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BUDGETS AND FLUXES OF SALT AND WATER: MODEL APPROACHES AND EXAMPLES FROM THE GREAT BEND PRAIRIE AND EQUUS BEDS REGION OF SOUTH-CENTRAL KANSAS

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EXECUTIVE SUMMARY

Introduction

This report develops a budgetary approach to describing and understanding the intrusion of natural salt into the freshwater aquifers and surface water bodies of south-central Kansas. The immediate stimulus for this development is the need to understand the distribution and movement of salinity in the groundwater of the northwestern portion of Equus Beds Groundwater Management District No. 2 (GMD2), particularly with respect to the municipal water supplies of the cities of Nickerson and Hutchinson. However, because this region has a complex mixture of both local salt sources and inputs of saline groundwater and surface water from the west, a regional understanding of salt dynamics is required. A recently-completed study of mineral intrusion in Big Bend Groundwater Management District No. 5 (GMD5) provides a basis for developing a regional model that can guide and be tested by the ongoing Equus Beds Mineral Intrusion (EBMI) study.

The type of "box models" used in the budgetary approach rely on the principle of conservation of mass to balance inputs, outputs, and inventories in the variously-defined "compartments" of the system under study. While such models have important limitations -- they are limited to relatively large-scale assessments, and cannot provide detailed or mechanistic simulations of complex processes -- they also have important advantages:

- The approach is well suited for the types and density of data available for most hydrologic and geochemical systems, for which data bases are usually inadequate to support detailed numerical models without a large number of assumptions and approximations.
- Because the model can be presented in intuitively obvious schematic diagrams and is based only on fundamental algebra and physical principles, it provides an excellent tool for public information and education.
- With proper definition of the budget "compartments," such models can provide useful management criteria for allocating resources, setting standards, etc.
- Where more detailed understanding is needed and possible, the models can easily be subdivided or "nested" by addition of more interactive compartments and fluxes.
- Once a model structure has been developed, its dynamic behavior and resource and management implications can be easily and quickly explored using inexpensive and readily available computer software.

Overview of report

Because we anticipate further development and application of the initial budget models developed in this report, Section I of the report is devoted to defining and explaining the terms and concepts underlying the approach, with an emphasis on providing information understandable by the non-specialist. This section addresses both single-component budgets (water or salt) and the additional power that is achieved by combining more than one component; by requiring water and salt budgets to balance simultaneously in a single system, it is often possible to develop additional equations describing the system with a minimal increase in the number of unknown quantities.

Section I concludes with a description of the mineral intrusion area, and a brief discussion of present and previous work in that area.

Section II of the report is presented in the spirit of a tutorial exercise, and describes an initial attempt to estimate the flux of salt into the EBMI study area via groundwater inflow. This flux estimate is based on observations and basic hydrology, and provides both an estimate of the quantity (75-190 metric tons of chloride per day, which is equivalent to roughly 125 to 315 metric tons of salt as sodium chloride), and an example of how budget components can be developed and applied. However, this approach is not a complete budget, so the flux estimates are unconstrained and there is no rigorous basis for resolving the apparent differences between the results of two slightly different formulations of the "compartment" boundary.

Section III constitutes the formal description of the combined salt and water budgetary process, and presents the results developed to date for budget models of the south, central, and north sections of the salt-affected regions of GMD5. The northern, and most heavily contaminated, section of GMD5 is immediately upgradient from the EBMI study area. As estimated in the preliminary flux assessment (Section II) and confirmed by modeling (Section III), this region supplies a substantial salt input to the EBMI region of interest.

Section IV presents a brief discussion and summary of the key conclusions.

Budget models

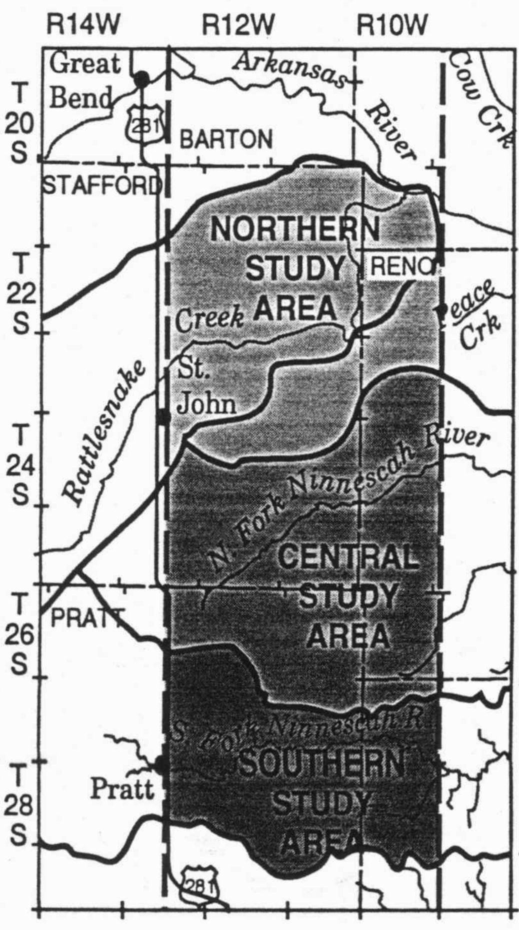
All of the models used are box models with multiple inputs and outputs for both salt and water. Water can enter the system through groundwater inflow (laterally within the alluvial aquifer), surface water inflow, bedrock discharge, and precipitation (or recharge). It can leave through groundwater outflow, surface water outflow, evaporation (or ET), and seepage (to the aquifer from the surface, and to the bedrock from the aquifer). Salt can follow the same pathways, except that the salt content of precipitation and evaporation (or ET) water fluxes is taken as zero, as is the salt load of the surface water inflow. The model process require the assumption of well-mixed compartments; although this would be unrealistic for interpreting details within the compartments, it is a generally reasonable assumption in view of the fact that the results of concern were the bulk outputs of salt and water to adjacent streams and groundwater bodies.

Available ground water, streamflow, water quality, and meteorological data were used to calculate or estimate fluxes and inventories. The power of the combined-budget approach was demonstrated by success in constraining the rate of salt inflow from the bedrock -- an important term that cannot be directly measured.

