Inc.
[5] Schaffranek, R.W, 1987, Flow model for open-channel reach or network: U.S. Geological Survey Professional Paper 1384, 12p.

Agriculture's SWAT[6] model that uses a physically based, quasi-distributed approach and readily-available input data to provide two-way communication between watershed and groundwater models, (2) a very complex integrated stream routing and groundwater model such as MIKE SHE,[7] and (3) customizing a river and reservoir management model such as RiverWare[8] to simulate groundwater and surface water interactions.

Linking fully dynamic hydraulic surface water and groundwater models is extremely complex and has found limited utility due to the high variability in the nature of stream and aquifer systems. The linking of SWAT and MODFLOW models has been a major investment by the Kansas Geological Survey,[9] which has developed an active linkage and applied the system of models in several watersheds in Kansas. Perkins and Sophocleous point out that the approach has disadvantages of complexity of model domains, computer code, data requirements, and operations; but has the advantage of providing an overall water balance for many parameters in the watershed. MIKE SHE provides a very sophisticated set of management tools that take into consideration the complex watersheds and groundwater systems and their interactions. RiverWare presents a very recent development in the linking of a surface water management type model with MODFLOW, and offers examples of linkage between the two models in active or passive modes.

RiverWare is, by far, much more closely associated with Texas' WAMs and GAMs than any of the other surface water and groundwater interaction models. RiverWare consists of a river basin system framework that may include reservoirs, diversions, river reaches, confluences, groundwater storage, and other user-defined expressions. The model represents the system components or "objects" as nodes that are linked together by the model user. Along with the data is a menu of engineering algorithms such as river reach routing and operating policies that specify conditions such as simulating diversions during specified streamflow conditions. The RiverWare framework is essentially nodes connected in various fashions to other nodes. The groundwater framework utilized is MODFLOW. The interaction is passive when the simulation

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[6] Neitsch, S.L., Arnold, J.G., Kiniry, J.R., and Williams, J.R., July 2005, Soil and Water Assessment Tool Theoretical Documentation: Grassland, Soil, and Water Research Laboratory, Agricultural Research Service and Blackland Research Center, Texas Agricultural Experiment Station.

[7] DHI Software, Website: http://www.dhigroup.com/Software/WaterResources/MIKE SHE.aspx

[8] Zagona, Edith A., Terrance J. Fulp, Richard Shane, Timothy Magee, and H. Morgan Goranflo (2001), RiverWare: A Generalized Tool for Complex Reservoir Systems Modeling, Journal of the American Water Resources Association, AWRA 37(4):913-929. Website: http://cadswes.colorado.edu/riverware/overview.html

[9] Sophocleous, Marios and Perkins, S.P., 2000, Methodology and application of combined watershed and ground-water models in Kansas: Journal of Hydrology 236(2000) 182-201.

starts by running MODFLOW, exports groundwater conditions to selected nodes, and the surface water component of RiverWare completes the simulation. The interaction between the two models can be active when RiverWare and MODFLOW are run simultaneously and interactively so that the two models pass results at key nodes and cells at the end of each time step. This active model linkage required additional coding of a MODFLOW package module which has been completed and tested. A February 7, 2007 conference presentation by a staff member of the Center for Advanced Decision Support for Water and Environmental Systems at the RiverWare User Group Meeting that illustrates both an active and passive integration of MODFLOW and RiverWare can be found at: http://cadswes.colorado.edu/riverware/ugm/2007/presentations/CADSWES/DavidAllisonPatrickSwGw.pdf.[10] Of interest, an ongoing development and application of RiverWare in Texas includes representation of surface water rights in the Lower Colorado River Basin and the Trinity River Basin.

In summary, the concepts described previously for linking the WAMs and GAMs in passive and active modes parallels the approach being developed by RiverWare researchers. It offers promise in:

- Adopting RiverWare computational algorithms and capabilities into WRAP, and
- Developing algorithms in WRAP that communicate information with MODFLOW using the MODFLOW modules developed for RiverWare.

Many of the paradigms mentioned earlier still remain, and extensive review and evaluation of existing WAM and GAM file structures is necessary to achieve effective linkage, effective data exchange, and model compatibility.

[10] See http://cadswes.colorado.edu/, if link becomes inactive.

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Section 4
Mid-Course Review and Adjustment

4.1 Stakeholder Survey

At the onset of planning and developing a linkage of the (Surface) Water Availability Model (WAM) and the Groundwater Availability Model (GAM), the HDR Engineering, Inc. team (HDR) conducted a survey of stakeholders in the water community to learn of their current uses, expectations for new information and uses of the linked models, concerns related to the linked models, and recommendations on future funding. This stakeholder survey, included in Appendix A, was in the form of a questionnaire that consisted of the following six questions:

1. Do you use data from a WAM or a GAM?
   a. If yes, do you perform model runs in-house (or with outside consultants), or do you rely on the State or other agencies (GCDs)?
   b. How are the data used by your organization?
2. What new data or information would you expect to obtain from a linkage of WAMs and GAMs that they don't already provide separately?
3. How would your organization use this information?
4. In which Texas river basins and major aquifers would this information be most important?
5. What do you think are the major issues in linking, maintaining, and updating the WAMs and GAMs?
6. How would you allocate the State's limited funding, by percentage, between the following?
   a. Improving WAMs _____ %
   b. Improving GAMs _____ %
   c. Linking WAMs and GAMs _____ %
   d. Other _____ % . What would "other" be? __________

The survey was conducted by a senior HDR engineer contacting a stakeholder, describing the study, and asking the above questions. The list of stakeholders was divided among five senior engineers who personally know the individuals in an attempt to facilitate a high level of openness for an in-depth response. This survey was conducted in April and May 2006.

Starting with the list of about 65 individuals, HDR was able to contact and discuss the linking and questionnaire with 50 stakeholders. The number of respondents and their affiliation included: 10 River Authorities or Water Utilities, 9 Groundwater Conservation Districts, 8 Consultants, 5 Universities, 4 Attorneys, 4 State Agencies (TWDB not included), 4 Environmental Groups, 3 Cities, 2 Federal Agencies, and 1 Government Relations. The list of stakeholder affiliations is provided in Appendix B (Table 1). In compiling the results of the survey, multiple responses to questions were recorded individually. For example, a stakeholder was allowed to identify several uses of the linked models and issues, not just the most important one. All comments were treated with equal weight.

4.1.1 Summary of Responses to Questionnaire

To aid in studying the results, the stakeholder comments were compiled by question and by stakeholder. For purposes of summarizing the survey and results, the ten affiliations were classified into six categories. These categories included: Groundwater Conservation Districts, River Authorities, Consultants and Attorneys, State and Federal Agencies, Cities and Government Relations, and Environmental and Universities. From this, graphical summaries were prepared by question, by category of stakeholder, and frequency of particular comments and are included in Appendix B (Figures 1 through 6). For an overall view of the responses, the survey of respondents is considered to be a reasonable representation or sample of the water community in Texas. Accordingly, all of the responses are grouped together and summarized by percent of respondents voicing a common comment.

Question 1: Do you use results from a WAM or a GAM? If so, who makes the runs? How are the results used?

> The survey indicates a wide use of the WAMs and GAMs. For the WAM, over 80 percent of the state and federal agencies, river authorities, consultants and attorneys, cities and water utility, and governmental relations categories use the WAM. For the GAM, half or more stakeholders in all categories except river authorities are users of the models. Overall, considerably more of the stakeholders rely on staff and their consultants than state agencies to make the model runs.
>
> Usage of the WAMs across the categories is reasonably uniform except for the groundwater districts and environmental/university categories which were much lower. The greatest use was shown to be for surface water permits and challenges which are followed by planning. GAM usage was concentrated to the groundwater district categories with most of the usages for planning and management .

Question 2: What new information do you expect from a linked WAM and GAM?

> The most common expectation is to define the impact of groundwater development on streamflow. The fairly common expectation is “None to Very Little” which was concentrated in the state and federal agencies, river authorities and groundwater districts. This “None or Very Little” expectation was most commonly expressed by stakeholders in the river authority category located in west and northeast Texas and the groundwater districts in the High Plains and Gulf Coast. Relatively strong expectations appear to be held by the university and environmental groups for addressing the impact of

groundwater development on streamflow and the impact of streamflow development on groundwater recharge. Other than impact of groundwater development on streamflow, the survey did not indicate any widespread or high expectations for new information from a linked model.

Question 3: How would you use information from a linked WAM and GAM?

Of interest, there are few common uses in any of the categories that were above about one-third. Though limited to one or two categories of stakeholders, the greatest uses appeared to be environmental flows, water planning, and surface water availability.

These results show that other than surface water availability, there was not an overall central use. Instead, the ten common uses were identified by 10 to 25 percent of the stakeholders. The fifth most common response (about one-fifth) was “None to Very Little”.

Question 4: Which river basins and aquifers are most important?

For river basins, the Guadalupe and San Antonio were most commonly mentioned, followed rather closely by the Nueces River Basin. The Colorado River basin was also identified rather often.

For aquifers, the Edwards-San Antonio was the most common and covered most categories of stakeholders, except for groundwater districts. The Carrizo-Wilcox is also commonly mentioned as being rather important.

Question 5: What do you expect to be the major issues?

With comments generally focused on specific topics, the summary was grouped into WAM, GAM, and linked WAM-GAM issues. For the WAM, few of the respondents expected that there would be significant issues. For the issues that were identified, accuracy and integrity of results were the most common.

For the GAM, there appears to be considerable skepticism about the accuracy of calibration and integrity of results, with at least 30 percent of the respondents in all the categories, except for environmental and universities. Another common concern is the lack of data to define relationships between streams and aquifers.

As shown in Figure 4-1 summarizing survey results regarding major issues in linking WAM and GAM, a much larger percentage of the stakeholders expressed concern about the GAM than the WAM. More specifically, the most common GAM concerns were: accuracy of calibration/integrity of results (34%) and lack of SW/GW interaction data (30%). When considering the issues of a linked version, the major concerns were: updates and accuracy (44%), accuracy and integrity of results (42%), and different modeling concepts (34%).

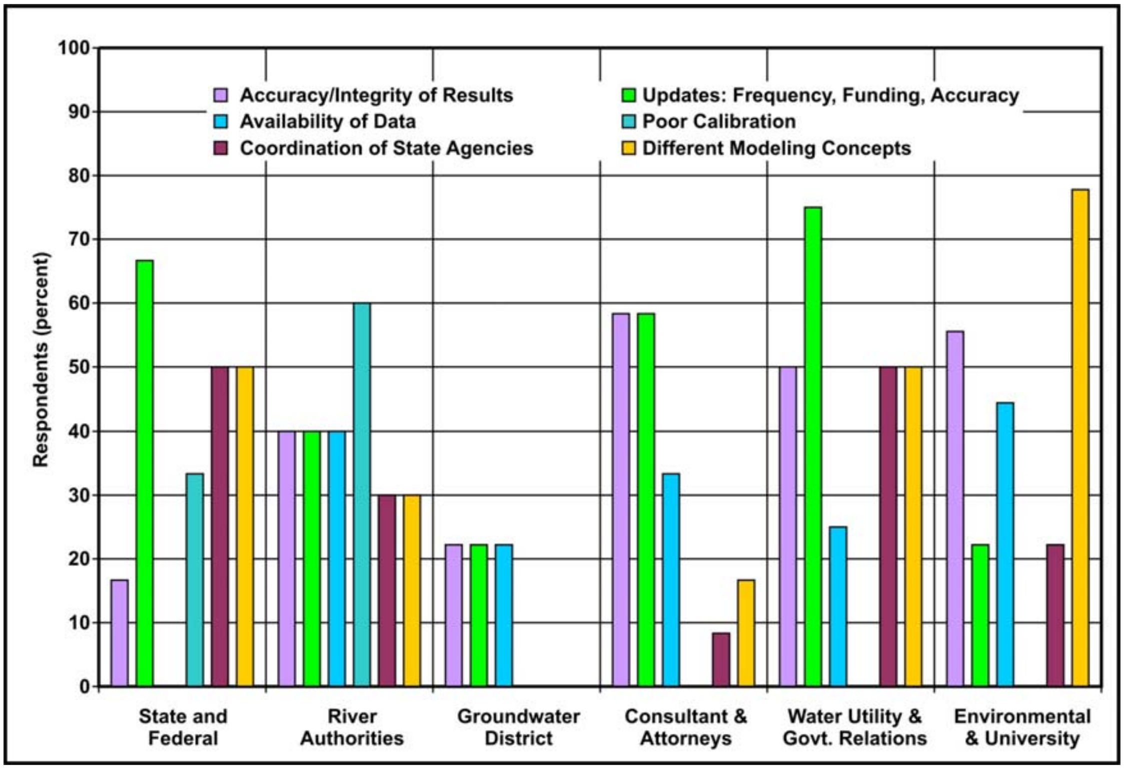

Figure 4-1. Major Issues Expected in Linking WAM and GAM Based on Survey Results

Question 6: What are the recommended allocations of available funds?

The responses were summarized into four groups, including improving WAMs, improving GAMs, linking the WAMs and GAMs, and "other", which were mostly related to data collection.

Key points of interest for these four groups include:

- *Other (data collection):* About 10 percent recommend all of the available funding go to data collection. Overall, about a fourth of the responses suggest a fourth or more of available funding go to data collection,
- *Linking WAMs-GAMs:* The overall level of interest in linking the WAMs and GAMs was lower than the other three activities,
- *Improving GAMs:* Except for a few stakeholders, improving the GAMs received the highest overall support for available funding, and
- *Improving WAMs:* About 40 percent recommended at least 30 percent of the funding go to improving the WAMs.

Finally, an overall funding priority is calculated by summing the recommended percentage for each of the four groups plus No Opinion and calculating an overall average. As shown in Figures 4-2 and 4-3, "Other, mostly data collection" has the highest funding request with 29 percent. The lowest funding request, not considering No

Opinion, is in linking the WAMs and GAMs with about 13 percent. Improving the GAMs and improving the WAMs had 27 and 24 percent, respectively.

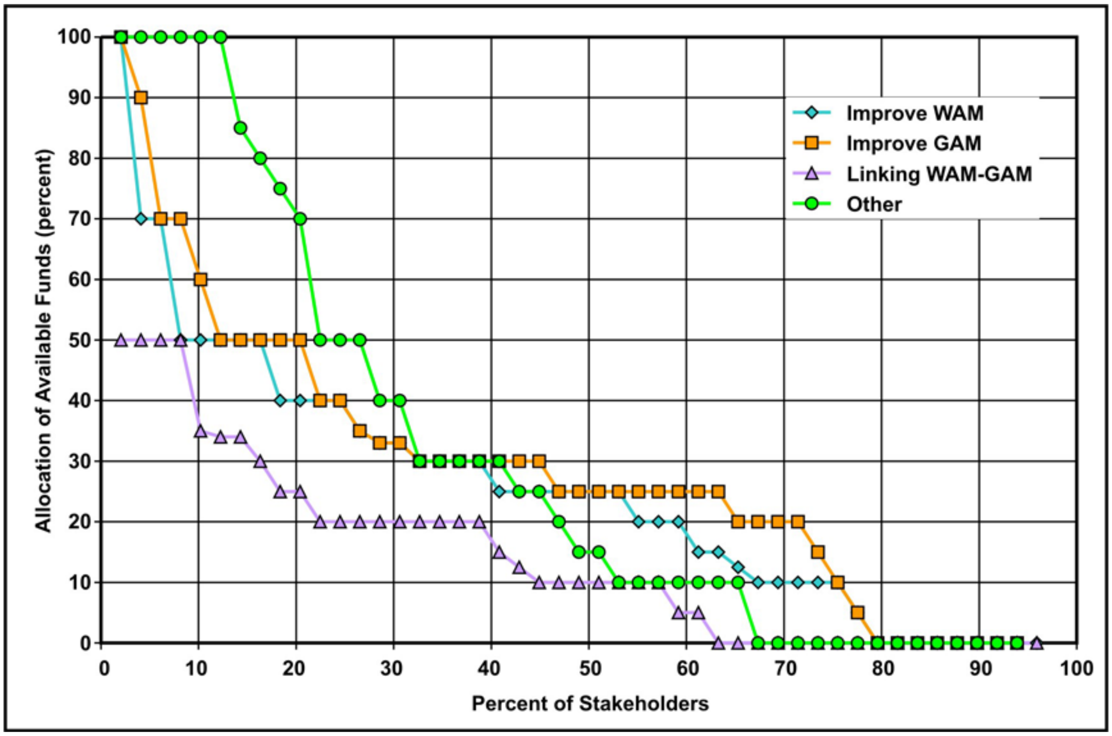

Figure 4-2. Recommended Allocation of Available Funds by Stakeholders

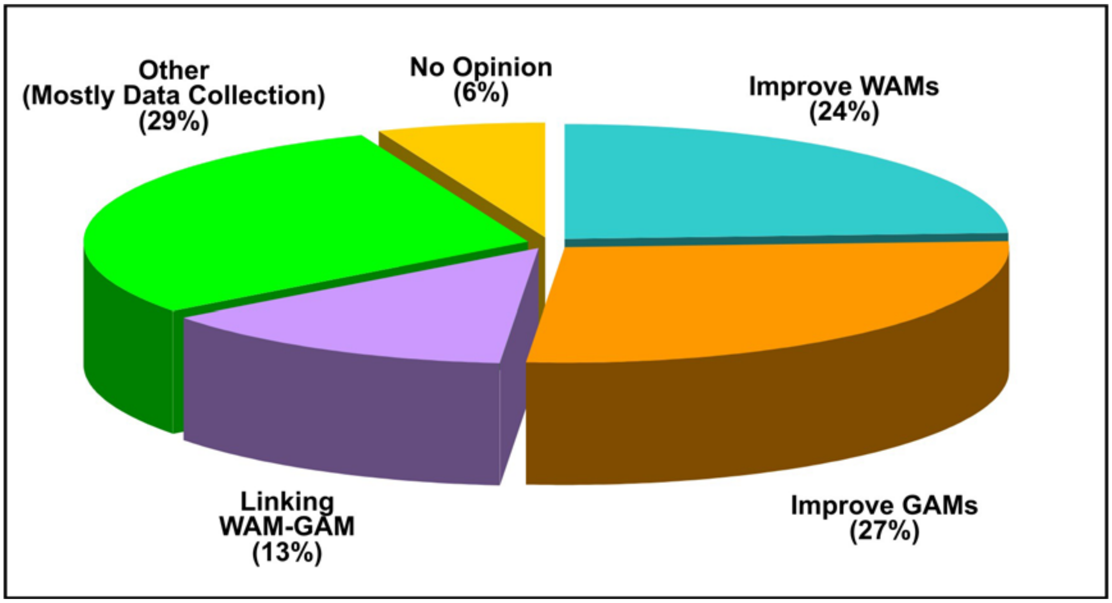

Figure 4-3. Overall Recommended Allocation of Available Funds

4.1.2 Overall Conclusion from Survey

The results of the survey indicate that the water community believes that improving the individual WAMs and GAMs should be given priority over linking the models. This is due mostly to the perception that (1) the information gained from linking the existing models is not as important as the information the two models provide independently, and (2) any additional information gained from linking them would have limited value due to current limitations on defining interactions between groundwater and surface water.

4.2 Options for Continuation of Contract

After completion of Tasks 1 and 2, representatives from the Texas Water Development Board (TWDB) and the HDR Team met on May 25, 2006 for a mid-course review (Task 3). Following extensive discussions of the survey results depicting the perceptions of the general Texas water community toward the WAMs and GAMs, the conceptual basis for developing and applying the WAMs and GAMs were described in order for the attendees to gain an understanding of the similarities and differences between the WAMs and GAMs, both in how the models were developed and how they are applied. The discussions included avenues through which the models might be able to interact (be linked) and potential strengths and weaknesses of each linkage pathway. On the basis of the discussions, HDR offered four options for moving forward, which are described in more detail in Appendix C. Briefly, these options were:

Option 1. Document fully the considerations as briefly discussed above in a final report, but do not pursue a linked model at this time based upon recognition that: (1) the two models are developed and operated with different paradigms, spatial scales, and temporal scales; (2) information is limited with which to describe groundwater-surface water interactions accurately; and (3) linkage of the two models would provide little additional information that the two models don't already provide separately. Option 1 includes a recommendation that linkage of the two models not be pursued at this time and that the State's resources be directed towards improving the WAMs and GAMs and collecting data such that groundwater-surface water interactions might be better defined in the future.

Option 2. Complete the discussion described in Option 1, but also develop a hypothetical situation using greatly simplified GAM and WAM configurations by which the mechanisms for linking the two can be demonstrated. Perform sensitivity analyses of various parameters in the two hypothetical models that relate to groundwater-surface water interactions, and document these results in the final summary report.

Option 3. Complete the discussion described in Option 1 and perform a limited case study using the Hill Country GAM and the GSA WAM to demonstrate the mechanisms by which the models can be linked and the differences in surface water availability that might result. This is essentially what is identified in the original scope of work for this project.

Option 4. Complete the discussions described in Option 1 and perform a limited case study using a combination of GAMs and one WAM that will more fully demonstrate the mechanisms by which the models may be linked, and also better demonstrate the magnitude of effects that incorporating a linked analysis might have on surface water supplies.

4.3 Selection of Option

On the basis of this information and considering the effort and limitations of the four options, the TWDB requested[1] that HDR complete this research contract with Option 1 to fully document the considerations but do not pursue a linked WAM and GAM model. Option 1 was selected based on the technical considerations described previously and the feedback obtained from the stakeholder survey. A linked WAM and GAM can still be pursued at some future time.

[1] Email from Yujuin Yang (TWDB) to David Dunn (HDR) on August 28, 2006.

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Section 5
Recommendations

5.1 Applications for Linked Models

Based on the survey discussed earlier, the most anticipated application of the linked models would be to assess the impact of groundwater development on streamflows, especially during low flow or drought conditions. In this case, a GAM would simulate a projected future pumping scenario of a well field and calculate the amount, location, and change in aquifer discharge to streams or springs and/or stream losses to the aquifer. Depending upon the settings, a well field may reduce streamflow gains over time, may change the stream from a gaining condition to a losing condition, or may increase streamflow losses. In all these cases, a GAM is capable of making these calculations. The model linkage would pass these baseflow changes to the WAM. The WAM would then calculate the reliability of the surface water rights in consideration of the well field for some future condition.

An indirect benefit of the linkage is to promote an awareness of surface water-groundwater issues in an attempt to quantify stream/aquifer interactions. As a result, understandings can be used to determine the overall importance of the interaction of streams and aquifers and where and when the interactions are important.

An application of linked models to assess the impact of surface water projects on groundwater availability seems to have very little, if any, potential. For example, a new upstream reservoir probably would reduce downstream flows and lower stream stages. A GAM simulation is not expected to be sensitive to the duration of the changes and/or the magnitude of lower stages.

In an assessment of conjunctive water use projects, such as using surface water when streamflows are at normal or higher conditions and groundwater during drought conditions, using linked models seems to have limited potential. These limitations are related to temporal and spatial scales and the insensitivity of aquifer conditions to temporary and relatively minor changes in stream stages.

Finally, there is the inherent conceptual difference in information presented by GAMs and WAMs, since a GAM produces a future, transient response, and a WAM is a repeat of historical hydrologic conditions with changes in water management superimposed on these conditions. So, a direct application of a WAM would not show gradual changes in the reliability of surface water supplies as a groundwater development project matures.

5.2 Future Model Revisions and Linkages

In the consideration of future revisions and linkages, several levels of effort are considered, including

- A complete redesign of the models to be suitable for meeting their current applications plus linking for new applications. This would be a major undertaking to develop a consensus on the objectives of the simulations and what is an acceptable format of the results. Such a program to rethink the WAMs and GAMs could easily take a decade and tens of millions of dollars. (Not Recommended)
- Focus on improving the utility, reliability, confidence, and standardization of the current models, especially the GAMs, in the next several years. Then, reconsider the linking of the two models in a structured manner. (Recommended)
- Support dialogue between the WAM and GAM modeling groups in an attempt to understand the information needs of the other, to develop innovative means of extracting results from one model for use in the other model, and restructuring traditional model runs to be more similar in concept. Potential forums for this dialogue include the development of the Regional Water Plans and determining the amount of manageable available groundwater in the Groundwater Management Areas. (Recommended)
- On a case by case basis, consider the water information need and look for means of utilizing the results from one model in the other model. Initially, this would be an informal 'passive' linkage where, for example, the reduced streamflows caused by a well field that was calculated by a GAM could be used to adjust flows (flow adjustments file) in a WAM simulation. (Recommended)

5.3 Model Improvements

5.3.1 WAMs

5.3.1.1 Update for Current Period of Record

One of the key elements of a WAM model run is the calculation of naturalized flows which are based on historical measured and estimated streamflows, diversion, return flows, and reservoir operations. The period of record for each WAM is presented in Table 5-1. Since development of the WAMs, additional streamflow data are available to suggest a new drought period of record in many areas of the State. Updating of the period of record to include this additional drought information would increase the reliability of the results.

Table 5-1
WAM — Periods of Record

WAM Model	Period of Record
Guadalupe and San Antonio	1934-89
Brazos and San Jacinto-Brazos Coastal	1940-97
Nueces	1934-96
Canadian	1948-98
Red	1948-98
Sulphur	1940-96
Cypress	1948-98
Sabine	1940-98
Neches	1940-96
Neches-Trinity Coastal	1940-96
Trinity	1940-96
Trinity-San Jacinto Coastal	1940-96
San Jacinto	1940-96
Colorado and Brazos-Colorado Coastal	1940-98
Colorado-Lavaca Coastal	1940-96
Lavaca	1940-96
Lavaca-Guadalupe Coastal	1940-96
San Antonio-Nueces Coastal	1948-98
Lower Nueces-Rio Grande	1948-98
Upper Nueces-Rio Grande	1948-98
Rio Grande	1940-00

In the update of calculated naturalized flows at control points, most all the values have to be estimated from relatively few streamgaging records. There is an opportunity to revisit the methods used to estimate flow values at ungaged control points. Research should be conducted and guidelines developed to provide the most appropriate and accurate means of estimating the streamflow at these ungaged locations. Also, flexibility and latitude should be included in the minor redesigns and updates to accommodate adjustments to streamflows that may be estimated by a GAM for certain scenarios.

5.3.1.2 Consistent Representation of Streamflow Gains/Losses

With the diversity of stream settings across Texas and a relatively large number of teams developing WAMs in a relatively short period, different approaches were used to represent surface water-groundwater interaction between two control points as shown in Table 5-2. When the interaction was represented explicitly, the channel loss factors value was static. In other words, the flux between the stream and aquifer was one direction and fixed, and did not consider seasonal conditions nor wet and dry years.

Table 5-2.
List of WAMs and Methods Used to Simulate Groundwater/Surface Water Interactions

River Basin(s)	*Simulates Groundwater/Surface Water Interactions*	
	Channel Losses Included?	*Flow Adjustment File Used?*
Guadalupe and San Antonio	Yes, throughout	Yes, Edwards Aquifer springflows
Brazos and San Jacinto-Brazos Coastal	Yes, throughout	No
Nueces	Yes, throughout	No
Canadian	Yes, throughout	No
Red	Yes, throughout	Yes
Sulphur	No	No
Cypress	No	No
Sabine	No	No
Neches	No	No
Neches-Trinity Coastal	No	No
Trinity	Yes, in limited reaches	No
Trinity-San Jacinto Coastal	No	No
San Jacinto	No	No
Colorado and Brazos-Colorado Coastal	Yes, in limited reaches	Yes
Colorado-Lavaca Coastal	No	Yes
Lavaca	No	No
Lavaca-Guadalupe Coastal	No	Yes
San Antonio-Nueces Coastal	Yes, throughout	No
Lower Nueces-Rio Grande	Yes, throughout	No
Upper Nueces-Rio Grande	Yes, throughout	No
Rio Grande	Yes, throughout	Yes

The recommended approach to the development of a consistent representation of streamflow gains and losses is to first conduct research on potential methods, available data, means of accommodating estimates from GAM simulations, and range of stream-aquifer settings.

5.3.2 GAMs

5.3.2.1 Consistent Representation of Hydraulically Connected Streams, Springs, Wetlands and Reservoirs

The computer program (MODFLOW) used in the GAMs allows surface water-groundwater interaction to be depicted in four alternative packages. Each of the packages uses the difference between the stage in the surface water body and head in the aquifer, and hydraulic flow properties of the subsurface between the surface water body and the aquifer. These packages include:

- *River:* Assumes the river can accommodate any rate of stream losses and gains, and the river stage either doesn't change with time or can be specified,
- *Stream:* Calculates a running balance of flow along the stream reaches and can calculate stream stage. Stream losses can only occur if there is sufficient flow in the stream,
- *Drain:* Allows water to only flow out of the aquifer, and
- *Reservoir:* Conceptually similar to the River Package

Table 5-3 shows the packages used in each GAM to simulate groundwater-surface water interactions, and which GAMS use the Evapotranspiration (ET) Package. Before updates to GAMs are undertaken, a guidance document should be developed that provides information regarding which package should be used for a range of stream, reservoir, spring, and wetland settings. Included in the guidance should be consideration of using the ET Package to represent wetlands.

Table 5-3.
List of GAMs with Methods Used to Represent Streams, Springs, and Reservoirs

GAM	Groundwater/Surface Water Interaction			ET
	Rivers/Streams	Springs	Lakes	
Carrizo-Wilcox/QCSP (Central)	The Stream Package was used to simulate streams and rivers.	The Drain Package was used to represent springs.	Reservoir Package was used to model reservoirs/lakes. Reservoirs are in the Transient model only.	✓
Carrizo-Wilcox/QCSP (Northern)	The Stream Package was used to simulate streams and rivers.	The Drain Package was used to represent springs.	Reservoir Package was used to model reservoirs/lakes. Reservoirs are in the Transient model only.	✓
Carrizo-Wilcox/QCSP (Southern)	The Stream Package was used to simulate streams and rivers.	The Drain Package was used to represent springs.	Reservoir Package was used to model reservoirs/lakes. Reservoirs are in the Transient model only.	✓
Edwards (Barton Springs Segment)	—	The Drain Package was used to represent springs.	—	—
Edwards (Northern)	Drains were used to simulate groundwater discharge to seeps, spring, and perennial streams.		—	—
Edwards (San Antonio Segment)	The River Package was used to simulate streams and rivers.	The Drain Package was used to represent springs.	—	—
Edwards-Trinity Plateau	The Drain Package was used to represent streams	The Drain Package was used to represent springs.	—	—
Gulf Coast (Central)	The Stream Package was used to simulate streams and rivers.	The Drain Package was used to represent seepage to springs and wetlands	The River Package was used to represent lakes of significant size (> 1mi2.)	✓
Gulf Coast (Northern)	The General Head Boundary Package was used to calculate flow between the stream and the aquifer.	—	—	—
Gulf Coast (Southern)	The Stream Package was used to simulate streams and rivers.	—	—	✓
Hueco Bolson	The Stream Package was used to simulate streams and rivers.	The Drain Package was used to represent the change from nonirrigated (undrained) to irrigated (drained) agricultural conditions.		✓
Lipan	The Stream Package was used to simulate streams, rivers, and springs. The Drain Package was used to simulate the North Concho River.		The Reservoir Package was used to model Twin Buttes, O.C. Fisher Reservoir, and Lake Nasworthy.	✓
Ogallala (Northern)	The River Package was used to simulate streams and rivers.	The Drain Package was used to represent springs.		—
Ogallala (Southern)	There are no perennial rivers or streams within the study area.	The Drain Package was used to represent springs along the margins of each of the salt lakes.	—	—
Seymour & Blaine	The Stream Package was used to simulate streams and rivers.	The Drain Package was used to represent springs.	—	✓
Trinity (Northern) & Woodbine	The Stream Package was used to simulate streams.	—	River Package was used to simulate reservoirs/lakes	✓
Trinity (Hill Country)	The Drain Package was used to represent rivers and streams		Constant head cells were used to represent lakes	—
West Texas Bolsons and Igneous	The Drain Package was used to represent streams and springs.		-	✓

5.3.2.2 Consistent Representation of ET

A summary of the application of the ET Package in the GAMs has been prepared by Scanlon.[1] Overall, about half of the GAMs represent water losses to riparian vegetation with the ET Package. For these GAMs, the root or extinction depth ranged from 0 to 47 ft, and the overall water losses (percent outflow) to the ET component ranged from 2 to 96 percent, as shown in Table 5-4. The quantification of surface water-groundwater interaction is a considerable challenge because model cells with ET usually overlap cells with streams, rivers, springs, or wetlands, and the observed or measured values of ET and baseflow for model calibration are very limited and highly variable. Thus, the modeler has great latitude in partitioning the water lost from the aquifer along a stream between ET and baseflow. Even with great care, the highly variable nature of ET can cause results to be poorly representative of actual conditions.

In moving forward in the periodic updating of the GAMs, a guidance document is recommended to identify conditions for which the ET Package should be used and in estimating maximum ET rates and extinction depths. It should also include guidance on model calibration considerations to guide modelers' attempts to partition the water flux in overlapping ET and stream cells.

5.3.2.3 Consistent Representation of Recharge

In the conceptualization of a GAM, the method and assumptions used to estimate recharge can strongly influence surface water-groundwater interactions. For example, a modeler may use net recharge which represents only the amount of water that reaches the main body of an aquifer. This representation generally eliminates the need to consider losses to ET and short-term losses to streams in the GAM model. Also, many GAMs have been developed that estimate recharge as a fraction of precipitation. However, this simplified assumption of the hydrologic process does not consider the fact that little or no recharge occurs in dry or drought conditions, and most of the recharge occurs during extended wet conditions, especially in the winter.

[1] Scanlon, B., Keese, K., Bonal, N., Deeds, N., Kelley, V., and Litvak, M. December 2005, Evapotranspiration Estimates with Emphasis on Groundwater Evapotranspiration in Texas: Prepared for Texas Water Development Board. http://www.twdb.state.tx.us/gam/resources/BEG_INTERA_ET_report.pdf

Table 5-4.
Summary of Groundwater ET in Current GAMs

Aquifer		***Sensitivity Analyses***	***ET Package***	***Percent Outflow***	***Root Depth or Extinction Depth (m)***	***Root Depth or Extinction Depth (ft)***
Major Aquifer						
Carrizo-Wilcox	Southern	No	Yes	31	mean 1.8	mean 6
	Central	Yes	Yes	60	4.6	15
	Northern	No	Yes	28	0 to 2.1	0 to 7
Edwards	Northern	—	No			
	Barton Springs	—	No			
	San Antonio	—	No			
Edwards-Trinity Plateau	—	—	No			
Gulf Coast	Northern	—	No			
	Central	No	Yes	3	1.5 to 9.1	5 to 30
	Southern	Yes	Yes	2	9.1	30
Hueco & Mesilla	Hueco Bolson		Yes	41	4.6	15
	Mesilla Bolson		Yes			
Pecos	—	—	No			
Ogallala	South	—	No			
	North	—	No			
Seymour	—	No	Yes	31	median 1.8	median 6
Trinity	Northern	Yes	Yes	96	2.1 to 5.8	7 to 19
	Hill Country	—	No			
Minor Aquifers						
Blaine (Modeled w/ Seymour)	—	No	Yes	31	0.3 to 2.1	1 to 7
Lipan	—	Yes	Yes	59	2.1 to 14.3	6.9 to 47
Queen City & Sparta (w/ Carrizo-Wilcox)	Southern	No	Yes	8	0.3 to 2.4	1 to 8
	Central	No	Yes	32	0.3 to 2.4	1 to 8
	Northern	No	Yes	48	0.3 to 2.4	1 to 8
West Texas Bolsons & Igneous	—	No	Yes	15	3.0	10
Woodbine (w/ Trinity)	—	Yes	Yes	96	2.1 to 5.8	7 to 19

Source: "Evapotranspiration Estimates with Emphasis on Groundwater Evapotranspiration in Texas, 2005.

Recharge to the Edwards Aquifer in the San Antonio and Barton Springs GAMs has historically been calculated on the basis of a contributing watershed analysis, which utilizes streamflow and precipitation data.

Recharge to the Northern Gulf Coast GAM is calculated as a head-dependent flux. For this representation, the water table near the land surface is assumed to be fixed and persistent over time, and the magnitude of the recharge increases as the water level in the top active layer declines. This method requires careful review to make sure the values are realistic.

In summary, to reasonably quantify the surface water-groundwater interaction that would be expected in linked WAMs and GAMs, research also needs to be conducted and guidelines prepared on the most appropriate means of estimating recharge in the GAMs. Two considerations needed in the preparation of the guidelines include variability of recharge on the basis of antecedent conditions and the purpose of the model's application.

5.4 Analyses of Available Data to Estimate Streamflow Gains and Losses

Historical estimates of streamflow gains and losses are needed for calibration of the GAMs and to refine the definition of streamflow for the WAMs. Developing these estimates is challenging for a number of reasons, including a scarcity of streamgages, relatively few streamflow gain/loss surveys, complexity of hydrologic conditions, riparian vegetation, reservoir operations, changing conditions, and many stream diversions and returns. Based on a review of some of the GAMs, the levels of effort and methods used to develop baseflow calibration targets are highly variable. To promote consistency of linked water availability models, there is a need for a common definition and methods to calculate or estimate streamflow gains and losses. Developing a more complete understanding and consistent guidelines will require a comprehensive effort because of multiple and overlapping streams and aquifer systems. This is in contrast to GAM development, where GAM was developed with little or no consideration of approaches used for other GAMs and no consideration of possible use with a WAM.

The recommended approach to estimating streamflow gains and losses involves at least two phases. The first is to develop the methods and guidelines for simulating streamflow gains and losses in both GAMs and WAMs, and the second is to perform the analyses by aquifer system and/or river basin.

5.5 Target Streams and Aquifer Systems

Recognizing that the efforts to improve the WAMs and GAMs and develop a suitable linkage are huge undertakings that will have to be accomplished in increments, recommendations are offered on dividing the State in areas and scheduling the development of information that is needed for model improvements and linkage development. In the development of these recommendations consideration is given to:

- Areas where the overall portion of the stream and aquifer water budget related to surface water-groundwater interaction is relatively great,
- Areas where the overall potential for critical in-stream flow conditions depends largely on baseflow, and
- Areas with the greatest likelihood of new and substantial groundwater development in the near future.

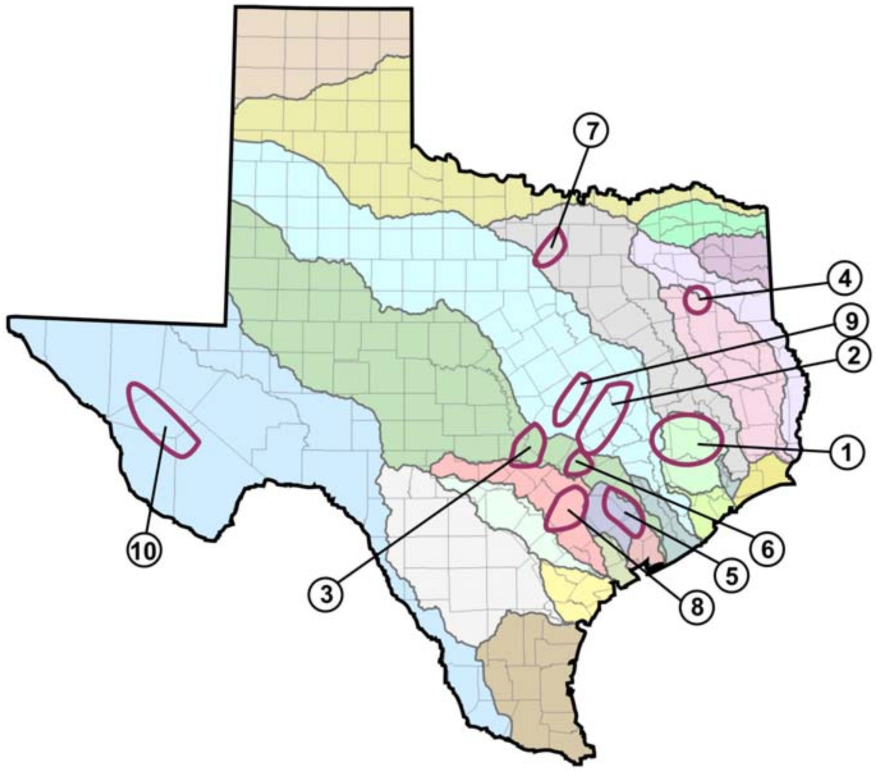
Figure 5-1 shows selected targeted areas for improving surface water and groundwater definition in WAMs and GAMs.

5.6 Collection of Additional Data

5.6.1 Systematic Baseflow Surveys

To get to a scale needed by a GAM to simulate streams crossing aquifer outcrops, localized baseflow surveys along stream reaches a few miles or tens of miles in length are needed. These surveys would need to account for tributary inflows, streamflow diversions, and returns in addition to measured streamflow at given intervals, as shown in Figure 5-2. In many cases these surveys are somewhat difficult to perform because of recent runoff events, lack of access to the stream at desired locations, and the operation of numerous diversions and discharges. To complicate matters, surveys during a wide range of hydrologic and climatic conditions are needed to define baseflow variability attributable to different flow regimes.

Even though the greatest interest in surface water-groundwater interaction is typically focused on the outcrop of major aquifers, interaction in areas of minor aquifers has the potential for being substantial. For example, a secondary impact can occur where heavy pumping in a relatively deep major aquifer will induce downward leakage from an overlying minor aquifer which may lower groundwater levels and reduce its discharge to a stream. This cascading of effects can become quite complicated and nearly impossible to quantify directly. As a result, the baseflow surveys should not be restricted to just the outcrop of major aquifers.