For the purposes of this initial report, the basic calculations were done primarily on spreadsheets. However, the budget systems were also input into the software package STELLA, a well-established budget model package available for both PC and Macintosh. This system provides a quick and convenient way to analyze transient responses in a changing system, to run sensitivity analyses, and to test the effects of nested models or system modifications on predictive outputs. This software is discussed briefly in the text, and in more detail in Appendix A.

Principal results

Output fluxes for the three regions are summarized below. In each region bedrock seepage to the groundwater accounts for nearly all of the salt input. In the south and central sections of the GMD5 area, a single-box model was used to represent the groundwater, since surface water dynamics and distribution are relatively simple in the absence of significant storage capacity. In the northern section, the presence of the Quivira marshes introduces a surface water component with a significant precipitation and evaporation budget, so a two-box model was used to describe this portion of the system.



Water and Salt Fluxes Out of the GMD5 Areas

PATH	Water (Mm3/yr)	Salt (MkgCl/yr)
GW	10	40
SW	43	86
GW	20	12
SW	137	41
GW	75	8
SW	60	24

An important aspect of all of the regions is that although the salt input is entirely to the groundwater, most of the salt output is via surface water as a result of groundwater discharge. This means that the total salt load of the groundwater body is very dependent on discharge and surface flow; water use, management, or climate change that decreases groundwater discharge and surface water outflow will result in progressive salinization of the aquifer, since it is reasonable to treat the bedrock salt discharge as approximately constant.

The more detailed analysis carried out for the northern study area yields a number of significant conclusions. Perhaps the most important finding of this study is that the total salt flux can be accurately estimated; this is a direct result of analyzing the combined stream-aquifer system with simultaneous budgets for salt and water.

Some modeling predictions change remarkably little for the different scenarios analyzed; they can be assumed to be characteristic features of the natural system which are likely to be substantially affected by human activities only when the hydrologic system is altered beyond its normal range of functioning. For example, the estimated total saltwater recharge from bedrock is remarkably constant, ranging from 2.5 to 3 Mkg/yr. The same is true for the ratio of surface to ground water salt fluxes, which ranges from 2 to 3.25.

Another important piece of information derived from the analysis is the residence time of the groundwater system. For the northern section under natural conditions, this is estimated as approximately 100 years; with development effects, this may drop to 50 years. However, this is still longer than most planning horizons. One of the implications of this time constant is that (for example) the effects of water management changes in the Rattlesnake Creek-Quivira Marsh region that shifted the ratio of surface water to groundwater salt loads might not be felt in western GMD2 for several decades -- and when observed, might not be attributed to the actual source.

In the northern section, the consideration of outflow relationships is complicated by the fact that surface water outflow goes predominantly to the Arkansas River, while groundwater outflow enters the western portions of the GMD2 aquifer. Both river and aquifer are important water resources, and operate on quite different time scales. The risks and trade-offs involved in water flow and salt load management may be perceived quite differently by various groups of stakeholders.

Summary and conclusions

- Usefulness of simple models

We demonstrated in this study that simple balance models are useful in three ways. First, they provide quantitative answers to questions regarding the overall system behavior, and so facilitate our understanding of complex systems. Second, they can be valuable tools to aid water managers in establishing policies dealing with resource allocation. In particular, these models can easily be set up to provide not only an estimate, but also attach a measure of reliability to it. Thus, managers can make decisions based on acceptable levels of risk for different situations. Finally, these simple models can be a valuable aid in developing more detailed models that are embedded into them. For example, results can be used to constrain parameter values and scope out a range of boundary conditions for more complex situations.

- Dealing with complexity -- embedded models, hierarchies, and information transfer

Different mass balance models can be developed for the same system, depending on the desired level of detail. More detail requires subdividing the study region in a larger number of reservoirs; this in turn requires the evaluation of more fluxes and the estimation of more parameters. This approach is discussed, but not fully demonstrated, in this report.

A given system can be represented with a hierarchy of models, depending on the questions to be addressed. Each model in the hierarchy can address questions at a different scale or resolution, by incorporating more or less detail as necessary. In this report we start with the simplest conceptual model that explains overall behavior. Because it uses the least number of variables, it is the most robust model to which we can refer to time and again; this is not a pre-model that you discard later on. Although parameters of this model can and do change as more information is incorporated, these parameters change less than those of models at finer scale or those of subregions because of the effects of averaging over both time and space.

- Steady-state versus system dynamics - residence time

Developing management policies requires an understanding of the dynamics of the system, both in terms of fluxes, and of residence (or response) times in each reservoir. In our model the controlling factor is the groundwater residence time, which ranges from 100 yr. in the baseline case to 50 yr. in the development case. While equilibrium models can be calculated on a spreadsheet, the software package STELLA is well adapted for modeling dynamics and transient responses in a time-dependent budget model.

- Uncertainty and risk analysis

Estimation introduces uncertainty because not all variables are accessible to measurement. For the northern study area, we illustrated how to deal with uncertain quantities (e.g., key fluxes) by using simple uncertainty analyses, which can provide reliability bounds on key fluxes and associated predictions.

Uncertainty also affects some of the variables that are measured on a regular basis, such as daily streamflows. This uncertainty is caused by the intrinsic variability, and can only be reduced by averaging. Daily streamflows are highly variable, so their prediction carries a large uncertainty. Even mean annual streamflows can be highly variable (e.g.

Rattlesnake Creek), and this affects the estimation of the average of the whole time series. In this report we only considered the uncertainty in the mean values, and its impact on model predictions.

The effects of uncertainty and natural variability on management policy and practice can be assessed by linking sensitivity analysis of the dynamic budget model with economic or regulatory criteria (e.g., the effects of maximum or average salt concentrations).

- Data limitations and possible improvements

Application of the combined water and salt budget model requires more data than a hydrologic model that focuses only on volumetric fluxes. Salt concentrations are a crucial piece of information to make realistic predictions of salt fluxes. Unfortunately, water quality data are far less available than discharge measurements. Model predictions can be updated when more data becomes available, but an increase in the reliability of predictions requires more "density" of information.

The model is a convenient tool for assessing the management benefits of collecting more data, compared with cost. In the type of stream-aquifer system studied here, there is a clear indication that water quality data should be gathered at more frequent intervals (e.g., weekly) at selected points. A small investment in gathering this type of information will reap large benefits in the form of improved model predictions.