Ranking	Area	GAM	WAM	Comment
1	Montgomery County	Northern Gulf Coast	San Jacinto	This is an area with a great increase in water demands, lots of "live" streams, and an aquifer showing some stress. Unknown instream flow concerns.
2	Lee, Milam, & Robertson Counties	Central Sparta, Queen City, Carrizo-Wilcox	Brazos	This is a target area for large, regional well fields. There is also large, local opposition to exports. Some "live" streams in area.
3	Hays, Blanco, Travis Counties	Hill Country Trinity	Colorado	Great growth in local GW supplies from a rather limited GW system. Few "live" streams. Industry important to regional springs (Barton & San Marcos).
4	Smith County	Northern Central Sparta, Queen City, Carrizo-Wilcox	Neches	There is a considerable amount of historical drawdown in the Tyler area. Fairly well isolated to the headwaters of the Neches River and its many tributaries.
5	Colorado, Wharton, & Lavaca Counties	Either Northern or Central Gulf Coast	Lavaca	The focused area of interest is the Lower Colorado Water Project. Substantial groundwater pumping for irrigation exists.
6	Bastrop County	Central Sparta, Queen City, Carrizo-Wilcox	Colorado	High growth area, local controverseries, and endangered species in Lost Pines area.
7	Parker & Wise Counties	Northern Trinity & Woodbine	Trinity	High growth area with a rather limited groundwater resource. Few "live" streams.
8	Gonzales County	Central or Southern Sparta, Queen City, Carrizo-Wilcox	Guadalupe-Blanco	Target area for regional well fields
9	Williamson & Bell Counties	Northern Trinity & Woodbine, & Northern Edwards	Brazos	A high growth area with limited water resources.
10	Presido & Jeff Davis Counties	West Texas Igneous and Bolsons	Rio Grande	The Valentine area is a target for regional well fields. Few "live" streams and springs. Considerable local and regional opposition.

Figure 5-1. Areas to Target for Improving Definition of Groundwater-Surface Water Interaction

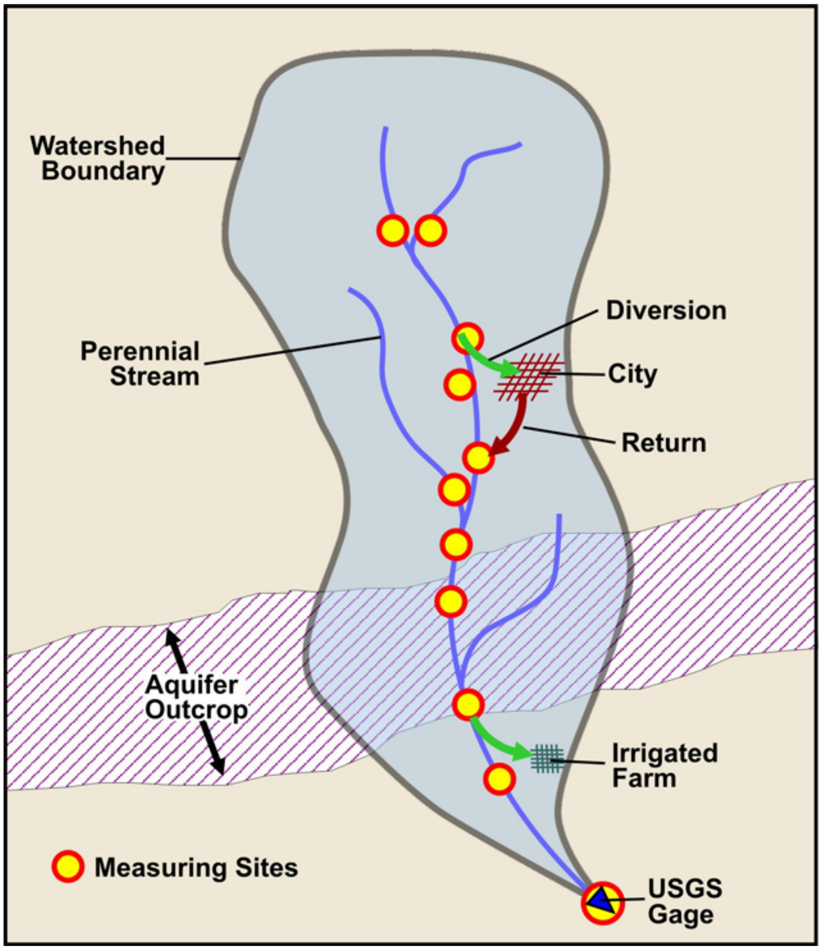


Figure 5-2. Components of a Typical Baseflow Survey

In the design of baseflow surveys, scheduling the surveys during the winter when ET, diversions and returns are at an annual minimum provides a significant advantage because of a simpler water budget. In addition, these surveys would coincide with groundwater level surveys which are also typically performed in the winter. Finally, selecting stream reaches with continuous streamflow gages provides information critical to defining the hydrologic conditions during a survey and, if needed, providing information for adjustments to individual measurements.

An excellent example of a comprehensive study to estimate groundwater recharge and surface water-groundwater interaction is an ongoing (2006) study in the San Antonio River basin. This five-year study is being conducted by the U.S. Geological Survey (USGS) with primary funding by the San Antonio River Authority, Evergreen Underground Water Conservation District, and the Goliad County Groundwater Conservation District. Major components of the study include: installing additional streamflow gages, conducting quarterly or more frequent baseflow surveys, installing several continuous water level recorders in wells, conducting surveys of groundwater levels, collecting and analyzing water samples for dating and tracing water quality, and developing a watershed model (HSPF) to estimate groundwater recharge.

5.6.2 Localized Measurements of Groundwater Levels and Stream Stages

In the GAMs, surface water-groundwater interactions are calculated on the basis of the stage level in the surface water body and groundwater levels in the underlying aquifer. To better define these relationships, local data are needed. A comprehensive network of monitoring stations would consist of a stage recorder for the stream and water level recorders in several wells that are screened at different depths, as shown in Figure 5-3. In order to define the expected variability, several such networks would be needed. A less comprehensive study could include a data collection network consisting of a stream gage that records stage measurements and recording aquifer water levels at several nearby, relatively shallow wells. The stage and water levels would be measured periodically and water level maps drawn so that an estimate of the groundwater level at the stream site could be made. If this research is conclusive, the data collection program should be comprehensive enough to have transfer value to other sites. In any case, scaling issues must be addressed between the local field site and representative values in a one-square mile model cell and the model layers.

5.6.3 Springflow and Baseflow in Small Tributaries

Often, it seems that the primary interest in surface water-groundwater interaction is on major streams and major springs. However, local springs and baseflows in small tributaries are very important and probably will be the first ones to be noticeably affected by water projects, especially groundwater development. Although they can be numerous, data collection on smaller tributaries is simpler than on major streams and access can often be gained by county roads.

The network of sites and the data collection protocol can be defined by local, regional, or State agencies. Often, the USGS can provide the field and data management services, but require a substantial part of the funding to be paid by cooperators. A second possibility is regional agencies (river authorities) to add and integrate this data collection into their other field

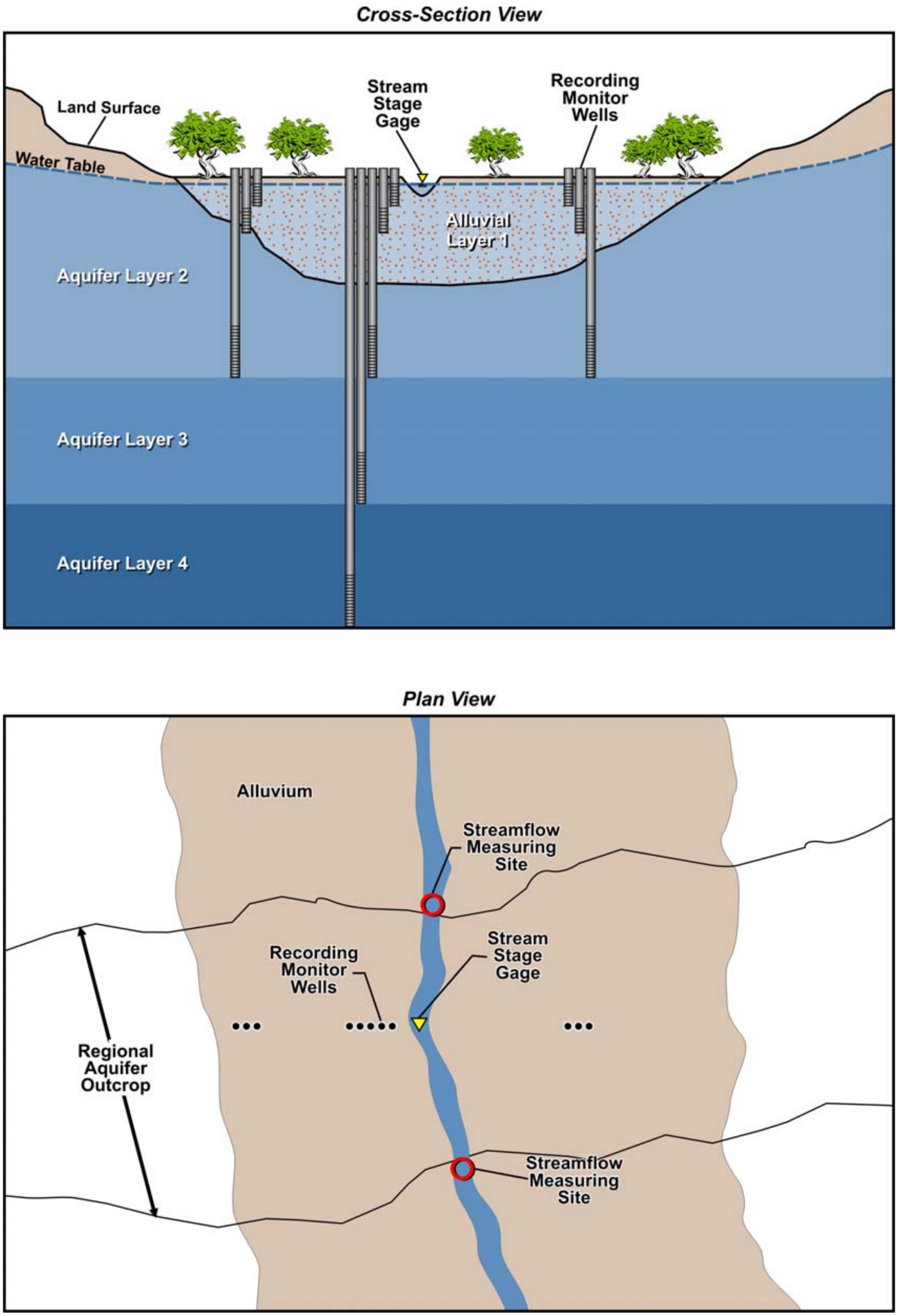


Figure 5-3. Data Collection Parameters for Stream/Aquifer Representation in GAMs

activities. A third possibility is for groundwater conservation districts with a data collection network of wells to add this data collection program to their field and data management activities. If an agency lacks the skills and equipment to measure streamflow, photos can taken to provide documentation for specialists to make discharge estimates at a later date, or for comparative purposes.

5.6.4 Improve Estimation of ET Extinction Depths

With a goal of improving the accuracy of partitioning the aquifer's discharge along a stream between baseflow and ET, the parameter with the poorest definition is the extinction depth, which is equivalent to plant rooting depths. Scanlon and others (2005) recommends: (1) using a MODFLOW ET Package (ETS1) where the zone between a maximum and zero ET rate can be subdivided, (2) setting the extinction depth at the combined depth of root zone and thickness of capillary fringe, (3) establishing a root zone depth and an ET rate based on vegetation type, and (4) defining a depth to the top of the capillary zone for the maximum ET rate. In a local, fine scale model (cell dimensions of a few tens of feet), the vegetation and soils could be very accurately mapped and would provide the most technically sound results. However, in the regional, coarse scale GAM models, accurately defining the required parameters and selecting a representative value is an overwhelming challenge because of the wide variations in a stream valley. The likely outcome may result in fitting a calibration by trial and error to an even more complex model.

HDR recommends the use of the simpler ET Package in MODFLOW, which requires definition of only the extinction and maximum ET depths. In an effort to provide guidance on the selection of these depths, we suggest conducting research using existing data to select representative test plots for field scale research. It is desirable to choose a stream valley setting where an uplands area transitions into a heavily vegetated (riparian) zone near the stream that obviously draws water from the water table; and, where the extinction depth can be estimated with the development of detailed land surface and water table maps. Empirical plots of the depth to the water table and some definition of vegetation type should be used to define the extinction depth. This research would have to be conducted at a number of locations for quality assurance and to establish confidence prior to transferring to other settings.

Phreatophyte characteristics and occurrence varies widely across the state, and current vegetation mapping lacks the appropriate definition and data to be incorporated into a GAM. In order to more fully and accurately consider the impacts of phreatophyte populations on regional groundwater resources, a comprehensive study to map specific phreatophyte species across the state is recommended. This study should also include field studies correlating average root depth with phreatophyte species, soil characteristics, depth to groundwater, annual precipitation, age and other possible explanatory factors to more accurately include this information in GAM models. Application of these data in GAM simulations would differ during early calibration periods versus predictive simulations.

5.7 Investigate Alternative Models to Simulate Surface Water and Groundwater Interaction

If looking beyond the current formulation of the WAMs and GAMs is an alternative, a rather recent and promising development is the RiverWare software for which MODFLOW has been incorporated into the programming structure (Section 3.8). The framework design of RiverWare is similar to WRAP (a network of nodes at key locations in a stream system that are linked together), which makes the transition from a WRAP based surface water rights model to RiverWare worthy of further investigation.

In the meantime, State officials and consultants should routinely explore other ways to meet the challenge of conjunctively evaluating the management of surface water and groundwater resources when local situations necessitate an interactive surface water and groundwater modeling framework.

Section 6
Conclusions

While the basic concept of linking the WAMs and GAMs to facilitate a "handshaking" of surface water and groundwater interactions appears advantageous in principle, logistical and vastly different model structures make WAM-GAM linkage a challenging and time-intensive task. Furthermore, with an incomplete understanding of groundwater and surface water interactions for river basins and aquifer systems in Texas, such a linkage would have the potential for providing inaccurate results. Significant improvements to the WAMs and GAMs are necessary in order to develop a suitable and widely accepted linkage. Most importantly, a consistent approach and procedure is needed to represent streamflow gains and losses in the WAMs and GAMs. For the GAMs, a consistent representation of ET, recharge, and hydraulically connected water features such as streams, springs, wetlands, and reservoirs is needed to increase the confidence in the results. Surface water and groundwater interactions are poorly understood and data are limited in most areas, and would require a full literature review and extensive field reconnaissance, including baseflow surveys of major and minor tributaries, localized groundwater level monitoring, springflow measurements, and detailed study of vegetation along stream channels to develop better evapotranspiration estimates and extinction depth parameters. Overall, for a successful linkage of WAMs and GAMs to be maintained over time, the TCEQ and TWDB would need to coordinate model updates and maintenance activities, and determine a funding mechanism for such updates and model improvements and data collection activities to refine and verify these improvements.

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Appendix A
TWDB Linking WAMs and GAMs
Stakeholder Telephone Survey

TWDB Linking WAMs and GAMs
Stakeholder Telephone Survey

Date: ________________ HDR Contact: _______________

Stakeholder Name: _______________ Organization: _________________

Phone No.: _____________

The Texas Commission on Environmental Quality (TCEQ) and the Texas Water Development Board (TWDB) have developed the TCEQ Water Availability Models (WAMs) and the Groundwater Availability Models (GAMs) for each major river basin and aquifer in the State. TCEQ uses the WAMs to determine surface water available to existing and proposed water rights. The TWDB uses the GAMs to determine the effects of projected pumping conditions. Both sets of models are used for planning by regional water planning groups, groundwater districts, water suppliers, and consultants.

The TWDB has contracted with HDR to investigate the feasibility of linking the WAMs and GAMs and mechanisms by which they might be linked. We will also do a pilot study, which will consider issues associated with linking the Hill Country GAM and the Guadalupe-San Antonio WAM. We are obtaining input from stakeholders who might have an interest in this project.

1. Do you use data from a WAM or a GAM? *Yes____* *No____*

   1a. If yes, do you perform model runs in-house (or with outside consultants), or do you rely on the State or other agencies (GCDs)? *In-house____* *State/Agencies____*

   1b. How are the data used by your organization?

2. What new data or information would you expect to obtain from a linkage of WAMs and GAMs that they don't already provide separately?

Examples. A. Effects of surface water development on recharge.
B. Effects of GW development on streamflow or water availability.

3. How would your organization use this information?

4. In which Texas river basins and major aquifers would this information be most important?

5. What do you think are the major issues in linking, maintaining, and updating the WAMs and GAMs?

6. How would you allocate the State's limited funding, by percentage, between the following?
   a. Improving WAMs _____ %
   b. Improving GAMs _____ %
   c. Linking WAMs and GAMs _____ %
   d. Other _____ % . What would "other" be? ___________________________

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Appendix B
Linking the WAM and GAM Models: Results of Stakeholder Survey

Linking the WAM and GAM Models: Results of Stakeholder Survey

Prepared for:

TEXAS WATER DEVELOPMENT BOARD

Prepared by:

HDR | ONE COMPANY *Many Solutions*℠

June 2006

Linking the WAM and GAM Models: Results of Stakeholder Survey

June 2006

1. Introduction

At the onset of planning and developing a linkage of the (Surface) Water Availability Model (WAM) and the Groundwater Availability Model (GAM), the HDR Engineering, Inc. team (HDR) conducted a survey of stakeholders in the water community to find out their current uses, expectations for new information and uses of the linked models, concerns related to the linked models, and recommendations on future funding. This stakeholder survey was in the form of a questionnaire that consisted of the following six questions:

1. Do you use data from a WAM or a GAM?
   - 1a. If yes, do you perform model runs in-house (or with outside consultants), or do you rely on the State or other agencies (GCDs)?
   - 1b. How are the data used by your organization?
2. What new data or information would you expect to obtain from a linkage of WAMs and GAMs that they don't already provide separately?
3. How would your organization use this information?
4. In which Texas river basins and major aquifers would this information be most important?
5. What do you think are the major issues in linking, maintaining, and updating the WAMs and GAMs?
6. How would you allocate the State's limited funding, by percentage, between the following?
   - a. Improving WAMs _____ %
   - b. Improving GAMs _____ %
   - c. Linking WAMs and GAMs _____ %
   - d. Other _____ % . What would "other" be? __________

A list of target stakeholders consisted of about 65 individuals who are affiliated with river authorities, groundwater conservation districts, major cities, state agencies, federal agencies, law firms, environmental groups, and universities. The survey was conducted by a senior HDR engineer calling a stakeholder, describing the study, and asking the above questions. The list of stakeholders was divided among five senior engineers who personally know the individuals in an attempt to facilitate a high level of openness for an in-depth response. This survey was conducted in April and May 2006.

2. Results of the Survey

Starting with the list of about 65 individuals, HDR was able to contact and discuss the linking and questionnaire with 50 stakeholders. The number of respondents and their affiliation included: 10 River Authorities or Water Utilities, 9 Groundwater Conservation Districts, 8 Consultants, 5 Universities, 4 Attorneys, 4 State Agencies (TWDB not included), 4 Environmental Groups, 3 Cities, 2 Federal Agencies, and 1 Government Relations. The list of stakeholder's affiliations is provided in Table 1. In compiling the results of the survey, multiple responses to questions were recorded individually. For example, a stakeholder was allowed to identify several uses of the linked models and issues, not just the most important one. All comments were treated with equal weight.

2.1 By Stakeholder Category

To aid in studying the results, the stakeholder comments were compiled by question and by stakeholder. For purposes of summarizing the survey and results, the ten affiliations were classified into six categories. These categories included: Groundwater Conservation Districts, River Authorities, Consultants and Attorneys, State and Federal Agencies, Cities and Government Relations, and Environmental and Universities. From this, graphical summaries were prepared by question, by category of stakeholder, and frequency of particular comments. These summaries are presented in Figures 1 through 6 for the six questions.

Question 1: Do you use results from a WAM or a GAM? If so, who makes the runs? How are the results used?

The survey indicates a wide use of the WAMs and GAMs (Figure 1a and b). For the WAM, over 80 percent of the state and federal agencies, river authorities, consultants and attorneys, cities and water utility, and governmental relations categories use the WAM. For the GAM, half or more stakeholders in all categories except river authorities are users of the models. Overall, considerably more of the stakeholders rely on staff and their consultants than state agencies to make the model runs.

Usage of the WAMs across the categories is reasonably uniform except for the groundwater districts and environmental/university categories (Figure 1c). The greatest use was shown to be for surface water permits and challenges which is followed by planning. GAM usage was concentrated to the groundwater district categories with most of the usages for planning and management (Figure 1d).

Question 2: What new information do you expect from a linked WAM and GAM?

The most common expectation is to define the impact of groundwater development on streamflow (Figure 2). The fairly common expectation is “None to Very Little” which was concentrated in the state and federal agencies, river authorities and groundwater districts. This “None or Very Little” expectation was most commonly expressed by stakeholders in the river authority category located in west and northeast Texas and the groundwater districts in the High Plains and Gulf Coast. Relatively strong expectations appear to be held by the university and environmental groups for addressing the impact of groundwater development on streamflow and the impact of streamflow development on groundwater recharge. Other than impact of groundwater development on streamflow, the survey did not indicate any widespread or high expectations for new information from a linked model.

Question 3: How would you use information from a linked WAM and GAM?

Of interest, there are few common uses in any of the categories that were above about one-third (Figure 3a and 3b). Though limited to one or two categories of stakeholders, the greatest uses appeared to be environmental flows, water planning, and surface water availability.

Question 4: Which river basins and aquifers are most important?

For river basins, the Guadalupe and San Antonio were most commonly mentioned, followed rather closely by the Nueces River Basin (Figure 4a). The Colorado River basin was also identified rather often.

For aquifers, the Edwards-San Antonio was the most common and covered most categories of stakeholders, except for groundwater districts (Figure 4b). The Carrizo-Wilcox is also commonly mentioned as being rather important.

Question 5: What do you expect to be the major issues?

With comments generally focused on specific topics, the summary was grouped into WAM, GAM, and linked WAM-GAM issues. For the WAM, few of the respondents expected that there would be significant issues (Figure 6a). For the issues that were identified, accuracy and integrity of results were the most common.

For the GAM, there appears to be considerable skepticism about the accuracy of calibration and integrity of results, with at least 30 percent of the respondents in all the categories, except for environmental and universities (Figure 6b). Another common concern is the lack of data to define relationships between streams and aquifers.

For the linking of the WAM and GAM, common concerns were: accuracy and integrity of results (consultants and attorneys and environmental groups and universities), different modeling concepts (state and federal agencies, consultants and attorneys, water utilities, and environmental and universities), and updates including frequency, and funding and accuracy (state and federal agencies, river authorities, and water utilities) (Figure 5c and d). Other commonly mentioned concerns were availability of data.

Question 6: What are the recommended allocations of available funds?

The responses were summarized into four groups, including improving WAMs, improving GAMs, linking the WAMs and GAMs, and "other", which were mostly related to data collection.

In consideration of the four groups (Figures 6a through 6d), about half of the state/federal agencies, river authorities, consultants/attorneys, and water utilities recommended spending 26-50 percent of available funds to improving the GAMs. More than half of the consultants and attorneys recommended spending 26-50 percent of available funds to improving the WAMs**.** Fifty percent or more of the river authorities, consultant/attorneys, and water utility/government relations respondents recommended between 10 and 25 percent for linking the WAMs and GAMs. Data collection was an emphasis for available funding (river authorities, State and Federal agencies, groundwater districts, and universities and environmental groups).

2.2. Overall Group of Stakeholders

For an overall view of the responses, the survey of respondents is considered to be a reasonable representation or sample of the water community in Texas. Accordingly, all of the responses are grouped together and summarized by percent of respondents voicing a common comment.

Regarding the responses on the use of the WAMs and GAMs, this summary is presented in Table 2. It shows about the WAMs and GAMs are used by about two-thirds of the stakeholders with the greatest use for the WAMs being permit application and challenges and the greatest use for the GAMs being planning. Table 3 shows the greatest expectation for a linked WAM and GAM is in defining the impact of groundwater development on streamflow.

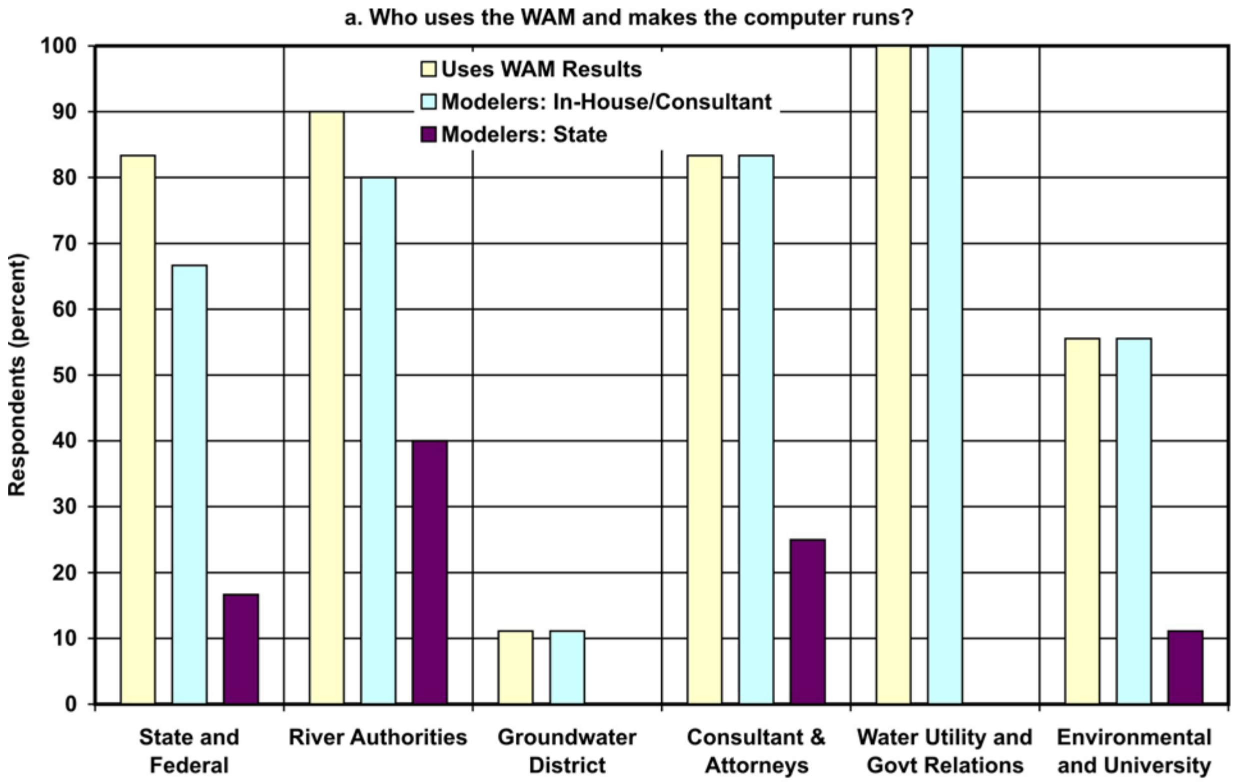
Regarding the use of information produced by a linked WAM and GAM (question 3), table 4 shows that other than surface water availability, there was not an overall central use. Instead, the ten common uses were identified by 10 to 25 percent of the stakeholders. The fifth most common response (about one-fifth) was "None to Very Little". When asked to identify the river and aquifers of greatest interest, table 5 shows rivers to be the Guadalupe, San Antonio, and Nueces and the aquifers to be the Edwards Aquifer-San Antonio and Carrizo-Wilcox. Table 6 summarizes the response to expected issues of developing and using a linked WAM and GAM (question 5). This summary shows a much larger percentage of the stakeholders expressed concern about the GAM than the WAM. More specifically, the most common GAM concerns were: accuracy of calibration/integrity of results (34%) and lack of SW/GW interaction data (30%). When considering the issues of a linked version, the major concerns were: updates and accuracy (44%), accuracy and integrity of results (42%), and different modeling concepts (34%). Looking further into stakeholder's attitudes and priorities, the highest responses to future funding (question 6) were about equally divided between improving the WAMs and GAMs with an allocation of between 10 and 50 percent of available funds to each (table 7). About 38 percent of the stakeholders recommended between 10 and 25 percent of available funding for linking the two models. The distribution of the recommended funding allocations by all stakeholders is illustrated in figure 7. Key points of interest include:

- *Other (data collection):* About 10 percent recommend all of the available funding go to data collection. Overall, about a fourth of the responses suggest a fourth or more of available funding go to data collection,
- *Linking WAMs-GAMs:* The overall level of interest in linking the WAMs and GAMs was lower than the other three activities,
- *Improving GAMs:* Except for a few stakeholders, improving the GAMs received the highest overall support for available funding, and
- *Improving WAMs:* About 40 percent recommended at least 30 percent of the funding go to improving the WAMs.

Finally, an overall funding priority is calculated by summing the recommended percentage for each of the four groups plus No Opinion and calculating an overall average (Figure 8). This shows "Other, mostly data collection" has the highest funding request with 29 percent. The lowest funding request, not considering No Opinion, is in linking the WAMs and GAMs with about 13 percent. Improving the GAMs and improving the WAMs had 27 and 24 percent, respectively.

3. Conclusion

The results of the survey indicate that the water community believes that improving the individual WAMs and GAMs should be given priority over linking the models. This is due mostly to the perception that (1) the information gained from linking the existing models is not as important as the information the two models provide independently, and (2) any additional information gained from linking them would have limited value due to current limitations on defining interactions between groundwater and surface water.



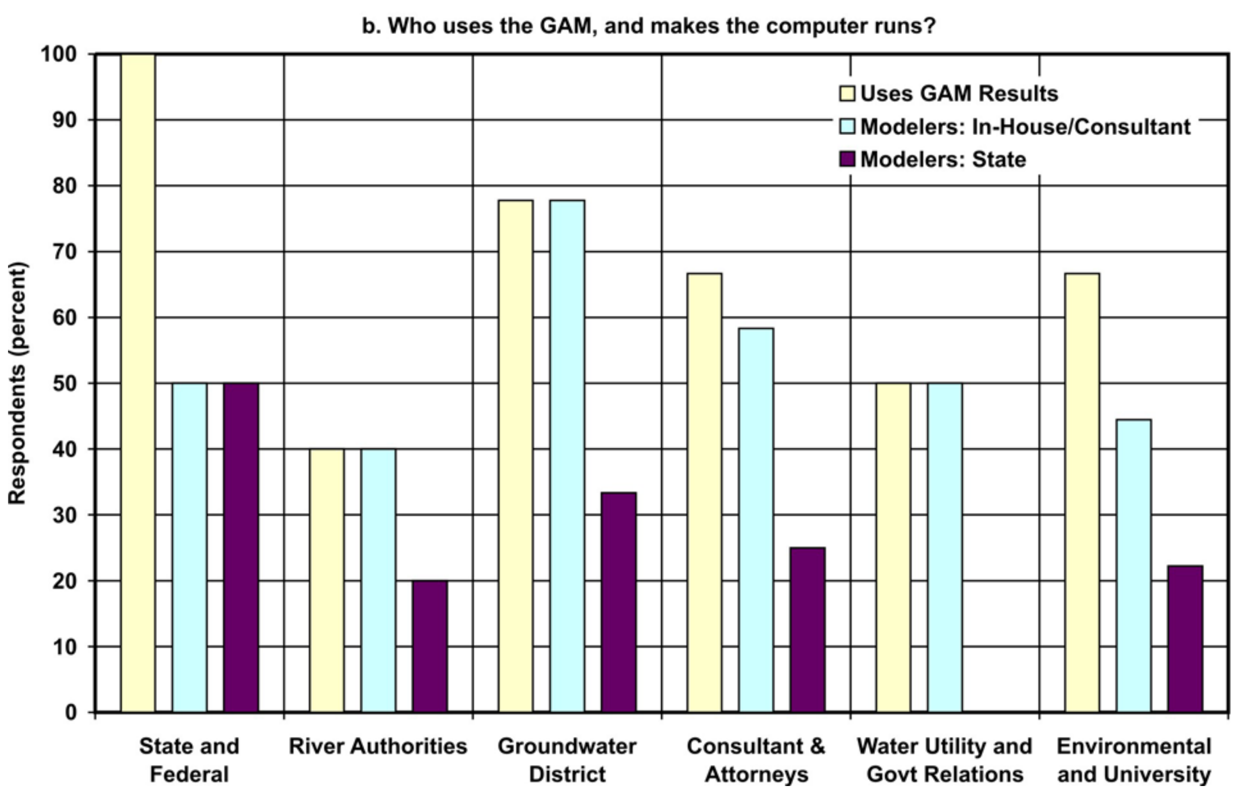
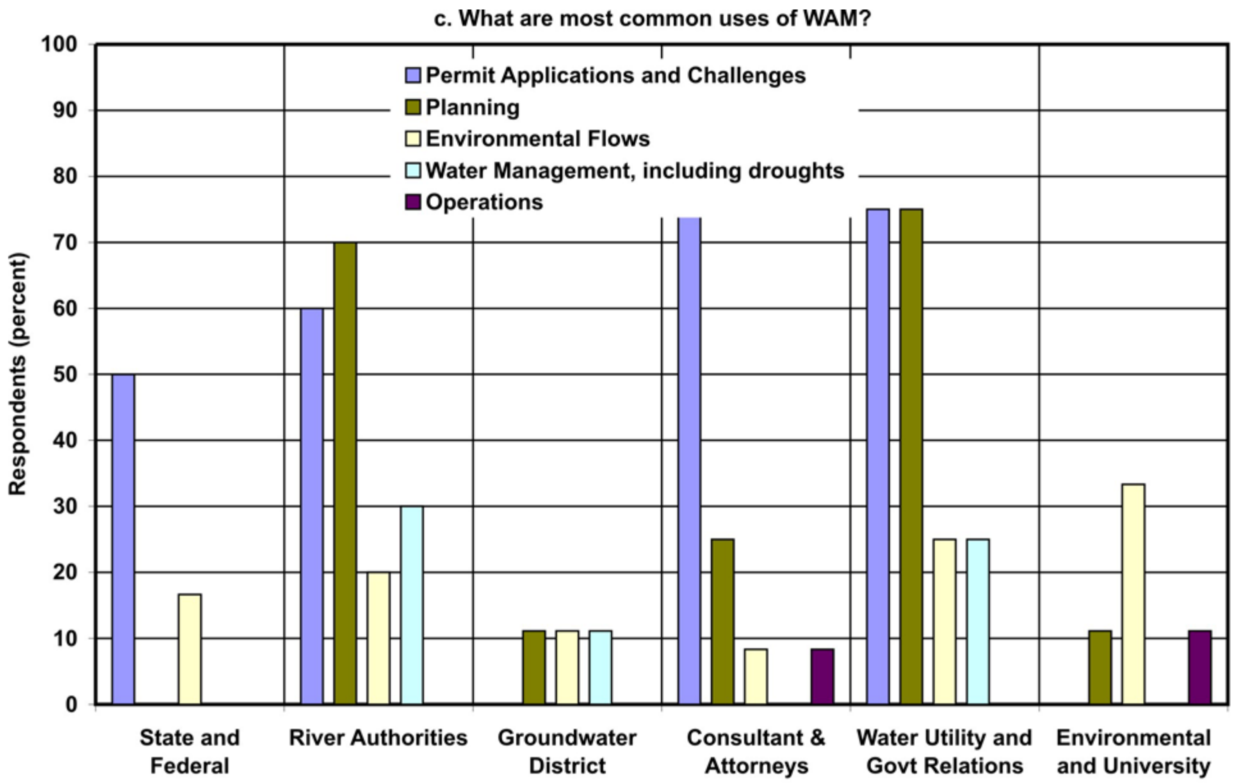


Figure 1. Summary of Responses to Question 1 (page 1 of 2)



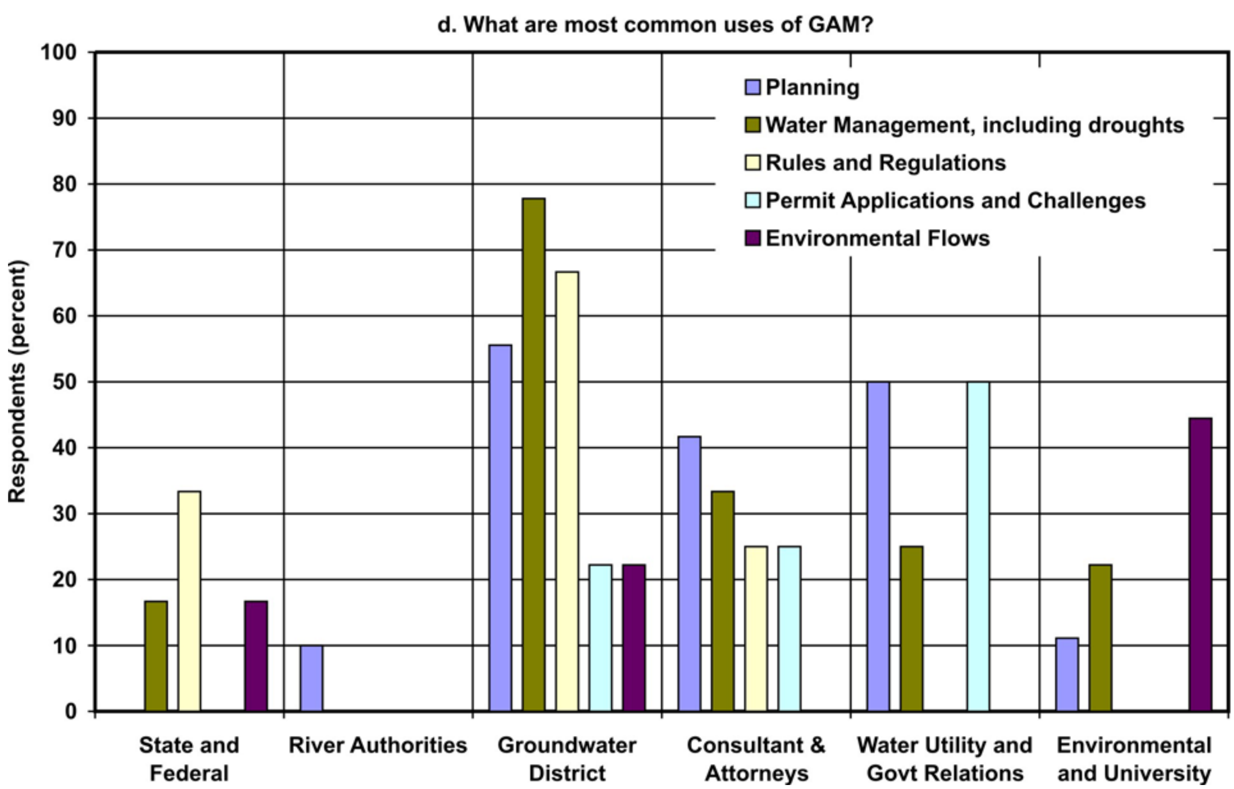


Figure 1. Summary of Responses to Question 1 (page 2 of 2)