I. INTRODUCTION AND BACKGROUND

A. Purposes of report

The general objective of this report is to develop and make initial application of a budgetary model of salt transport and distribution in the areas of south-central Kansas where natural salinity is an important control on the use of water resources. Programs of research and assessment are producing substantial quantities of relevant data throughout the region of interest, and we anticipate that the estimates that we are now able to produce will be greatly refined over the next one to two years. This budget-based modeling approach has not been fully developed or rigorously applied in the past, and because we believe that it has important potentials to assist both scientific understanding and management of the resource, we intend that this report will provide the basis for both technical review and general understanding of the method. We proceed in the following stages:

- In this introductory section of the report, we describe in general terms the conceptual approach to developing and applying multi-component budget-based models to a variety of problems and systems, and we describe the salient features of the salt-affected systems of south-central Kansas.

- In the following section, we develop a simple example of a flux-based budgetary calculation of the transport of salt by groundwater flow from the northeastern portion of Groundwater Management District No. 5 (GMD5) to the western portion of Groundwater Management District No. 2 (GMD2). This illustrates both the power and limitations of the approach in its simple form.

- We then describe the development of a fully quantitative budgetary model for salt and water in a well-defined portion of the region. By doing so, we demonstrate the ability to establish or constrain values for parameters that cannot be adequately measured directly; we also establish the basis for future refinements and extensions of the budget model process.

- Finally, we discuss briefly the implications of this initial study for salinity-oriented research, assessment, and management in the region, and discuss some of the future directions and potential applications.

By pursuing this approach, and by providing technical appendices that describe in some detail the software, calculational approach, and other aspects of the model effort, we hope that a well-understood, appropriately refined, and generally accepted approach can be developed that will support the detailed modeling and management strategy development as additional data become available.

B. Conceptual approach to multi-component budgets

The budgetary approach to water resources is often exemplified by the "bank account" analogy -- if you consistently remove more from a reservoir or aquifer than is replenished, the level (inventory, or "bank balance") drops. This is a common-sense derivation of the physical principle of conservation of mass -- everything has to be somewhere, and it all has to add up. This principle underlies all of the modeling and calculational approaches to water and chemical budgets, but is often not the explicit focus of system description or understanding.

We can illustrate this -- and some of the concepts and opportunities that derive from a budgetary focus -- by considering Figure 1. This illustrates a "box model" approach to a water mass (the perceptive reader will suspect -- correctly -- that the selection of flux arrows is not entirely random; this will turn into our "real aquifer" model as we proceed). For the moment we consider only a single component.

If I is the inventory (volume (L^3) or mass (M)) of material in the system, ΔI is the change in that inventory over time, Qi is the total inflow ($Qi = \Sigma Qi_{1..n}$; L^3/T or M/T) and Qo is the similarly defined total outflow, then the scientific formulation of the "bank account analogy" is simply

$$Qi - Qo = \Delta I$$

or, the "balance" changes to reflect directly the difference between deposits and withdrawals. At this point, let's use the single component system shown in Figure 1a to explore some of the budgetary "tricks of the trade" that make model approaches powerful, but sometimes confusing.

1. Steady-state, equilibrium, etc.

If $\Delta I = 0$ (that is, there is no net change in inventory) then $Qi = Qo$. The assumption that this is actually the case is very common in groundwater hydrology, for several reasons. One basic reason, that is usually applied to "natural" (predevelopment) systems, stems from a fundamental difference between bank accounts and aquifers -- nature, unlike the average banker, puts some limits on how much your account can hold. As groundwater levels rise, discharge to the surface, surface flow, and evapotranspiration all increase, so that the aquifer capacity has a physical limit. If, on average, the aquifer is "full," then it is in a long-term steady state.