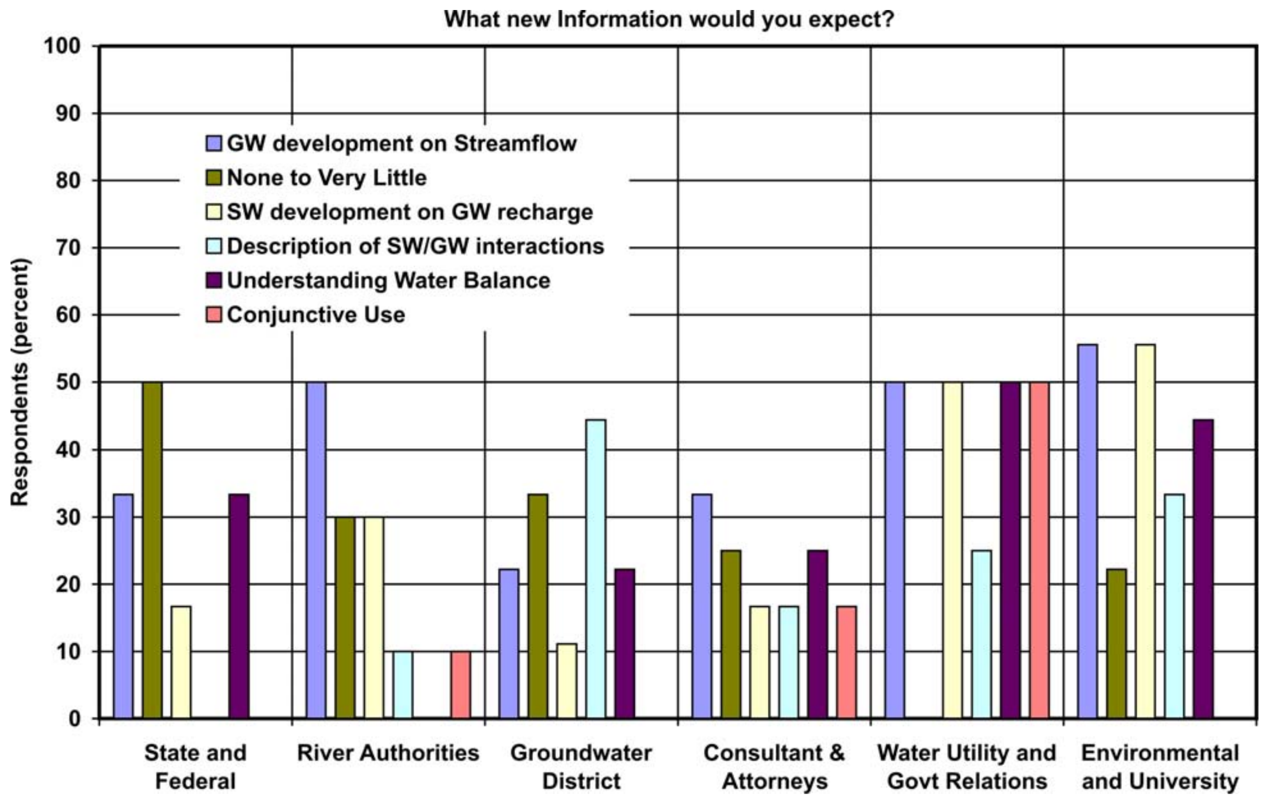


Figure 2. Summary of Responses to Question 2

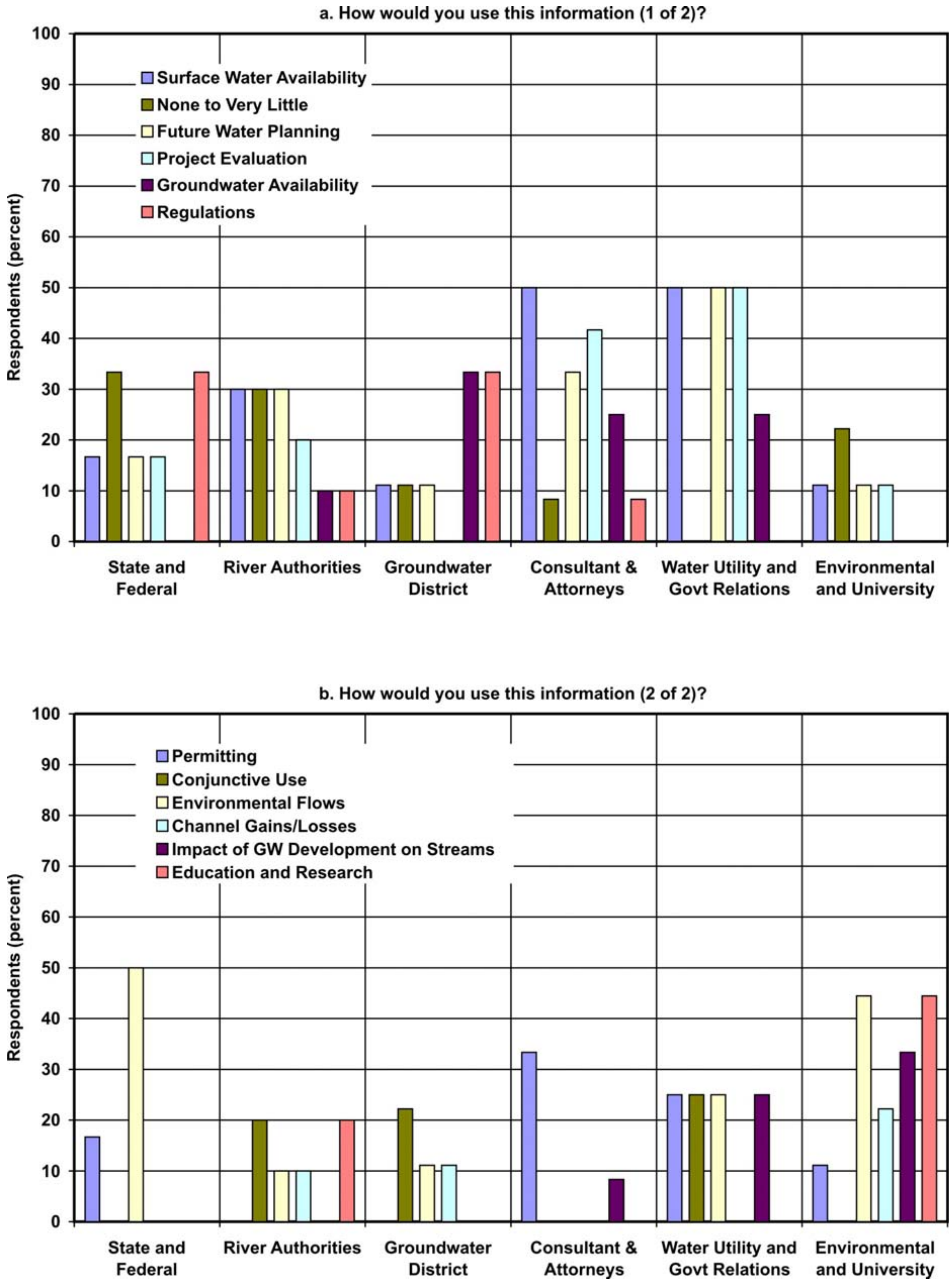
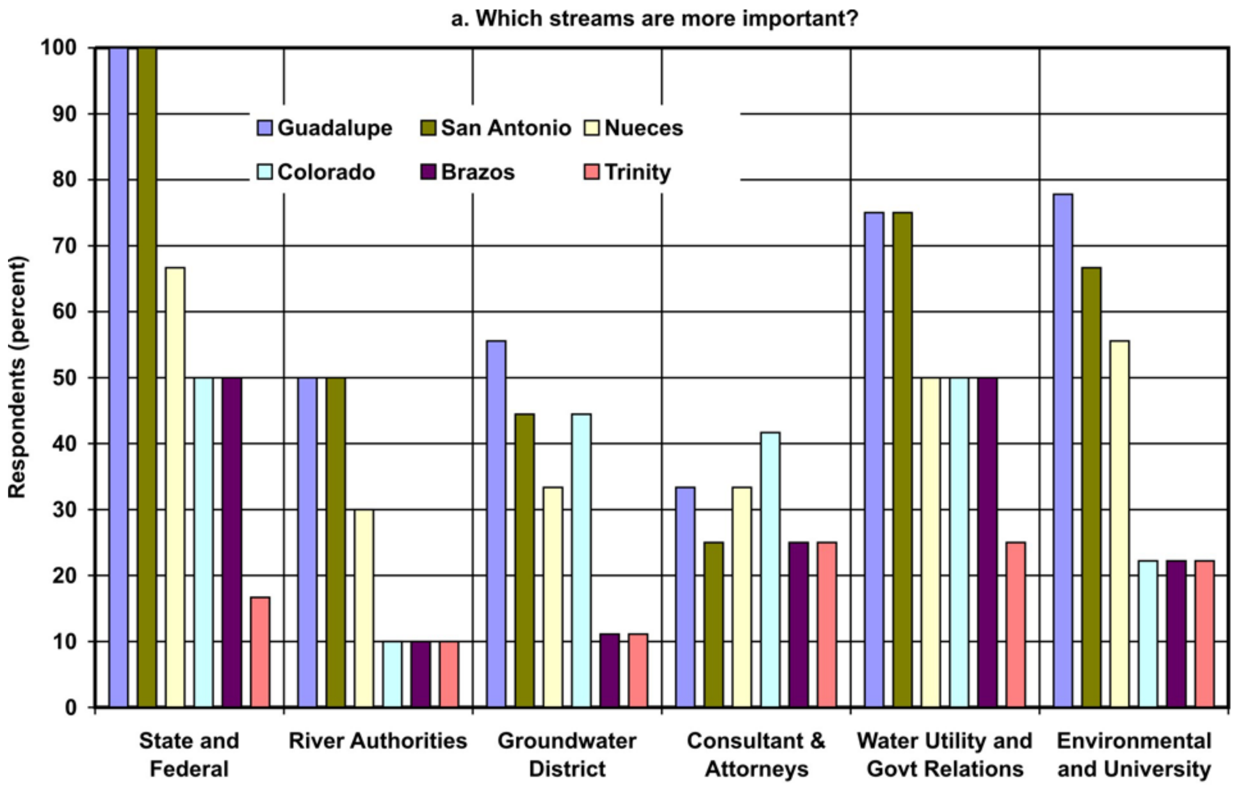


Figure 3. Summary of Responses to Question 3



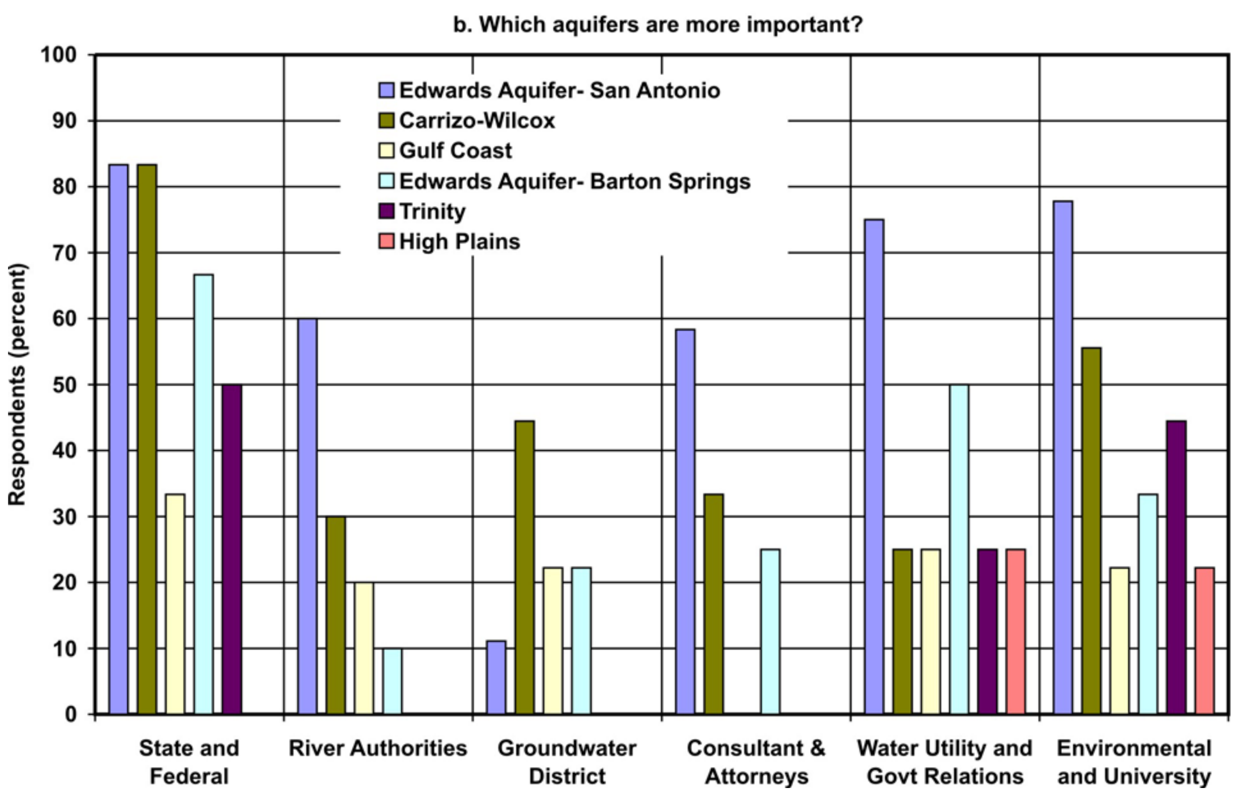
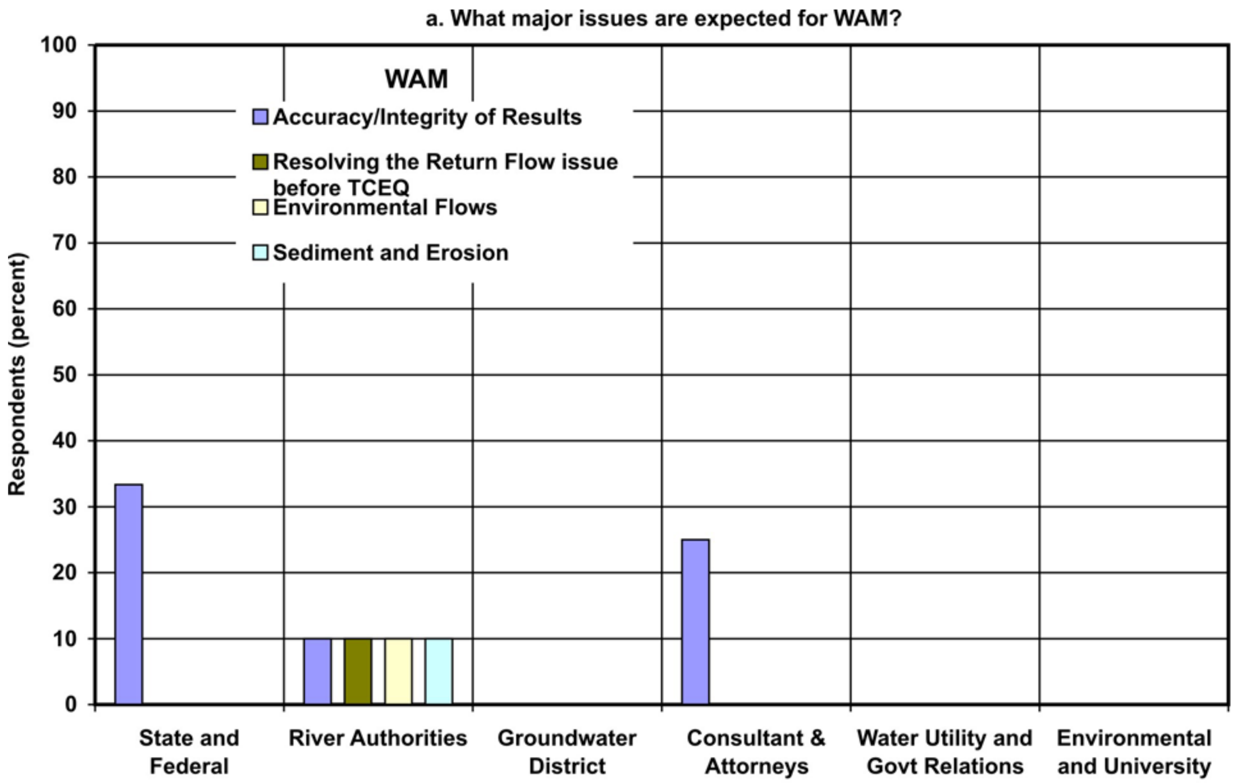


Figure 4. Summary of Responses to Question 4



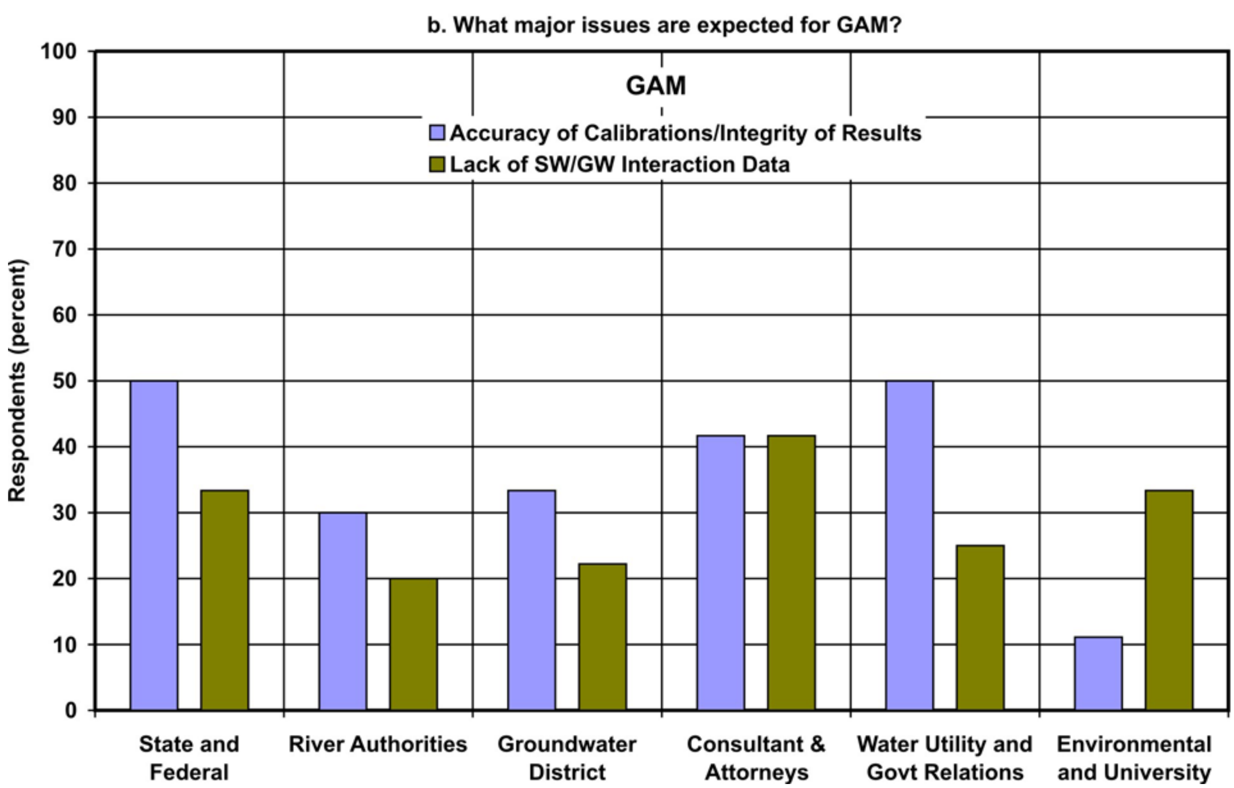
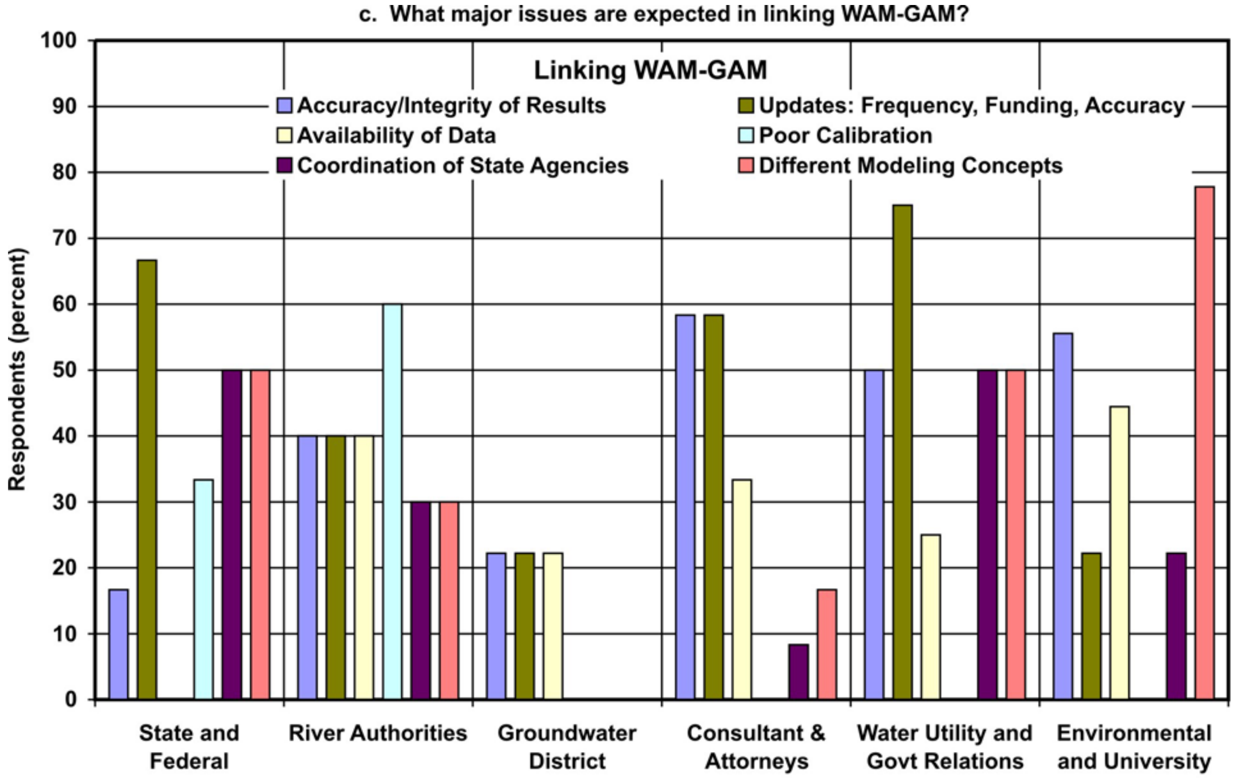


Figure 5. Summary of Responses to Question 5 (page 1 of 2)