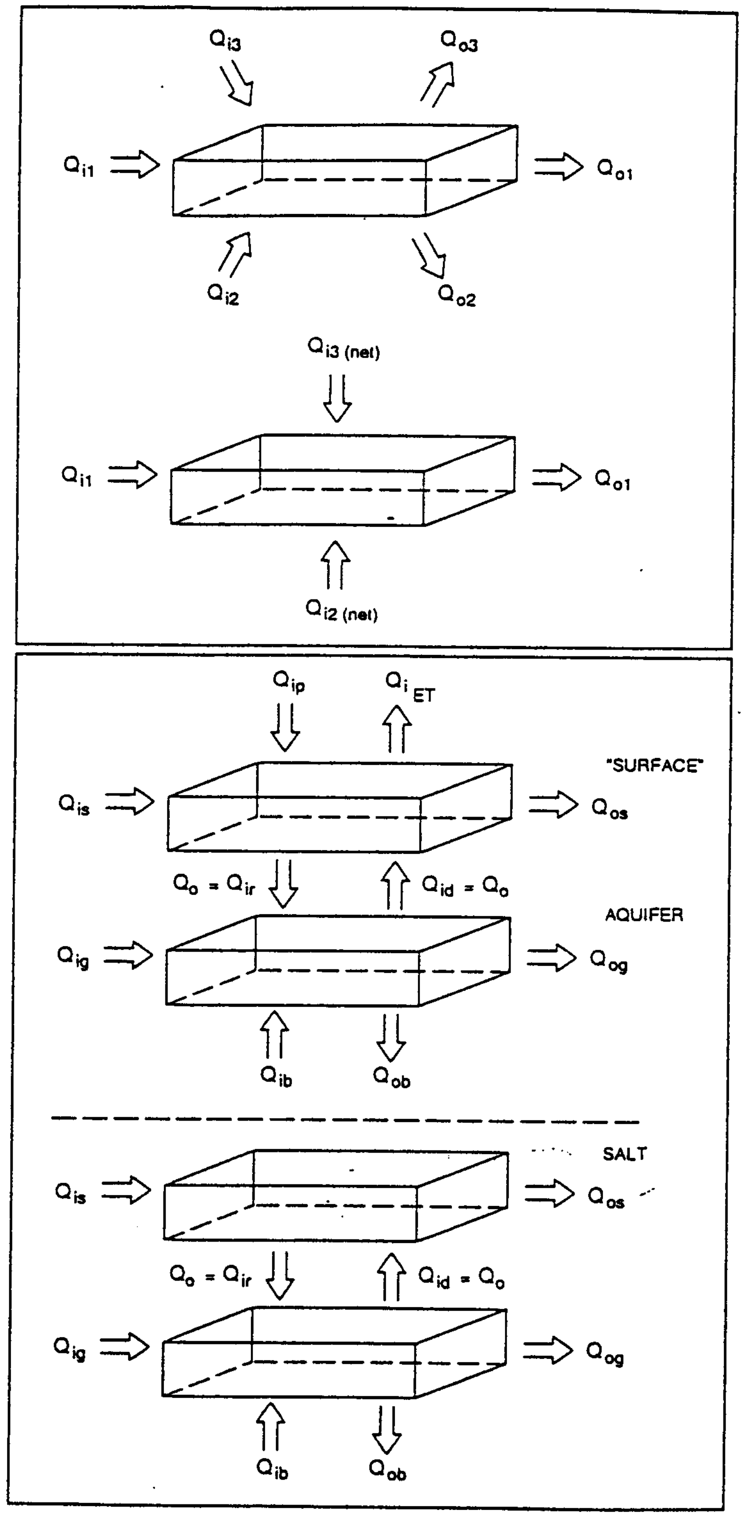


Figure 1. Box models used for budget calculations. The boxes represent inventories, and the arrows fluxes, of materials. (a) Single-box models, representing the simplest form of budget calculation. (b) A multi-box model, with a variety of fluxes affecting the individual boxes and their interactions.

2. Time constants or residence time

Before we continue with discussion of steady-state assumptions, let's look at the question of characteristic time scales of the system. There are a variety of formulations of the time constants of physical, chemical and biological systems, but for water, the concept of residence time is both common and useful. That is the same as the average "age" of the water, if "birth" is taken as the moment of entry into the system (e.g., a specific volume of aquifer) we are considering. For a system that is at or near steady state, the residence time is

$\tau = I/Q$, where $Q = Q_i = Q_o$.

This tells us something about the renewal or replacement rate of the resource, and about the appropriate time and space scales for management and experimentation. However, it also points to one of the strengths of the budgetary approach -- the ability to incorporate other types of measurements. In this case, if we can use isotopic or chemical techniques to measure the age of the water, or the difference in age between up- and down-gradient ends of the system, we do not need a direct measurement of the fluxes, which are often difficult to determine.

3. The power of approximations

Albert Einstein is reputed to have said that "Everything should be as simple as possible, but no simpler." Budget-based models make it easy to follow this axiom, and to adapt the approach to the specific question at hand. As an example, if we have determined that the water in a selected volume of aquifer has a residence time (or average age) of 100 years, we can make straightforward comparisons of the importance of various factors at a variety of time scales. If the inventory of water in the saturated thickness is equivalent to an average free-water depth of 10 meters, and if the net annual recharge is 5 cm, or 0.05 m (both values that are reasonable for south-central Kansas), then the average annual recharge input is only 0.5% of the inventory.

For a system with such characteristics, some questions on a time scale of years may be adequately addressed without considering recharge. If the annual average value of the recharge is a fraction of a percent of the total inventory, and especially if it does not dominate the total water input to the system, other factors may introduce errors or uncertainties greater than that due to neglecting recharge -- for example, intra- and inter-annual inventory variability can be on the order of percents, and the accuracy of our knowledge of the absolute values of aquifer and hydrologic characteristics is often on the order of tens of percents. Considering the relative magnitudes of various factors, especially in relation to the range of uncertainties, often leads to use of "quasi- (or pseudo) steady state" assumptions -- which, in effect, say that we may know that the physical system is not in equilibrium or that the model does not exactly represent the real world, but that assumption is good enough for the purposes at hand.

A important point to consider under the heading of approximations is the issue of limiting values and "conservative" estimates. For example, if we neglect to consider recharge in a model, we can be sure that our inventory and outflow estimates may be somewhat depressed. The calculated values then (if other terms are well known) become lower limits on the actual value, and if we would like the inventory to be as large as possible, then the lower limit estimate is "conservative" with respect to estimating water resources. Such limiting values can be far easier to obtain than a really good estimate of the actual value, and can be gradually improved as the model evolves in complexity (see Figure 1b) and range of possible applications.

A formal or systematic approach to such questions is sensitivity analysis -- the process of varying inputs and outputs to a model to determine which variables are most important, and how the accuracy or precision of the output can be improved. This kind of basic understanding plays a big role in the cost-effective design of monitoring systems, for example, as well as in guiding the scientist to a working model that is "as simple as possible, but no simpler."

4. Multiple concurrently modeled components

Figure 1b illustrates a more complex situation, in which separately definable sub-systems exchange material as well as having their own separate fluxes. We can also consider the situation in which we are budgeting two different materials -- such as salt and water -- in the same system. In such systems the power inherent in the "tricks of the trade" discussed above can be amplified by selective application to simplify or limit specific problems or uncertainties. For example, by addressing net exchanges rather than their component parts (Figure 1a), or by focusing on long or short time scales, the more complex systems can be collapsed into simpler ones, or limiting conditions and sensitivities can be explored. The other important advantage of multiple-component systems is that (for example) the salt and the water follow similar but not identical pathways, and both budgets have to balance independently. This can increase the number of equations faster than it increases the number of unknowns -- an advantage discussed and illustrated in more detail in section III below.

C. The mineral intrusion area of south-central Kansas

Large portions of central Kansas are underlain by natural salt-bearing formations that increase the salinity of surface water and groundwater (See Figure 2). Understanding the natural controls on salinity and how they interact with human water use and management is critical to the economic development of the area, and in extreme cases, to the health of the inhabitants. This task is complicated by the fact that nature is not the only contributor to salinization of water -- humans add to the problem with oil field, salt-mining, municipal, and industrial wastes, and by increasing evapotranspiration through (for example) agricultural and domestic irrigation.

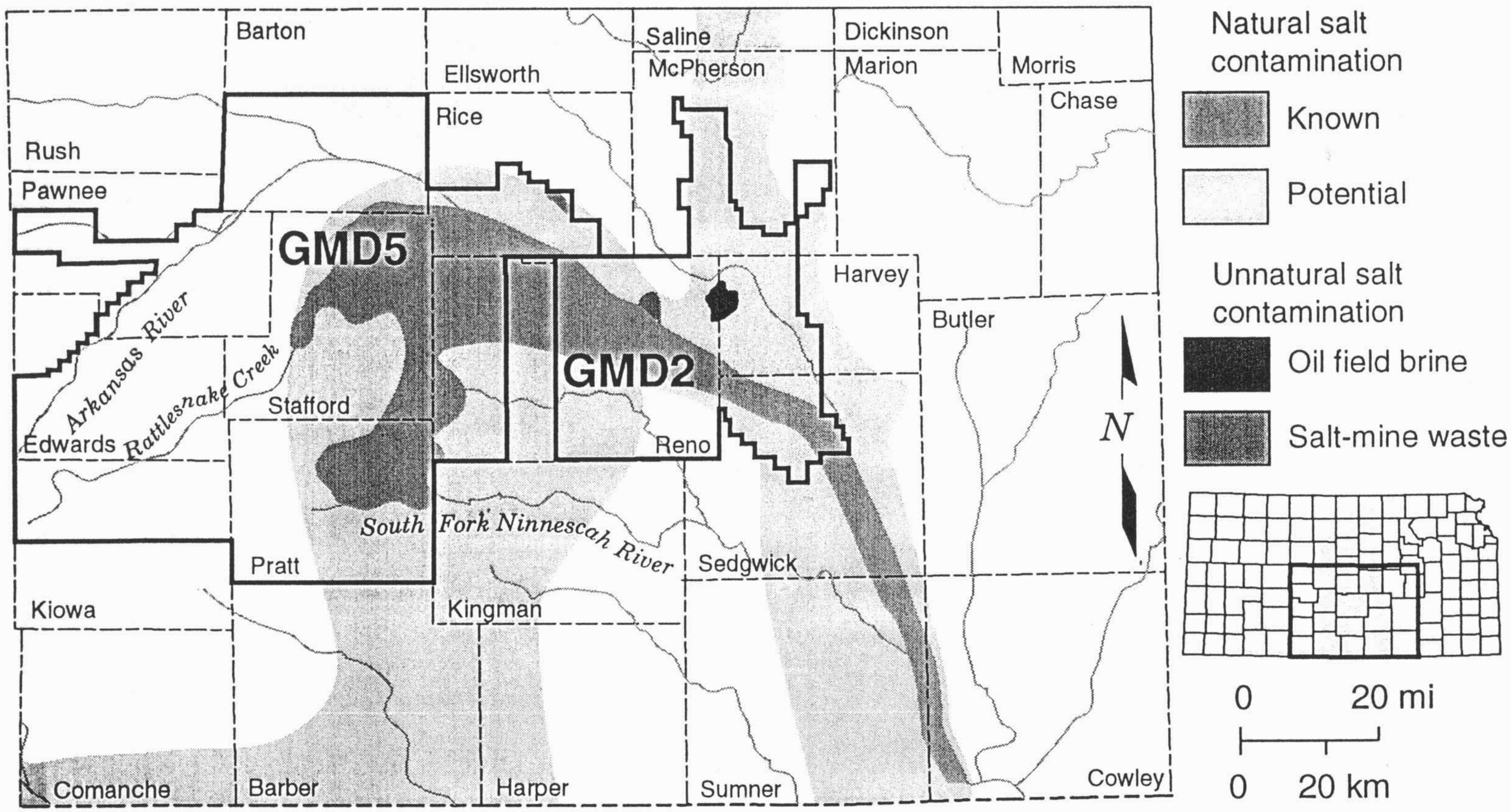


Figure 2. Areas with known or potential saltwater contamination in south-central Kansas. Areas identified as "known" natural salt contamination have saltwater within the freshwater aquifer. In the areas labeled "potential" natural salt contamination, subsurface bedrock formations containing salt or saltwater are in contact with the overlying freshwater aquifers (from Buddemeier et al., 1995).

In south-central Kansas the problem is most acute where the important freshwater aquifers are in contact with, or in close proximity to, the salt-bearing bedrock formations. Here, the Great Bend Prairie and Equus Beds aquifers, and the Groundwater Management Districts associated with them, provide agricultural, municipal, and industrial water supplies to an important region of the state.

In the western part of this region, the Cretaceous bedrock underlying the aquifer thins and disappears, leaving the salt-bearing Permian formation in hydraulic contact with the overlying alluvium. This boundary, depicted in Figure 3, is roughly coincident with Highway 281, and the subcrop of the Cedar Hills formation and/or hydrostratigraphic unit shown there is a major source of mineral intrusion.

In this region, there are clearly some hot spots of saltwater discharge from the bedrock (see Discussion of previous work below). This salt is mixed into the freshwater system and transported both as groundwater flow and as discharged surface water -- some of which may re-infiltrate into the groundwater down-gradient.

In the downgradient and more lightly affected areas, it is extremely challenging to differentiate among local saltwater intrusion, salt advected from an upgradient source by groundwater flow, salt originating from recharge of inflowing surface water, and the local sources of contamination discussed above. Since these various sources have very different predicted future effects and implications for management, the distinction is critical. In such cases a budgetary approach to the overall system can be extremely helpful in constraining the possibilities and in providing focus for detailed investigations.