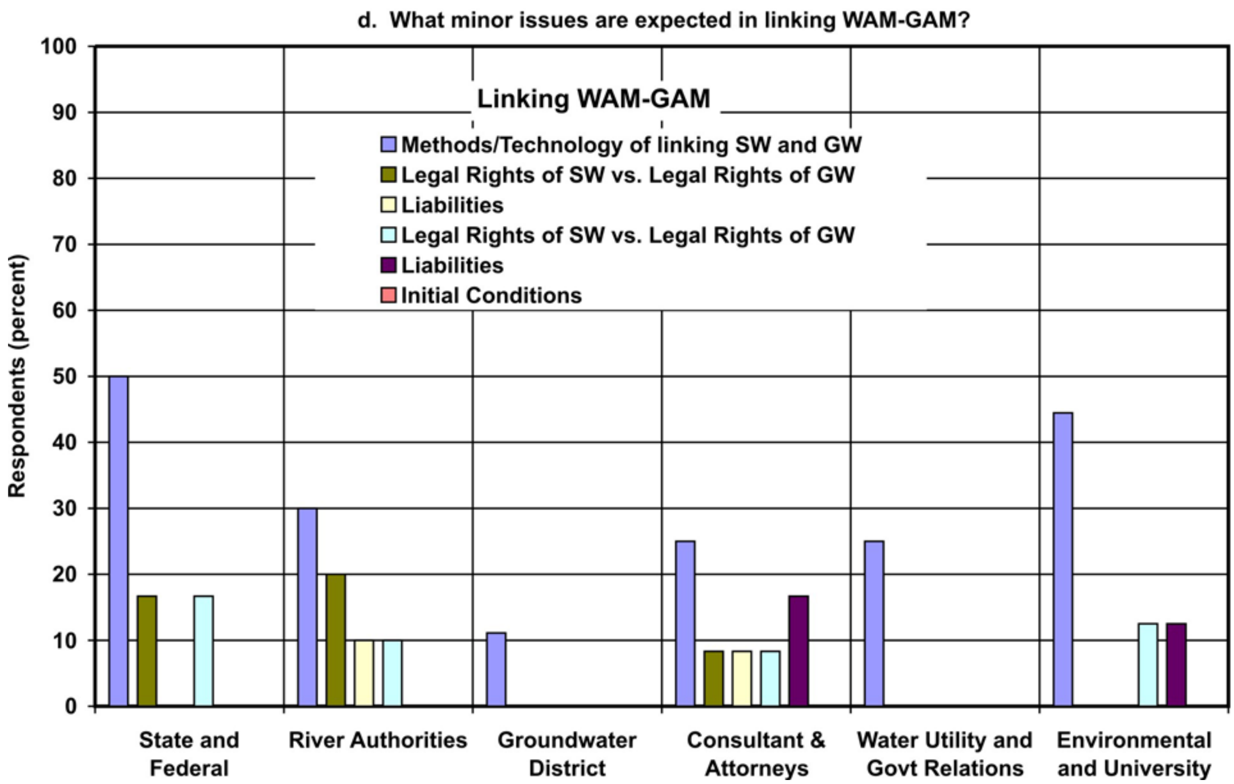
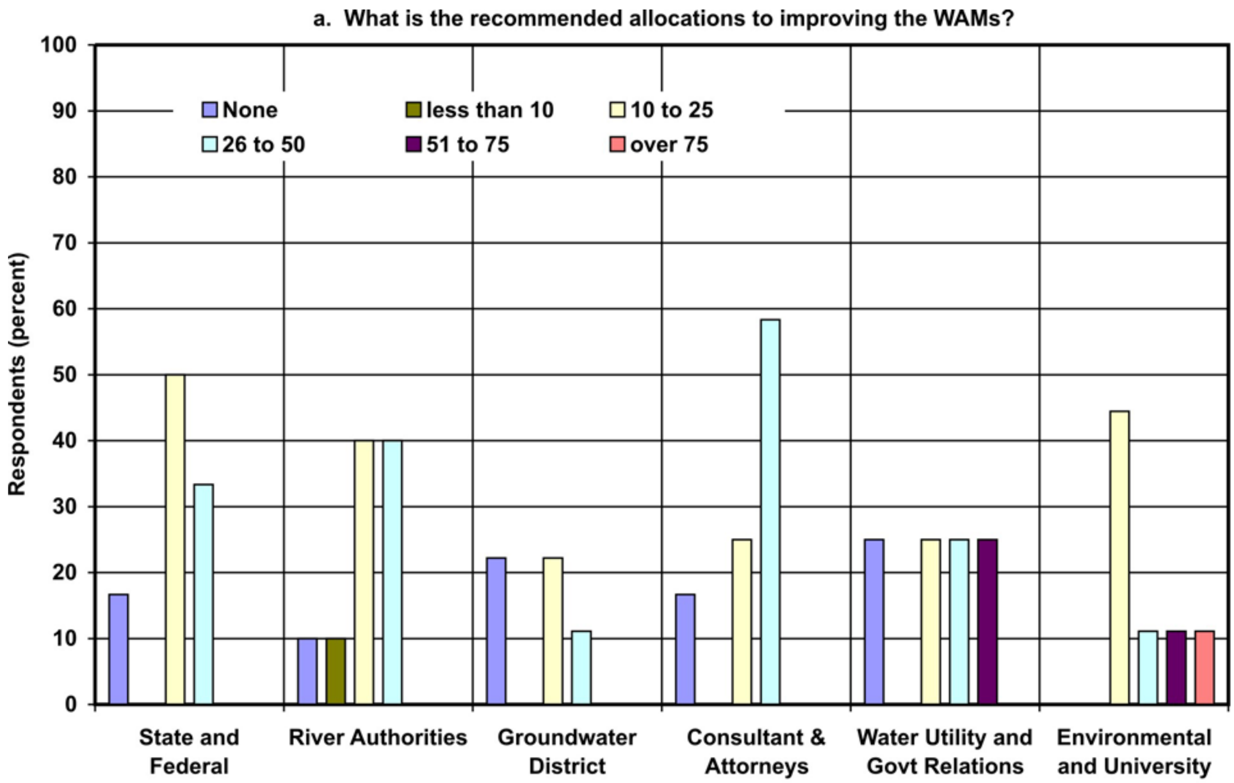


Figure 5. Summary of Responses to Question 5 (page 2 of 2)



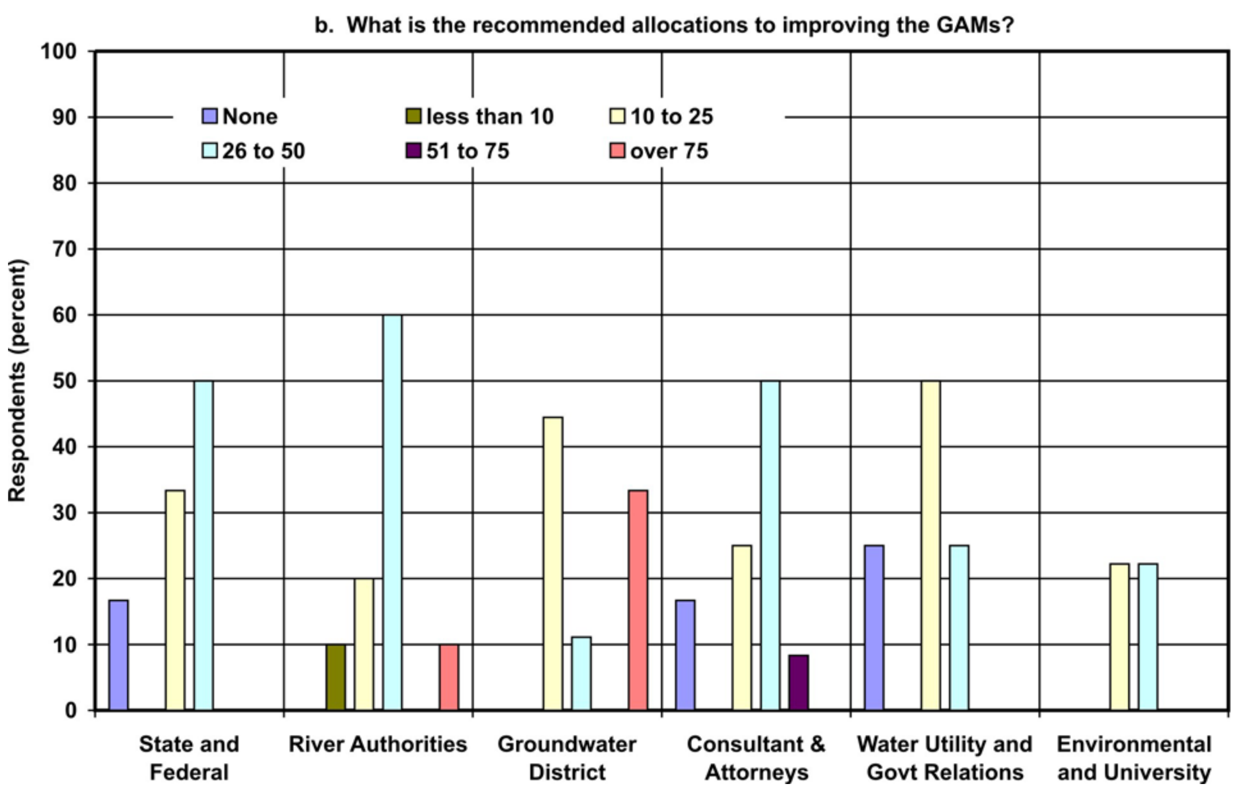
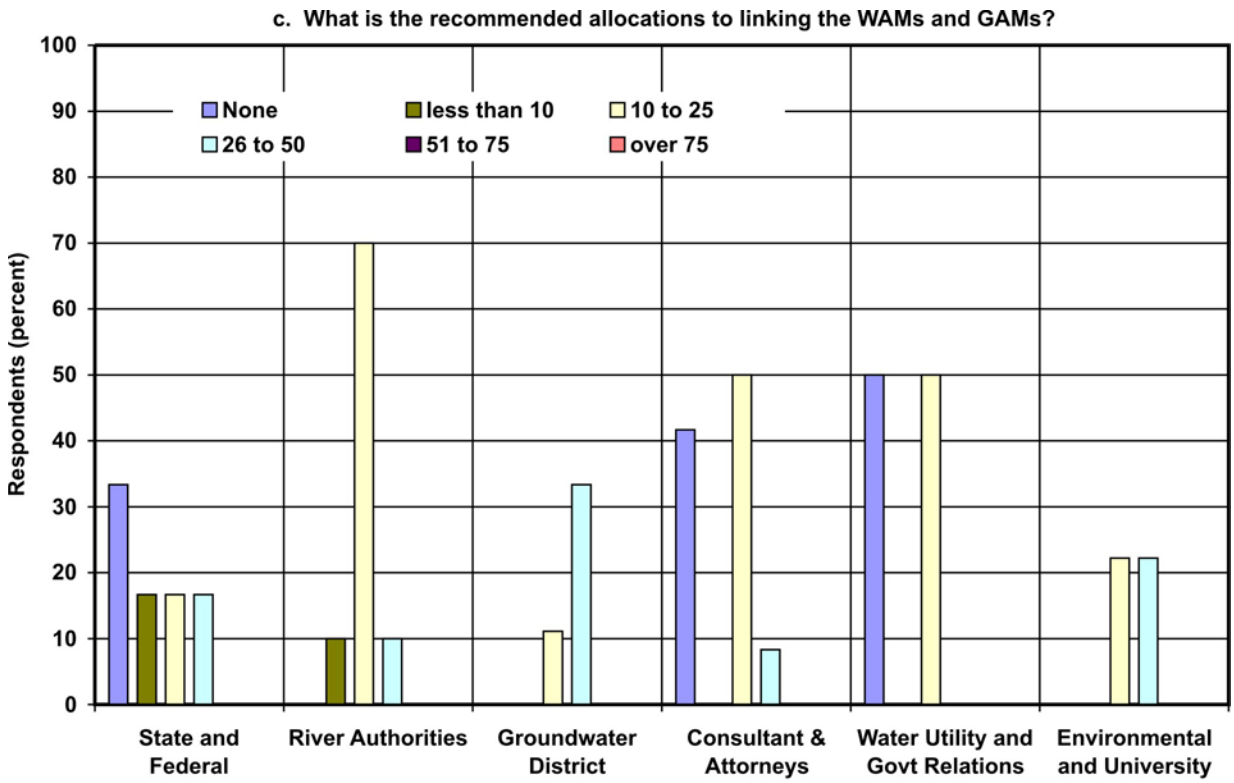


Figure 6. Summary of Responses to Question 6 (page 1 of 2)



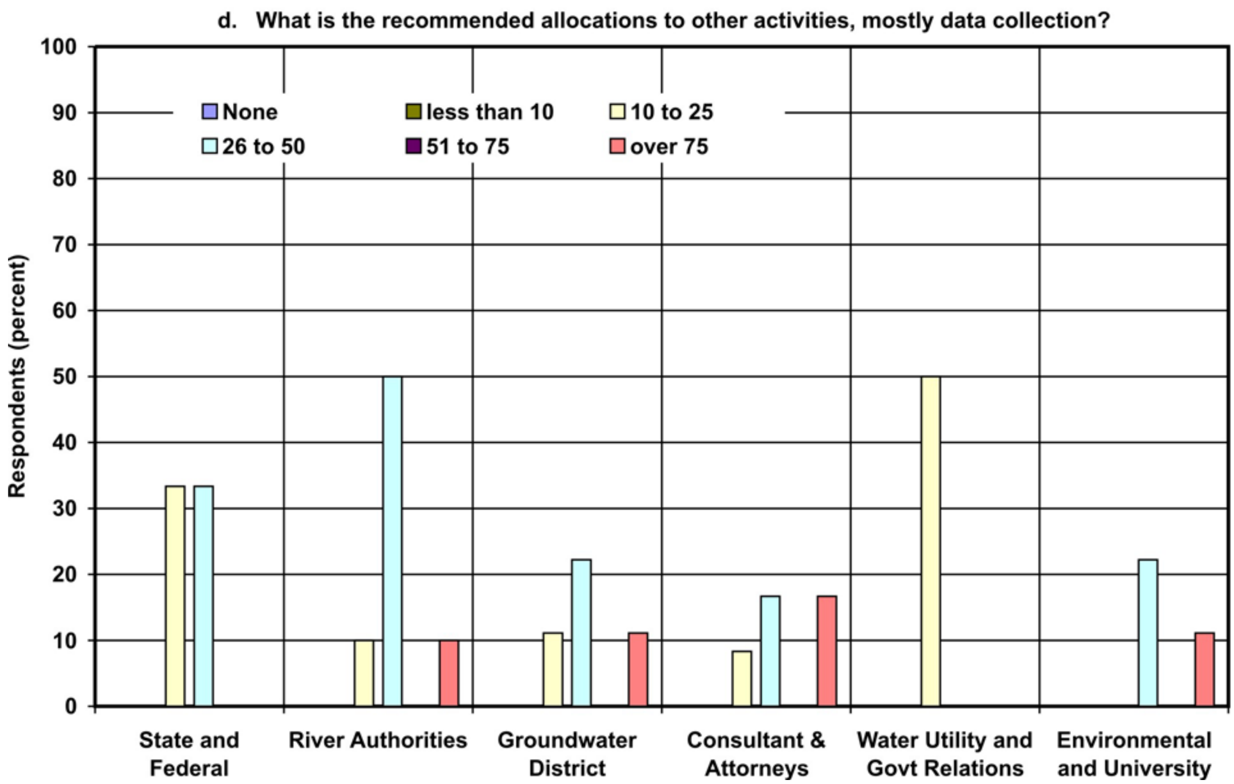


Figure 6. Summary of Responses to Question 6 (page 2 of 2)

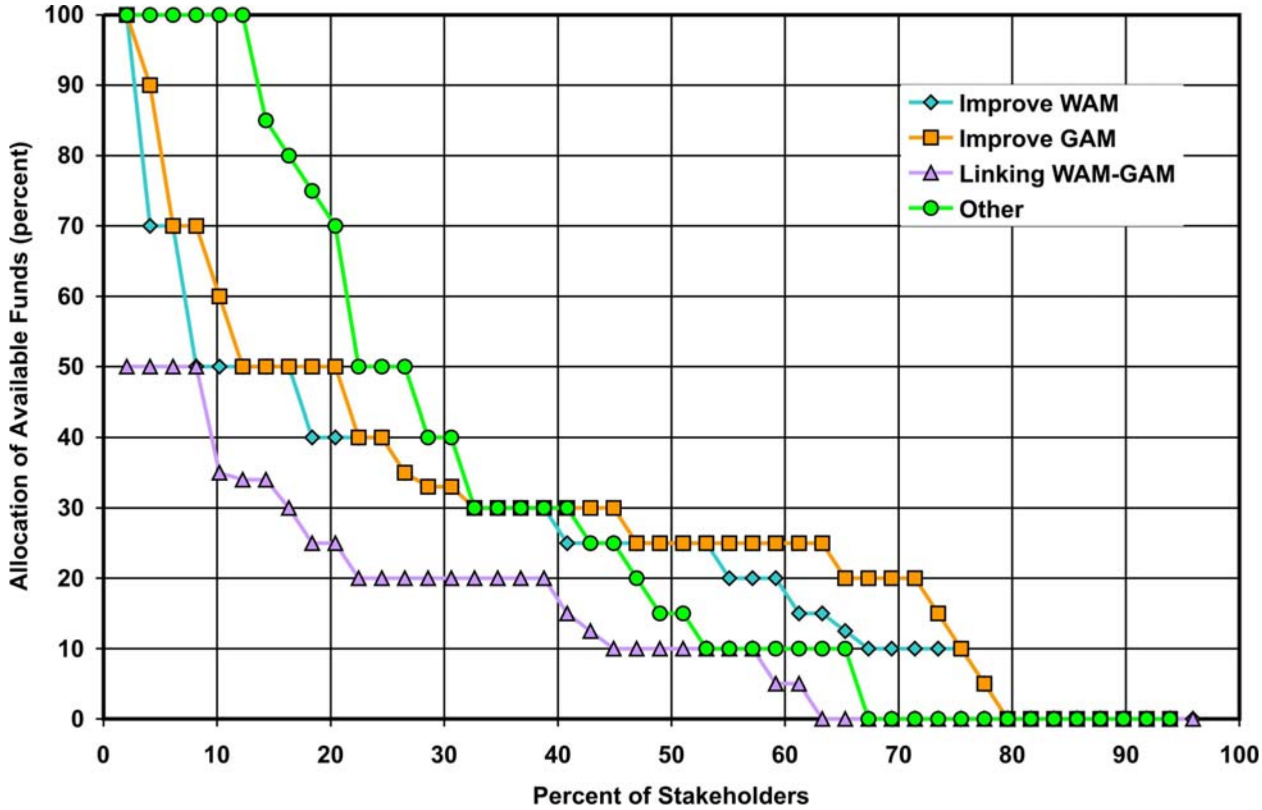


Figure 7. Recommended Allocation of Available Funds by Stakeholders

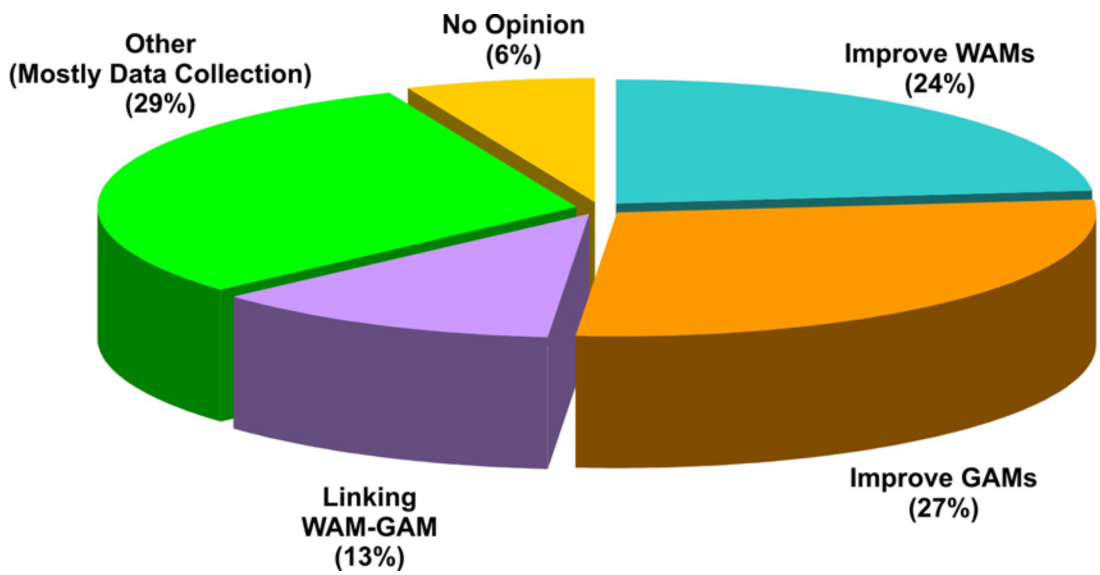


Figure 8. Overall Recommended Allocation of Available Funds

Table 1.
List of Stakeholders (Page 1 of 2)

Firm or Agency	***Affiliation***
Bickerstaff Heath Smiley Pollan Kever and McDaniel	Attorney
Independent Attorney	Attorney
Independent Attorney	Attorney
Lloyd Gosselink Blevins Rochelle and Townsend	Attorney
Espey Consultants	Consultant
Freese and Nichols	Consultant
Kier Consulting	Consultant
LBG-Guyton Associates	Consultant
R.J. Brandes Company	Consultant
R.W. Harden and Associates	Consultant
Turner Collie and Braden	Consultant
URS Corp	Consultant
Environmental Defense	Environmental
Natl Wildlife Federation	Environmental
Natl Wildlife Federation	Environmental
Sierra Club	Environmental
US Army Corp of Engineers	Federal Agency
US Geological Survey	Federal Agency
Texas Water Conservation Association	Government Relations
Barton Springs GW District	Groundwater District
Clearwater GW District	Groundwater District
Edwards Aquifer Authority	Groundwater District
Evergreen GW District	Groundwater District
Goliad County GW Conservation District	Groundwater District
Gonzales County GW District	Groundwater District
Harris-Galveston Subsidence District	Groundwater District
Lost Pines GW District	Groundwater District
South Plains GW District	Groundwater District
Brazos River Authority	River Authority
Guadalupe-Blanco River Authority	River Authority
North Texas Municipal Water District	River Authority
Nueces River Authority	River Authority
Sabine River Authority	River Authority
San Antonio River Authority	River Authority
Tarrant Regional Water District	River Authority

Table 1.
List of Stakeholders (Page 2 of 2)

Firm or Agency	***Affiliation***
Trinity River Authority	River Authority
Colorado River Municipal Water District	River Authority
West-Central Texas Municipal Water District	River Authority
Texas Commission on Environmental Quality	State Agency
Texas Commission on Environmental Quality	State Agency
Texas Commission on Environmental Quality	State Agency
Texas Parks and Wildlife	State Agency
Texas State University-San Marcos	University
Texas Tech University	University
Texs A&M University	University
UT-Center for Research in Water Resources	University
UT-San Antonio	University
City of Dallas	Water Utility
City of Houston	Water Utility
San Antonio Water System	Water Utility

Table 2.
Overall Summary for Question 1

	Percent of All Respondents
Do you use the WAM and/or GAM?	
WAM: Yes	68
GAM: Yes	66
Who performs the runs?	
WAM Modeler:	
In-House/Consultant	64
State	18
GAM Modeler:	
In-House/Consultant	54
State	26
How are results used?	
WAM	
Permit Applications and Challenges	42
Planning	30
Environmental Flows	18
Project Design and Evaluation	16
Water Management	10
Research and Development	6
Board and Public Briefings, Education	4
Operations	4
GAM	
Water Management	30
Planning	28
Rules and Regulations	22
Environmental Flows	18
Permit Applications and Challenges	14
Understanding of Water Resources	14
Project Design or Evaluation	8
Board and Public Briefings, Education	4

Table 3.
Overall Summary for Question 2

	Percent of All Respondents
What new information is expected?	
GW development on Streamflow	40
None to Very Little	28
SW development on GW recharge	28
Understanding Water Balance	26
Description of SW/GW interactions	22
Conjunctive Use	10
More Reliability	10
Regional Planning	6
"Real-Time" linkage for Operations	2
Application for Water Right	2

Table 4.
Overall Summary for Question 3

	Percent of All Respondents
How would you use this information?	
Surface Water Availability	28
Future Water Planning	24
Project Evaluation	22
Environmental Flows	20
None to Very Little	18
Groundwater Availability	16
Regulations	14
Permitting	14
Education and Research	12
Conjunctive Use	10
Impact of GW Development on Streams	10
Channel Gains/Losses	8
Coordination among Agencies	6
Direct Aquifer Discharge to Bays and Estuaries	6
Impact of SW Development on Aquifers	4
Contamination of SW on GW	2
Trends in Watersheds	2

Table 5.
Overall Summary for Question 4

	Percent of All Respondents
Which rivers and aquifers are more important?	
Rivers	
Guadalupe	60
San Antonio	54
Nueces	42
Colorado	34
Brazos	24
Trinity	18
Canadian	8
Rio Grande	4
Sabine	2
Cypress	2
Red River	2
Concho	2
Aquifers	
Edwards Aquifer- San Antonio	58
Carrizo-Wilcox	44
Edwards Aquifer- Barton Springs	30
Gulf Coast	18
Trinity	16
High Plains	6
West Texas Bolsons	4
Brazos River Alluvium	4
Edwards-Trinity Plateau	4

Table 6.
Overall Summary for Question 5

	Percent of All Respondents
What are the major issues?	
WAM	
Accuracy/Integrity of Results	12
Return Flows	2
Environmental Flows	2
Sediment and Erosion	2
GAM	
Accuracy of Calibrations/Integrity of Results	34
Lack of SW/GW Interaction Data	30
Linking WAM and GAM	
Updates: Frequency/Funding/Accuracy	44
Accuracy/Integrity of Results	42
Different Modeling Concepts	34
Methods/Technology of Linking SW and GW	30
Availability of Data	30
Coordination of State Agencies	22
Poor Calibration	16
Legal Rights of SW vs. Legal Rights of GW	8
Liabilities	4

Table 7.
Overall Summary for Question 6

	Percent of All Respondents
What is Your Recommended Allocation of Available State Funds?	
Improve WAMs	
26 to 50 percent	32
10 to 25 percent	34
None	14
51 to 75 percent	4
less than 10 percent	2
over 75 percent	2
Improve GAMs	
26 to 50 percent	38
10 to 25 percent	30
over 75 percent	8
None	8
less than 10 percent	2
51 to 75 percent	2
Linking WAM-GAM	
10 to 25 percent	38
None	18
26 to 50 percent	16
less than 10 percent	4
Other — (Data Collection)	
26 to 50 percent	26
10 to 25 percent	14
over 75 percent	10

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Appendix C
Linking WAMs and GAMs
TWDB Contract No. 2005-483-557
Summary of Technical Considerations and
Recommended Work Plan for Linkage Case Study

Linking WAMs and GAMs
TWDB Contract No. 2005-483-557

Summary of Technical Considerations
and
Recommended Work Plan for Linkage Case Study

Background

Pursuant to Tasks 2 and 3 of the scope of work for this study, representatives from the Texas Water Development Board (TWDB), HDR Engineering, Inc. (HDR), Dr. Ralph Wurbs, and Michael McDonald met on May 25, 2006 to discuss technical issues related to linking the Texas Commission on Environmental Quality (TCEQ) Water Availability Models (WAMs) and the TWDB Groundwater Availability Models (GAMs). The results of a stakeholder survey concerning perceptions of the general Texas water community toward the WAMs and GAMs, and the concept of linking the WAMs and GAMs were presented and discussed. A draft memorandum summarizing the survey results was provided at the May 25, 2006 meeting and has subsequently been refined and submitted to the TWDB as a final memorandum (June 2006).

Following discussion of the survey results, the conceptual bases for developing and applying the WAMs and GAMs were identified and discussed in order for the attendees to gain an understanding of the similarities and differences between the WAMs and GAMs, both in how the models were developed and how they are applied. Avenues through which the models might be able to interact (be linked) were identified, and potential strengths and weaknesses of each linkage pathway were discussed. Potential "active" and "passive" linkages were then discussed. Finally, various approaches for performing a case study (Scope of Work – Task 4. Develop and Test Linkage) were discussed. The meeting adjourned with the TWDB staff directing HDR to develop a recommended work plan for the case study.

This document provides a summary of the technical considerations discussed during the May 25, 2006 meeting, and includes a recommended work plan for performing a case study that is intended to guide future TWDB activities related to linking the WAM and GAM models.

Technical Considerations for Linking the WAMs and GAMs

Numerous technical considerations require review when discussing a linkage between the WAMs and GAMs. Many of these are centered on the inherent differences between the two modeling systems; methodologies for how a linkage would be defined, both hydrologically/geologically and specifically how the two models will communicate; and other considerations related to that facts that most WAMs have the potential to interact with multiple GAMs, and vice versa, and that the two models[1] are maintained by sister, yet separate, State agencies.

Differences between the WAMs and GAMs

The WAMs and GAMs differ in many fundamental ways, and cannot be considered as completely analogous to one another from alternative groundwater and surface water perspectives.

The Models Operate Under Different Paradigms. The WAM simulates the response of water rights (diversions and reservoirs) to a repeat of the hydrologic period of record, generally about 1940 through 1997. The GAM, on the other hand, simulates future aquifer conditions under assumed projected pumping. The GAM models, with the exception of the Edwards Aquifer GAM[2], do not repeat the hydrologic record, but use average annual recharge applied each year during the simulation period. A single drought stress period is inserted somewhere within the simulation period, usually near the end. This drought stress period utilizes below average annual recharge values based on recharge estimated during the drought of record. The GAM can be thought of as predictive in nature, i.e., "what will happen in the future if…," whereas the WAM is more descriptive and retrospective, i.e., "what would have happened if…" GAM results are typically analyzed by looking at future water levels, while WAM results are usually analyzed by looking at time series data and statistical measures of reliability.

The Models Use Different Geographic Scales. The typical GAM utilizes a one-square mile grid cell, within which aquifer properties are averaged. The WAM is defined by site-specific control points or nodes that reference streamflow passing specific locations. The GAM spatial resolution makes it strongly applicable for defining and estimating regional aquifer responses to larger regional stresses, but not well suited for addressing localized effects of regional or localized pumping. The WAM focuses on the behavior of local, specific water rights and their interactions with other rights, while the GAM focuses on overall regional system responses.

The Models Use Different Temporal Scales. Typically, aquifer systems respond relatively slowly to stresses such as prolonged droughts or increasing withdrawals, simply due to the scale of the systems and the physics of groundwater flow. River systems, however, are sensitive to short-term stresses; they respond immediately to changing hydrologic conditions and increased water use. For these reasons, the GAM (with the exception of the Edwards Aquifer) simulates a series of annual stress periods, while the WAM utilizes a monthly simulation time step.

[1] Note: For brevity, the multiple GAM and WAM models will often be referenced collectively in the singular as the "GAM" and the "WAM".
[2] The GAM for the Edwards Aquifer (EAA segment) utilizes temporally-varying recharge, calculated for each month of the period of record.

Considerations for Defining Linkages

Groundwater and surface water systems interact primarily through the intersection of surface water features with aquifer outcrop areas. Streamflow and water impounded in reservoirs can percolate into underlying aquifer formations through the beds and banks of streams and reservoirs. Groundwater can enter the surface water system through well-defined springs, as well as by a general flux (seeps) from an aquifer to a stream along a length of channel. Often, this flux from a groundwater system constitutes a substantial portion of the base flow of a stream. As aquifer levels vary, base flow in a stream can vary as the flux changes direction; stream flow can move back into the aquifer from the stream. Flux along a channel can change from positive to negative at different locations at the same point in time as the relationship between aquifer water levels and the stream channel elevation varies longitudinally.

Quantification of groundwater-surface water interactions is a complex science, primarily due to complexities caused by geographic, geologic, and climatic variations. In addition, limited data exists to define these interactions precisely. Linking the WAM to the GAM will involve defining not only the hydrologic responses of both the groundwater and surface water systems, but also defining how the two models will interact to pass this information back and forth.

<u>Definition of GW/SW Interactions</u>

The WAM currently includes two primary means for defining how groundwater systems might influence stream flow. The first is through a naturalized flow adjustments file, whereby changes to the naturalized flows used in the WAM are modified to account for changes in spring flows or in the flux from an aquifer to a stream channel. The WAM naturalized flows are based upon gaged stream flow records and inherently reflect historical interactions with ground water systems. Hence, most WAM naturalized flows reflect historical groundwater development.

In order to move to some defined future "managed" groundwater development condition that may have greater pumping than that which occurred in the early part of the simulation period, but less than recent pumping, flows in earlier years might be decreased while flows in later years might be increased. This is the case in the Guadalupe-San Antonio River Basin WAM (GSA WAM), which includes a flow adjustments file used to adjust naturalized flows to reflect a regulated pumping level from the Edwards Aquifer of 400,000 acre-feet per year. These adjustments are applied to the major springs discharging from the Edwards Aquifer (San Marcos, Comal, Hueco, San Antonio, and San Pedro), and are translated through control point locations downstream of the spring locations. The adjustments are actually the differences between two aquifer simulations[3]. The first simulation reflects springflows occurring during historical pumping conditions; the second simulation reflects springflows occurring under the assumed aquifer pumping.

[3] The TWDB GWSIM4 model of the Edwards was used. The GWSIM4 model is the current GAM for the Edwards Aquifer, pending adoption of the recent MODFLOW model developed by the U.S. Geological Survey.

The difference in monthly springflows between the two model simulations forms the basis for the flow adjustments applied in the GSA WAM. Additional adjustments are applied to correct for model calibration, thereby allowing the magnitudes of the simulated historical springflows to more closely agree with observed historical springflows.

The WAM includes a second methodology that partially reflects groundwater-surface water interactions through the application of a channel loss function. Channel losses are entered into the WAM as a fixed percentage, and reflect the portion of the flow "lost" between sequent upstream and downstream control point locations. These losses reflect not just seepage from stream channels, but also free surface evaporation from the stream and evapotranspiration from vegetation growing along the stream channel. Because the naturalized flows already reflect naturally occurring channel losses, the channel loss factors are applied only to changes in flow caused by diversions, wastewater effluent discharges (return flows), and reservoir operations. Channel losses are also applied to the flow changes input into the flow adjustment file. Channel losses are used widely in only three of the WAMs: the Nueces, Guadalupe-San Antonio, and the Brazos. The Trinity, Colorado, and Red River WAMs utilize channel losses to a limited extent, but they are not applied basin-wide.

The WAM might also be able to model recharge to an aquifer system and discharge from an aquifer using one or more "water rights" that remove or add water to the surface water system, keyed to specific output parameters from the GAM. For water rights that remove water from the surface water system (and are assumed to input water to the groundwater system), the relationship of these flows to naturally occurring recharge must be well defined and incorporated into the recharge calculations in the GAM. Since most GAM models use average annual and drought-averaged annual recharge, additional statistical inference would have to be made from the monthly water right output in order to adjust the annual recharge values. One situation where this might be used is in the case of a reservoir constructed over an aquifer recharge zone, i.e., Lake Corpus Christi over the Gulf Coast Aquifer. While the WAM does not contain specific capabilities for defining leakage from a reservoir, relationships could be input whereby water would leave the WAM as a function of reservoir level. These surface water losses could then be combined with natural recharge estimates in the applicable GAM.

However, in very few cases will alterations to the surface water system result in noticeable changes in aquifer recharge. New water rights granted by the TCEQ are unlikely to completely dry up a stream because they will be subject to instream flow requirements and will be required to pass inflows to downstream senior rights. Precise knowledge of the hydraulic connections between streams and aquifer systems is limited, and changes in base flow elevations will not result in appreciably different levels of computed seepage to the underlying aquifer. As long as the stream bed does not completely dry up in the WAM simulation, it can safely be assumed that interactions between the stream and the aquifer will continue to occur within the accuracy that the different options in MODFLOW allow. Exceptions to this might be in the case of structures built and permitted specifically to enhance recharge to an aquifer, or to water rights located upstream of highly permeable recharge zones where little of the water entering a stream reach exits as stream flow and a substantial fraction is "lost" to the underlying aquifer. These situations are primarily associated with the outcrop of the Edwards Aquifer and should be treated as special cases.

The computer program used in the GAM, MODFLOW, includes four packages that can be used to simulate groundwater-surface water interactions from a groundwater system perspective: stream package, recharge package, river package, and drain package. All have different capabilities and applications, and the method used varies among individual GAM models. Most include an imprecise delineation between water lost from the aquifer to evapotranspiration and water lost as leakage from the aquifer to a stream channel. However, all are based (at least in part) on computed aquifer levels, and the user is able to define a quantity of water lost to a stream or gained from a stream as a function of aquifer water level. Quantities can be computed in an execution of the GAM that can be input to the WAM as changes to the naturalized flows using the WAM flow adjustments file. These adjustments would actually reflect differences between two GAM simulations, a baseline simulation that is reflective of historical conditions, and a projected simulation that reflects conditions after future groundwater development.

The GAM influence on streamflow for a specific scenario must be defined in association with a specific point in time in the future. A point in time must be selected at which the cumulative effects of groundwater development on streamflow would be introduced into the WAM. This would normally be a constant change in flow at each defined point of interaction that would not vary temporally throughout the WAM simulation period. For example, a planner might want to assess the effects of increased groundwater pumpage on water rights in a specific river basin based on aquifer levels at the end of a 50-year GAM projection simulation. In this case, the GAM would provide a single change in baseflow value at each applicable WAM control point that would be applied at all WAM time steps.

In general, the GAM will be much less sensitive to changes in the surface water system because of the dynamic, time-varying nature of the surface water model and the regional, slowly changing characteristics typical of groundwater systems. In simple terms, groundwater systems typically have much more mass (storage) and inertia and are not "driven" by surface water conditions. A linkage between the GAM and WAM would be most useful in quantifying the impacts of the groundwater system on surface water rights and water availability, rather than attempting to capture the more subtle effects of surface water rights on the groundwater system. Overall, groundwater-surface water interactions are not well-quantified statewide and little data or research results exist upon which to base an entire GAM or WAM linkage. In some locations, site-specific studies may have been performed, but the spatial scale of the GAM precludes direct application of results on a regional basis without first acknowledging this limitation.

Practical Mechanisms for Linking WAMs and GAMs

Two general approaches (active and passive linkages) have been identified to define how the WAM and GAM could communicate in a practical sense. An active linkage is possible, whereby the WAM and GAM share data back and forth on a time-step/stress-period basis. Changes in springflows or aquifer flux (which would be the difference between baseline (historical) and projected values) would be computed after each GAM stress period. These data would then be passed to the WAM, the current month WAM flows adjusted, and the WAM simulation would commence for the current month. Following completion of the WAM simulation for the current month, the WAM would pass data (such as enhanced recharge) back to the GAM, and the GAM would complete another time step. This sequence of direct "handshakes" would continue until the entire period of record is completed, with GAM and WAM output providing "real-time" feedback to the other model.

This process was used by the South Central Texas Regional Water Planning Group to assess a potential water management strategy know as "Recharge and Recirculation."[4] In this process, recharge was enhanced in the GAM (GWSIM4), this enhanced recharge increased springflows in the GSA WAM, and the increased springflows were made available to further enhance recharge in the GAM by being pumped back to the recharge zone of the aquifer. In this particular application, the WAM and GAM provided feedback to one another on a month-by-month basis.

This type of approach is only applicable in situations similar to the Edwards/GSA system in which: a) the aquifer is dynamically sensitive to short-term temporal variations in hydrology and pumping; b) the GAM uses a monthly stress period that matches the WAM monthly time step; and c) the WAM will provide feedback that significantly affects subsequent GAM stress periods. The Edwards is the only GAM to use a monthly stress period; all others typically use a standard annual stress period because these systems are not particularly sensitive to short-term fluctuations in either hydrology or pumping.

An active linkage of this type requires substantial computer code modifications to both the WRAP model (used by the WAM) and the MODFLOW and GWSIM4 models (used by the GAM) in order for the two to communicate on a month-by-month basis. As the generalized computer programs used by the GAM and WAM are periodically updated with additional capabilities and data sets are updated to reflect improved information or changed conditions, any hard-coded handshake linking the two would need to be ported to the updated models and tested. This could be facilitated if the handshake capability was incorporated as a standard feature in both models.

A passive linkage operates under the assumption that data needs to be passed in only one direction because model-to-model feedback on a month-by-month basis is unnecessary. This is the case with most WAM and GAM situations, where changes in groundwater pumping might reasonably be expected to alter surface water base flows through long-term changes in spring flows or groundwater flux. Output from the GAM is post-processed to identify potential changes in streamflow expected to occur at a selected point within the projection time frame. Such a passive linkage can be facilitated without modification to the code of either the WAM or GAM model by developing a third

[4] South Central Texas Regional Water Planning Group, 2001 Regional Water Plan, January 2001.

program written expressly for that purpose, spreadsheet analysis tools, or a combination of the two.

Regardless of whether an active or a passive link is used, specific knowledge of the hydrology, geology, and geography of the river basins and aquifer systems to be studied is required, in addition to familiarity with both the GAMs and WAMs to be linked. Professional judgment is required to determine how best to accumulate flow changes from the MODFLOW package (stream, river, recharge, or drain) used by a specific GAM, and where to assign these flow changes within the WAM depiction of a river basin. Basin-specific WAM knowledge is required that includes familiarity with the methodology for distributing naturalized flows from gaged to ungaged control point locations and knowledge of which stream reaches could be affected by changes in springflows or groundwater flux. It is unlikely that any simple, generic methodology can be developed that would apply to all GAMs and WAMs. However, once the "homework" has been completed related to defining the linkages between specific WAMs and GAMs, the same data that define the linkage framework for specific WAMs and GAMs can continue to be employed so long as the base model data sets are not altered (official WAM and GAM data sets are periodically updated by the TCEQ and the TWDB, respectively). Geographic Information Systems can be useful in developing much of the base linkage information required, as are several of the proprietary MODFLOW interface packages such as Groundwater Vistas[5].

Other Considerations

The WAM and GAM systems are maintained by separate State agencies, and are used by these agencies for entirely different purposes. The TCEQ uses the WAM to analyze water available to existing rights and evaluate applications for new appropriations. TCEQ staff routinely updates the various WAM data sets to reflect new and amended water rights. These WAM updates frequently include new control point locations and updated methodologies used to model specific water rights. Furthermore, the WRAP model capabilities are continually being updated by Texas A&M University to allow the model to simulate new or more complex water right situations. The WAM system is in a continual state of change, with both data sets and model codes being updated on a frequent basis. The TWDB uses the WAM models for water supply planning (reservoir firm yield estimates, surface water supply from run-of-the-river diversions, and evaluation of the effects of new water supply systems on instream flows and freshwater inflows to bays and estuaries). Certain TCEQ assumptions required for permitting perpetual water rights are not necessarily applicable to the water supply planning activities of the TWDB just as some of the assumptions used by the TWDB are not necessarily appropriate for water rights permitting.