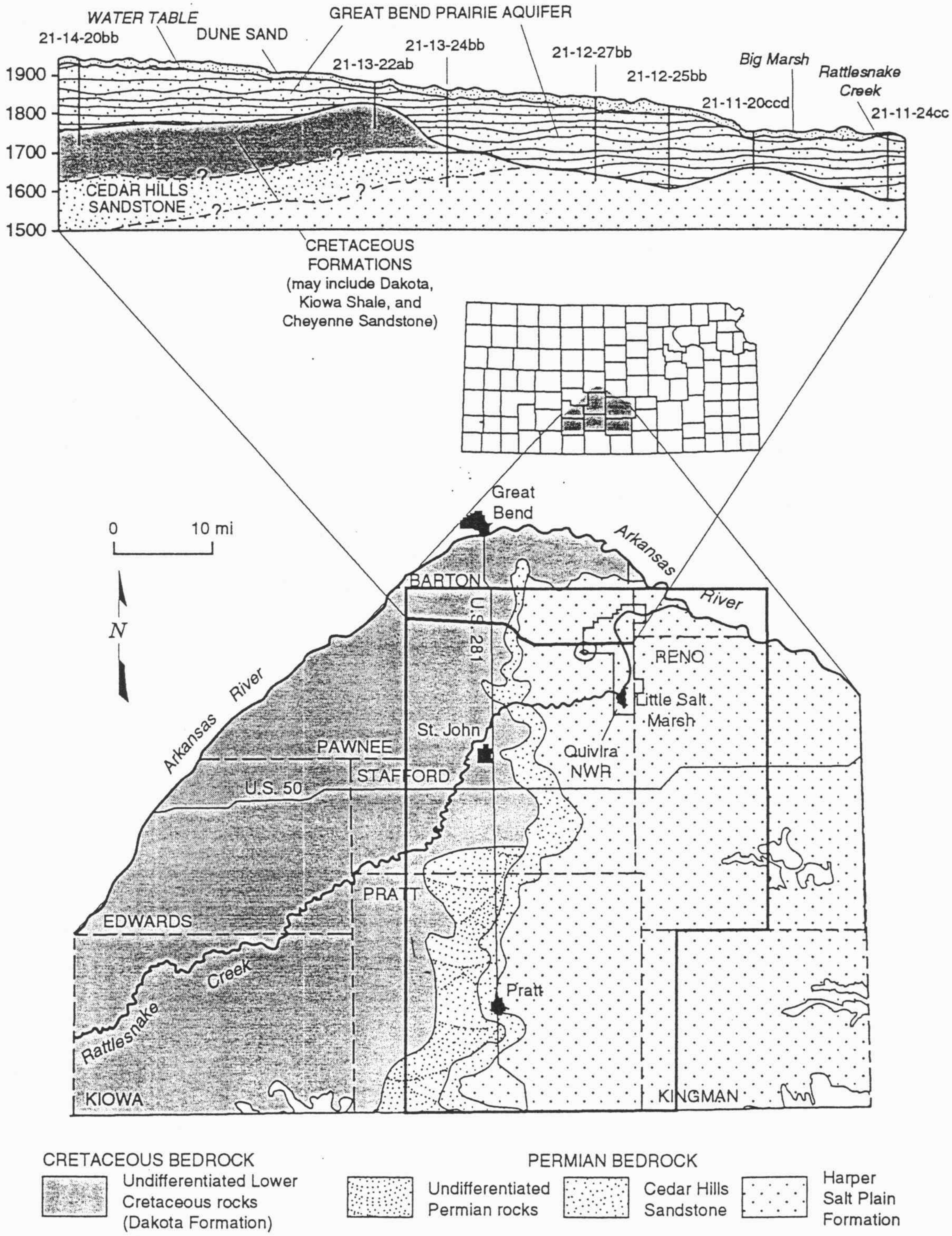


Figure 3. Location map and hydrogeologic setting. The Great Bend Prairie aquifer, a Quaternary alluvial deposit in South-Central Kansas, overlies the salt-containing Cedar Hills and other Permian formations. In the west, Permian formation brines are confined by the Cretaceous Dakota formation, but in the east, saltwater is free to mix upward and contaminate the overlying freshwater aquifer and the baseflow component of streams.

D. Previous and ongoing work

1. GMD5

The eastern portion of Groundwater Management District No. 5 has been a focus of mineral intrusion investigations for many years (see figures 2 and 3). In large areas of eastern Stafford Co. and Reno Co., groundwater and surface water are essentially unusable for most purposes. Patches of mineral intrusion occur in other areas, with effects on both groundwater quality and the Ninnescah River system -- both of which are important water sources for the cities of the region, as well as for local domestic and agricultural use. A cooperative study of the distribution, mechanisms, and effects of mineral intrusion in eastern GMD5 was recently completed by KGS, GMD5, and the Kansas Water Office; Appendix D presents a compilation of recent KGS reports and publications based on that study.

The GMD5 study was based primarily on a network of monitoring wells installed on a township (6-mile) grid. This permitted regional characterization, but was rather coarse for the purpose of attempting to make determinations at scales of a few miles. However, the hydrology is sufficiently well-known to permit reasonable estimates of the flow velocity and direction (see Figure 4 for an illustration of potentiometric surface contours in the northern part of the study area). This information, plus basic knowledge of aquifer characteristics and estimates of vertical salinity profiles, permits estimation of salt and water fluxes in various parts of the system.

Discussion of the methods of characterization and the overall results may be found in Garneau (1995) and the various references given in Appendix D. From the standpoint of budget models, the salt load (total amount of salt contained in a given volume, regardless of concentration or distribution) is an important feature, since this has to be conserved in the model. Figures 5 and 6 show two alternative presentations of the salt load in the region. Figure 5 gives the load relative to the saturated thickness of the aquifer (which varies over about a factor of two), and Figure 6 depicts the salt load at each of the northern monitoring sites in absolute terms. Both present the load in terms of equivalent thickness of a groundwater layer of 42,000 ppt Cl (the estimated value for the bedrock brine), but this can be transformed into mass of salt or any other measure desired (for example, one m^3 of water containing 42,000 ppt Cl would contain 1000 liters of solution, and therefore 42 kg of Cl; if salt is assumed to be NaCl (halite, or sodium chloride) the total mass could be about 69 kg of salt).

For this report, two points are worth noting from Figures 4-6 -- first, that there is a significant salt load immediately upgradient of western GMD2, and second, that the distribution appears to have a maximum in north-central Stafford county -- it seems to decrease, rather than remaining constant or increasing to the east. Because of the widely spaced data points, however, these tentative conclusions must be viewed with caution. This is noteworthy, because if groundwater flow were the only path by which salt leaves the area, and if the system were in long-term steady state, we would expect a constant load downgradient if the sole source were the Cedar Hills subcrop, and an increasing load if there were additional bedrock sources to the east of the major input.

2. GMD2

At present, a cooperative study involving GMD2, KWO, KGS and the US Bureau of Reclamation (USBR) is in progress in eastern GMD2, with a primary objective of evaluating the long-term implications of mineral intrusion and transport for the municipal water supplies of Hutchinson and Nickerson. A preliminary scoping study by Whittemore and Sophocleous (1996) reviews the background information, problems, and settings for the study. This investigation, following the GMD5 study, is the motivation for developing robust budgetary approaches to understanding the nature of, and influences on, mineral intrusion into this region. The following sections of the report explicitly or implicitly pursue this development.