The TWDB uses the GAM for water supply planning, and also to assist groundwater conservation districts in managing regional groundwater supplies. With the exception of the Edwards GAM, the TCEQ appears to be an infrequent user of GAMs in the course of

[5] Scientific Software Group, Sandy, Utah, www.groundwater-vistas.com. Trade names are mentioned here for identification purposes only and do not reflect endorsement by the TWDB or the State of Texas.

its activities. A linked approach could be used by the TCEQ to assess the long-term effects of groundwater development on stream flows and the reliability of water rights, which could be used to assess potential surface water appropriations. However, additional detail may be necessary in State law and/or TCEQ rules in order to more fully integrate consideration of groundwater/surface water interactions in the regulatory process.

Overall, for successful linkages of WAMs and GAMs to be maintained over time, the TCEQ and TWDB would need to coordinate model updates and maintenance activities.

An additional complexity inherent in linking WAMs and GAMs is the fact that most river basins cross and interact with multiple aquifer systems, and most large aquifer systems underlie more than one river basin. As such, in order to ascertain the cumulative effects of groundwater development on streamflows in a particular river basin, multiple GAM models may need to be linked to each individual WAM. The complexity of linking multiple GAMs with a single WAM effectively precludes the use of an active linkage between the GAMs and the WAM in question. A passive linkage from the GAM outputs to the WAM input appears to be the more reasonable approach. Because there is limited overall impact of surface water development on groundwater systems, it is unlikely that any individual GAM would need to be linked to multiple WAMs to quantify the influences of multiple river basins on a single groundwater system.

Options for Proceeding with Study

The foregoing is a summary of the considerations discussed during the May 25, 2006 meeting. At the conclusion of the meeting, four options were identified for continuation of this project.

<u>Option 1.</u> Document fully the considerations as briefly discussed above in a final report, but do not pursue a linked model at this time based upon recognition that: (1) the two models are developed and operated with different paradigms, spatial scales, and temporal scales; (2) information is limited with which to describe groundwater-surface water interactions accurately; and (3) linkage of the two models would provide little additional information that the two models don't already provide separately. Option 1 includes a recommendation that linkage of the two models not be pursued at this time and that the State's resources be directed towards improving the WAMs and GAMs and collecting data such that groundwater-surface water interactions might be better defined in the future.

<u>Option 2.</u> Complete the discussion described in Option 1, but also develop a hypothetical situation using greatly simplified GAM and WAM configurations by which the mechanisms for linking the two can be demonstrated. Perform sensitivity analyses of various parameters in the two hypothetical models that relate to groundwater-surface water interactions, and document these results in the final summary report.

Option 3. Complete the discussion described in Option 1 and perform a limited case study using the Hill Country GAM and the GSA WAM to demonstrate the mechanisms by which the models can be linked and the differences in surface water availability that might result. This is essentially what is identified in the original scope of work for this project.

Option 4. Complete the discussions described in Option 1 and perform a limited case study using a combination of GAMs and one WAM that will more fully demonstrate the mechanisms by which the models may be linked, and also better demonstrate the magnitude of effects that incorporating a linked analysis might have on surface water supplies.

Recommended Work Plan for Case Study

Based on discussions with TWDB staff concerning the four options identified and further discussions amongst HDR staff, HDR offers the following recommended Work Plan for pursuing a demonstration case study of linking the WAM and GAM, based on Option 4 described above. The following Work Plan incorporates a passive link between the GSA WAM and the four GAMs that physically interact with surface water in the Guadalupe-San Antonio River Basin: the Hill Country, Edwards (GWSIM4 model), Southern Carrizo-Wilcox, and Gulf Coast. The GAMs will include projected pumping levels consistent with those used in the 2006 Regional Water Plans. The GSA WAM will include existing surface water rights, return flows consistent with the SB1 planning process, and recommended water management strategies from the 2006 South Central Texas Regional Water Plan. Utilizing these four GAMs with the GSA WAM (with regional water planning assumptions) will facilitate the following:

1. Demonstration of the influence of large, well-defined springs discharging from the Edwards Aquifer which provide a strong monthly-varying influence on surface water flows. In addition, the technique used to compute flow changes from the major Edwards springs applied to the WAM resulting from different pumping scenarios will be documented. The technique used includes not just differencing modeled springflows between the baseline (historical) pumping and projected pumping, but also adjustments to account for calibration differences between observed and simulated historical springflows.

2. Demonstration of linking at least three different modes of groundwater-surface water interactions used in the GAM: (1) the drain package as applied to the Hill Country GAM; (2) the river package as applied to the Carrizo and Gulf Coast GAMs; and (3) strong, well-defined springflow discharges (Edwards GAM).

3. Demonstration of the relative magnitudes of individual and cumulative influences that GAM results might have on WAM results. With the inclusion of water management strategies recommended in the 2006 South Central Texas Regional Water Plan, the relative differences in influence between projected groundwater development and other water management strategies can be demonstrated.

4. Demonstration of linking multiple GAMs with a single WAM.

The case study will proceed as follows:

Task 1. Update TCEQ GSA WAM. Obtain the current GSA WAM used by the TCEQ for permitting perpetual water rights (Run 3) and add in the future return flows assumed for the Region L water plan as well as the recommended water management strategies from the Region L and Region J water plans. Execute the modified GSA WAM to obtain baseline streamflows at selected locations and water availability for selected rights.

Task 2. Analyze Edwards Springflows. Incorporate the projected future Edwards Aquifer pumping into the GAM (GWSIM4) used by Region L, and compute flow changes at the major springs for inclusion into the modified GSA WAM. Document the techniques and procedures used in differencing the modeled spring flows and adjusting for model calibration differences between observed and simulated historical springflows. Run the GSA WAM with the Region L assumptions, and compare streamflows and water availability with values obtained in Task 1. This will demonstrate the effects of the Edwards GAM linkage on the surface water system.

Task 3. Update GAMs. Update the Hill Country, Southern Carrizo-Wilcox and Gulf Coast GAMs with projected pumping from the applicable regional water plans. Note that the 2004 Southern Carrizo-Wilcox and Gulf Coast GAMs have already been updated for the Region L planning group.

Task 4. Develop Linkage Framework and Data. Relate springflow and groundwater flux features from the GAMs to control point locations in the GSA WAM. Develop data sets that describe these relationships and develop methodologies that can be used to transform the GAM springflow and groundwater flux information into flow changes in the WAM as a passive linkage. As the modeling systems will allow, develop generalized techniques (outside computer programs, spreadsheet techniques, or a combination thereof) that are applicable to a variety of WAM/GAM situations. HDR envisions that a definitions file will be developed for a specific WAM/GAM linkage that describes how specific GAM data are to be assigned to WAM control point locations. This would be a static definitions file (GAM and WAM specific) that could be applied to various alternative pumping scenarios. This technique, for all but the Edwards GAM, will result in constant changes in stream flow applied in all months at specific WAM control points. The changes in springflow from the Edwards GAM will vary monthly, as the dynamics of the specific situation require.

Task 5. Apply GSA WAM with Linked Data. Apply the GSA WAM with the GAM linkage data developed under Tasks 2, 3, and 4. Compare WAM results incorporating all four GAM effects with those from Tasks 1 and 2 to demonstrate relative magnitudes of the overall effects of incorporating GAM flow changes into the WAM.

Task 6. Prepare a final report. The final report will describe considerations summarized in this memorandum, document the techniques, computations and computer programs used to perform the linkage demonstrations, and summarize and discuss the various comparisons of model results. Based on the results of this case study, HDR will offer recommendations regarding future WAM/GAM linkages.

Updated Schedule

Based on the following schedule and assuming that TWDB accepts the proposed Work Plan by July 24, 2006, HDR forecasts that a draft report will be delivered for TWDB review on or about the week of December 11, 2006.

Task 1. Complete within 2 weeks following TWDB acceptance of Work Plan.

Task 2. Complete within 2 weeks following completion of Task 1.

Task 3. Complete within 4 weeks following TWDB acceptance of Work Plan.

Task 4. Complete within 8 weeks following completion of Task 3.

Task 5. Complete within 4 weeks following completion of Task 4.

Task 6. A draft report will be provided to the TWDB for review within 4 weeks following completion of Task 5. HDR will provide the final report, data files, and computer programs developed to facilitate transfer of data from the GAMs to the WAMs within 3 weeks following receipt of review comments from the TWDB.

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Appendix D
TWDB Draft Report Review Comments and HDR Responses

TWDB Draft Report Review Comments

May 4, 2007

REC'D MAY 7 2007

Mr. David Dunn
Vice President
HDR Engineering, Inc.
4401 West Gate Blvd., Suite 400
Austin, TX 78745

RE: Research and Planning Fund Contract between HDR Engineering, Inc. (HDR) and the Texas Water Development Board (Board), TWDB Contract No. 2005483557, Draft Final Report

Dear Mr. Dunn:

Staff members of the Texas Water Development Board have completed a review of the draft report under TWDB Contract No. 2005483557. The review comments are enclosed. As stated in the above-referenced contract, HDR will consider addressing review comments from the EXECUTIVE ADMINISTRATOR (shown in Attachment I), as well those of other reviewers into the Final Report. HDR must include a copy of Attachment I in the final report.

The Board looks forward to receiving one (1) electronic copy of the entire Final Report in Portable Document Format (PDF) and nine (9) bound double-sided copies. HDR shall also submit one (1) electronic copy of any computer programs or models and an operations manual developed under the terms of this CONTRACT.

If you have any questions concerning this contract, please contact Mr. Yujuin Yang, the Board's Contract Manager for this project at (512) 936-2385.

Sincerely,

William F. Mullican, III
Deputy Executive Administrator
Office of Planning

Enclosure

c: Yujuin Yang, TWDB

ATTACHMENT I
REVIEW COMMENTS ON TWDB CONTRACT NO. 2005483557
Linking WAM and GAM Models: Considerations and Recommendations

General:

The draft report summarizes various aspects related to linking wam and gam. It makes reasonable conclusions and recommendations for future work, although most recommendations are qualitative and common sense type. The graphics do an excellent job supporting the text. Overall the report is well written and meets contractual requirements.

Some of the discussion concerning groundwater modeling and GAM is misleading. It appears the familiarity with WAM greatly outweighed the authors understanding of the mechanics and development of the GAMs and MODFLOW.

Specific:

Executive Summary:

1. Paragraph 2, 1st sentence, page vi : Suggest rewording for clarification from, "…and the GAMs do not account for streamflow changes associated with permitted surface-water withdrawals and/or return flows." to "…*and the predictive simulations using the GAMs do not account for streamflow changes associated with permitted surface-water withdrawals and/or return flows*." Many of the calibrated models do indirectly account for streamflow changes related to historical permitted withdrawals and return flows since they use streamgages as targets. O.K.

2. Section ES.1 WAMs, paragraph 4, page vii: Explain why "changes in stages of different baseflows are unlikely to result in appreciably different levels of computed seepage to the underlying aquifer", and why "one can reasonably assume that interactions between the stream and the aquifer will continue to occur within the accuracy represented in a GAM".

3. Section ES.2 GAMs, paragraph 1, second sentence, page viii: Please reword from, "When completed there will be 31 GAMs in Texas, including coverage of 17 major aquifers and 14 minor aquifers" to "*When completed there will be 31 GAMs in Texas, including coverage of 9 major aquifers and 21 minor aquifers*." While it is true that 17 GAMs were developed to cover the 9 major aquifers, the 21 minor aquifers will be incorporated into 20 different GAMs not 14. Of the 20 different GAMs needed to provide coverage for the minor aquifers, we have 14 more models to develop, finish, or adopt. The major and minor aquifers are either combined geographically into individual models or broken into separate models depending on various flow regimes and/or complexity of the aquifer system(s).

4. Table ES-1 WAM and GAM Features and Distinctions, page ix: Please reword GAM geographic scales from "three-dimensional one-square mile grid cells" to "*three-dimensional no greater than one-square mile grid cells*" since several of the models use smaller grid spacing dimensions. Also please update GAM temporal scales from "responds slowly to hydrologic and climatic variations' to "*response to hydrologic and climatic conditions varies according to the aquifer system*" since karstic aquifers, such as the Edwards-Balcones Fault Zone, respond relatively quickly to wet conditions. O.K.

5. Page vii, could clarify that there are 15 major, plus 8 coastal river basins.

Section 1: Introduction

1. Paragraph 4, 1st sentence, page 1-1: Suggest rewording for clarification from, "...and the GAMs do not account for streamflow changes associated with permitted surface-water withdrawals and/or return flows." to "*...and the predictive simulations using the GAMs do not account for streamflow changes associated with permitted surface-water withdrawals and/or return flows.*" Many of the calibrated models do indirectly account for streamflow changes related to historical permitted withdrawals and return flows since they use streamgages as targets.

Section 2: Description of the WAMs and GAMs

1. Paragraph 2, page 2-1: Please reword from, "When completed there will be 31 GAMs in Texas, including coverage of 17 major aquifers and 14 minor aquifers" to "*When completed there will be 31 GAMs in Texas, including coverage of **9** major aquifers and **21** minor aquifers.*" While it is true that 17 GAMs were developed to cover the 9 major aquifers, the 21 minor aquifers will be incorporated into 20 different GAMs not 14. Of the 20 different GAMs needed to provide coverage for the minor aquifers, we have 14 more models to develop, finish, or adopt. The major and minor aquifers are either combined geographically into individual models or broken into separate models depending on various flow regimes and/or complexity of the aquifer system(s).

2. Figure 2-1 Location of WAMs and GAMs in Texas: Would suggest also noting the Pecos Valley aquifer was modeled with the Edwards-Trinity (Plateau) GAM.

3. Page 2-4, paragraph 3, 5th sentence, the use of "rainfall depths" is confusing. Suggest using only the word "rainfall" in place of "rainfall depths".

4. Section 2.2.1, paragraph 2, 2nd sentence, page 2-12: Please clarify statement to indicate 14 additional GAMs are needed to finish coverage for the minor aquifers.

Section 3: Technical Considerations for Linkage

1. Figure 3-2, page 3-3: A typical GAM uses annual time steps instead of monthly steps.

2. Section 3.4.1, last paragraph, pages 3-5 to 3-6: Same as for Executive Summary-2

Section 4: Mid-Course Review and Adjustment

1. In the description of the options considered, HDR should consider clarifying that the choice of Option 1 was based on the technical obstacles described by the contractors and the feedback gathered from stakeholders. It is likely that other options will be pursued at a later date.

Section 5: Recommendations

1. Section 5.6.1, paragraph 2, 3rd sentence, page 5-10: Please replace the word 'quiet' with 'quite'.

2. Figure 5-1, page 5-11: For ranking number 3, area box, please clarify 'Blum Country' and for ranking number 7, WAM box, please replace 'Norther' with 'Northern'.

3. Section 5.6.4, page 5-15: Preliminary to improvement of ET extinction depths is a comprehensive study of the occurrence of phreatophytes in Texas including detailed mapping of where they occur and some correlation to average root depth per plant species. Current vegetation maps are too coarse to accurately extrapolate this information into a GAM. Root depth may also be related to age of the plant, as well as the associated soil type. Invasion of some species, such as saltcedar, may not be applicable during early calibration periods but may predominant the system as the plant establishes itself.

4. Section 5.7, page 5-16: Was the USGS Diffusion Analogy Surface-water Flow Model (DAFLOW) reviewed as an alternative?

HDR Responses

ONE COMPANY *Many Solutions*℠

Memo

To: William F. Mullican, Texas Water Development Board	
From: David D. Dunn, P.E.	Project: Linking WAMs and GAMs
CC: Yujuin Yang, TWDB	
Date: May 17, 2007	Job No: 33189

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RE: Research and Planning Grant Fund Contract between HDR Engineering, Inc. (HDR) and the Texas Water Development Board (Board), TWDB Contract No. 2005483557, Responses to Comments Concerning the Draft Final Report

The following are HDR's responses to review comments received from the Board regarding the above-referenced report. The final report has been modified to reflect the changes noted below. Numbers and sections relate to specific comments received in a letter from the TWDB dated May 4, 2007 (attached).

Executive Summary

1. Change incorporated as requested.

2. Paragraph 4 has been revised to the following in order to better explain these assertions:

"Precise knowledge of the hydraulic connections between stream and aquifer systems is limited. However, changes in stages of different baseflows are unlikely to result in appreciably different levels of computed seepage to the underlying aquifer. Under baseflow conditions (typically small discharges), substantial differences in baseflow discharges result in relatively minor differences in stage, typically much less than one foot. Stage (hydraulic head) is a primary factor controlling the rate of seepage through the streambed, and with all other variables held relatively constant (wetted perimeter, permeability), small changes in stage will not substantially change the rate at which seepage occurs. As long as the stream bed does not completely dry up in the WAM simulation, it can reasonably be assumed that interactions between the stream and aquifer will continue to occur within the accuracy represented in a GAM. The driving force (hydraulic head of the water in the stream channel) is unlikely to vary substantially and knowledge of the relationship between stage and seepage is uncertain enough that any changes in stage are well within the precision limitations of the computational methods."

3. The sentence has been revised to the following in order to denote the number of GAMs (31) and the number of different aquifers modeled within those GAMs (9 major and 21 minor):

"When completed, there will be 31 GAMs in Texas, including coverage of 9 major aquifers and 21 minor aquifers."

4. a. Change incorporated as requested.
b. The text was written to denote that the surface water based WAM responds quickly to hydrologic variability, but the typical GAM does not. The table text has been changed to read as follows:

"Typical GAM response is slow, but response to hydrological and climatic conditions varies according to the aquifer system."

5. The following sentence was inserted as the first sentence in the first paragraph in Section ES.1

“There are 15 major and 8 coastal river basins in Texas.”

Section 1: Introduction

1. Change incorporated as requested.

Section 2: Description of the WAMs and GAMs

1. The sentence has been revised to the following in order to denote the number of GAMs (31) and the number of different aquifers modeled within those GAMs (9 major and 21 minor):

“When completed, there will be 31 GAMs in Texas, including coverage of 9 major aquifers and 21 minor aquifers.”

2. Change incorporated as requested.

3. Change incorporated as requested.

4. The sentence has been modified to the following:

“The fourteen additional models needed to cover the minor aquifers are either completed, in progress, or planned.”

Section 3: Technical Considerations for Linkage

1. The springflow time series depicted has been changed to show an annual average to be consistent with the typical GAM stress period.

2. The paragraph text has been modified to read as follows:

“However, in very few cases will alterations to the surface water system result in noticeable changes in aquifer recharge. New water rights granted by the TCEQ are unlikely to completely dry up a stream because they will be subject to instream flow requirements and will be required to pass inflows to downstream senior rights. While precise knowledge of the hydraulic connections between stream and aquifer systems is limited, differences in stages due to changes in baseflows are unlikely to result in appreciably different levels of computed seepage to the underlying aquifer. Under baseflow conditions (typically small discharges), substantial differences in baseflow discharges result in relatively minor differences in stage, typically much less than one foot. Stage (hydraulic head) is a primary factor controlling the rate of seepage through the streambed, and with all other variables held relatively constant (wetted perimeter, permeability), small changes in stage will not substantially change the rate at which seepage occurs. As long as the stream does not completely dry up in the WAM simulation, one can reasonably assume that interactions between the stream and the aquifer will continue to occur within the accuracy represented in a GAM. The driving force (hydraulic head of the water in the stream channel) is unlikely to vary substantially and knowledge of the relationship between stage and seepage is uncertain enough that any changes in stage are well within the precision limitations of the computational methods. Exceptions include in the case of structures built and permitted specifically to enhance recharge to an aquifer, or to water rights located upstream of highly permeable recharge zones where little of the water entering a stream reach remains as streamflow and a substantial fraction is “lost” to the underlying aquifer. These situations are primarily associated with the outcrop of the Edwards Aquifer and should be treated as special cases.”

Section 4: Mid-Course Review and Adjustment

1. The following text has been added to the end of the 1st paragraph in Section 4.3.

"Option 1 was selected based on the technical considerations described previously and the feedback obtained from the stakeholder survey. A linked WAM and GAM can still be pursued at some future time."

Section 5: Recommendations

1. The typo has been corrected.

2. The typo has been corrected.

3. We have added this consideration as an additional aspect of our recommendation in this area. The following paragraph was added as the third paragraph in section 5.6.4.

"Phreatophyte characteristics and occurrence varies widely across the state, and current vegetation mapping lacks the appropriate definition and data to be incorporated into a GAM. In order to more fully and accurately consider the impacts of phreatophyte populations on regional groundwater resources, a comprehensive study to map specific phreatophyte species across the state is recommended. This study should also include field studies correlating average root depth with phreatophyte species, soil characteristics, depth to groundwater, annual precipitation, age and other possible explanatory factors to more accurately include this information in GAM models. Application of these data in GAM simulations would differ during early calibration periods versus predictive simulations."

4. The USGS DAFLOW model was not reviewed as an alternative because it does not have an appropriate conceptual framework analogous to the WAMs like the RiverWare software mentioned. The DAFLOW model is a hydraulic model that simulates unsteady flow in open channels, similar to UNET, DAMBREAK, and the unsteady flow capability in HEC-RAS. The link of DAFLOW and MODFLOW was accomplished to simulate short-term interactions between ground and surface water. The time scale of DAFLOW is on the order of hours or smaller. DAFLOW does not have any method for accounting for water rights or management of surface water resources.

A reference back to Section 3.8 describing the RiverWare system has been added to the first sentence in Section 5.7.

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