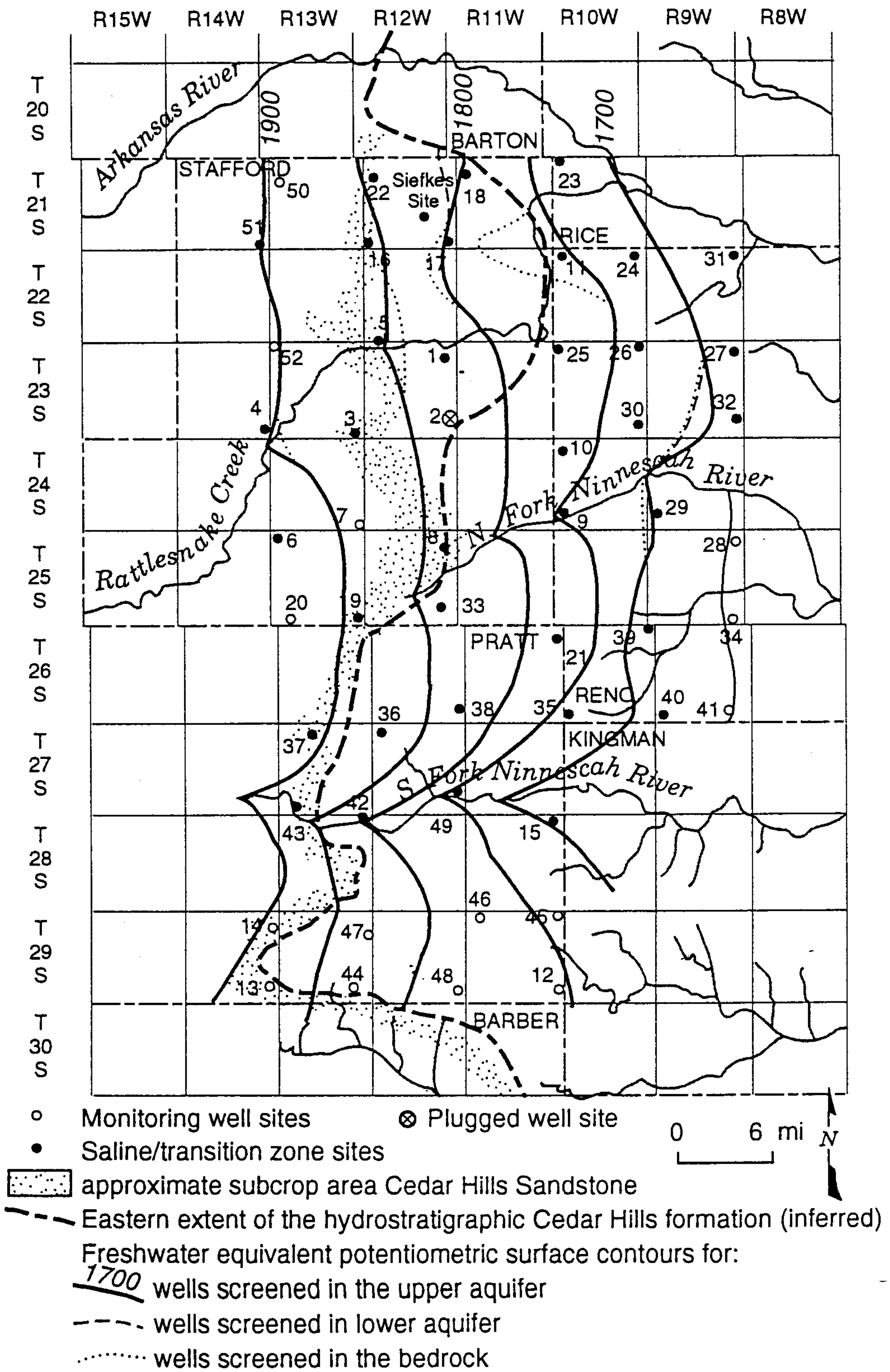


Figure 4. Fresh-water equivalent potentiometric surfaces for various depths within the mineral intrusion study area of the Great Bend Prairie aquifer (1994). From Garneau (1995).

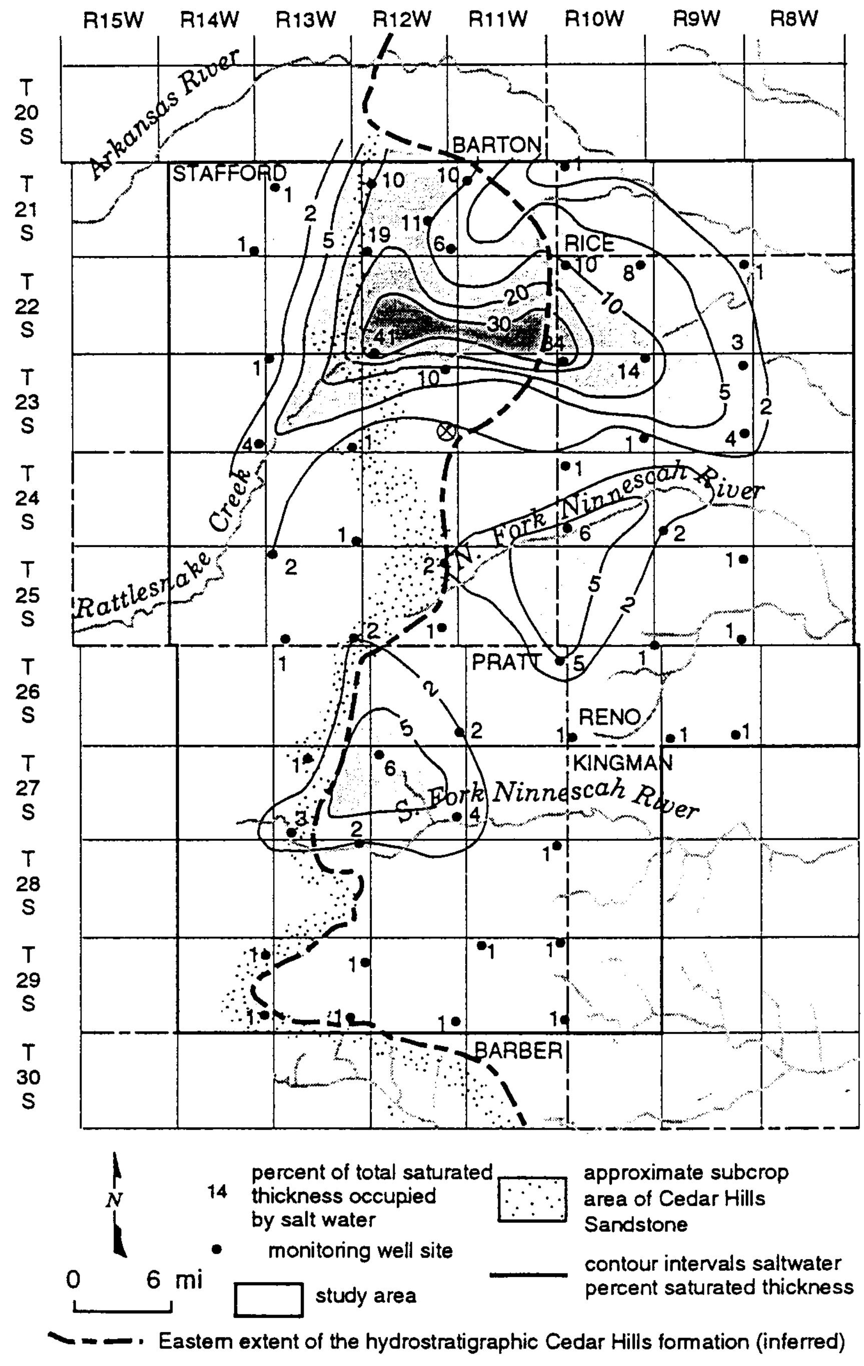
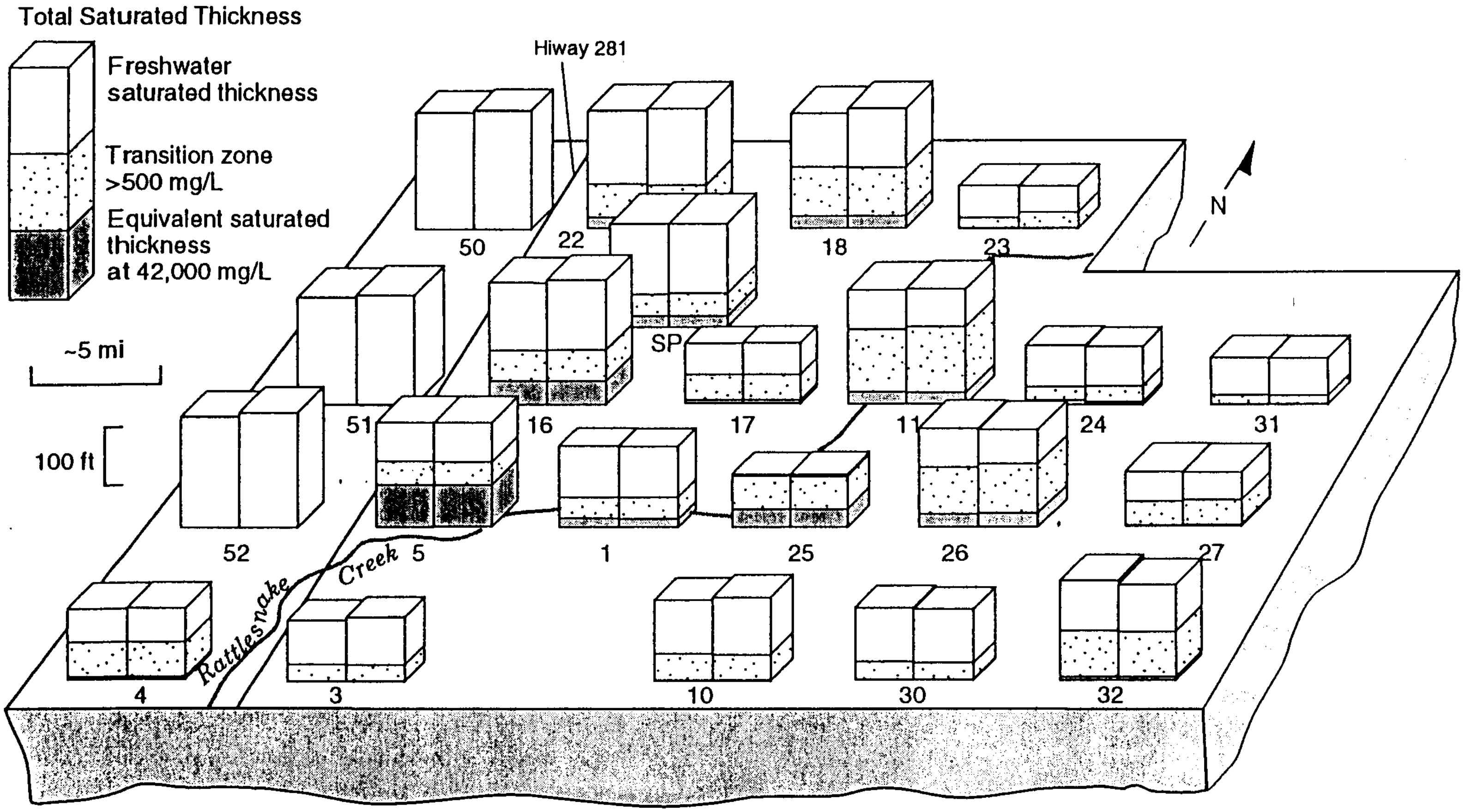


Figure 5. Distribution of total Great Bend Prairie aquifer salt load expressed as percent of saturated thickness that would be occupied by an equivalent volume of brine with 42,000 mg/L Cl (the average maximum brine concentration determined in water samples obtained from the upper Permian bedrock). Composite of data from 1993 and 1994 (Garneau, 1995).



1993 (left block) 1994 (right block)

Figure 6. A representation of the total saturated thickness (height of column) and the saturated thickness that would be occupied by the volume of Permian brine equivalent to the salt content of the total water column (height of dark column). At each site, 1993 values are on the left, 1994 on the right. The height of 500 mg/L limit of the mixed zone is shown by light stippling; this has no budgetary significance, but shows the extent of vertical mixing and the amount of usable fresh water at each site. From Garneau (1995).

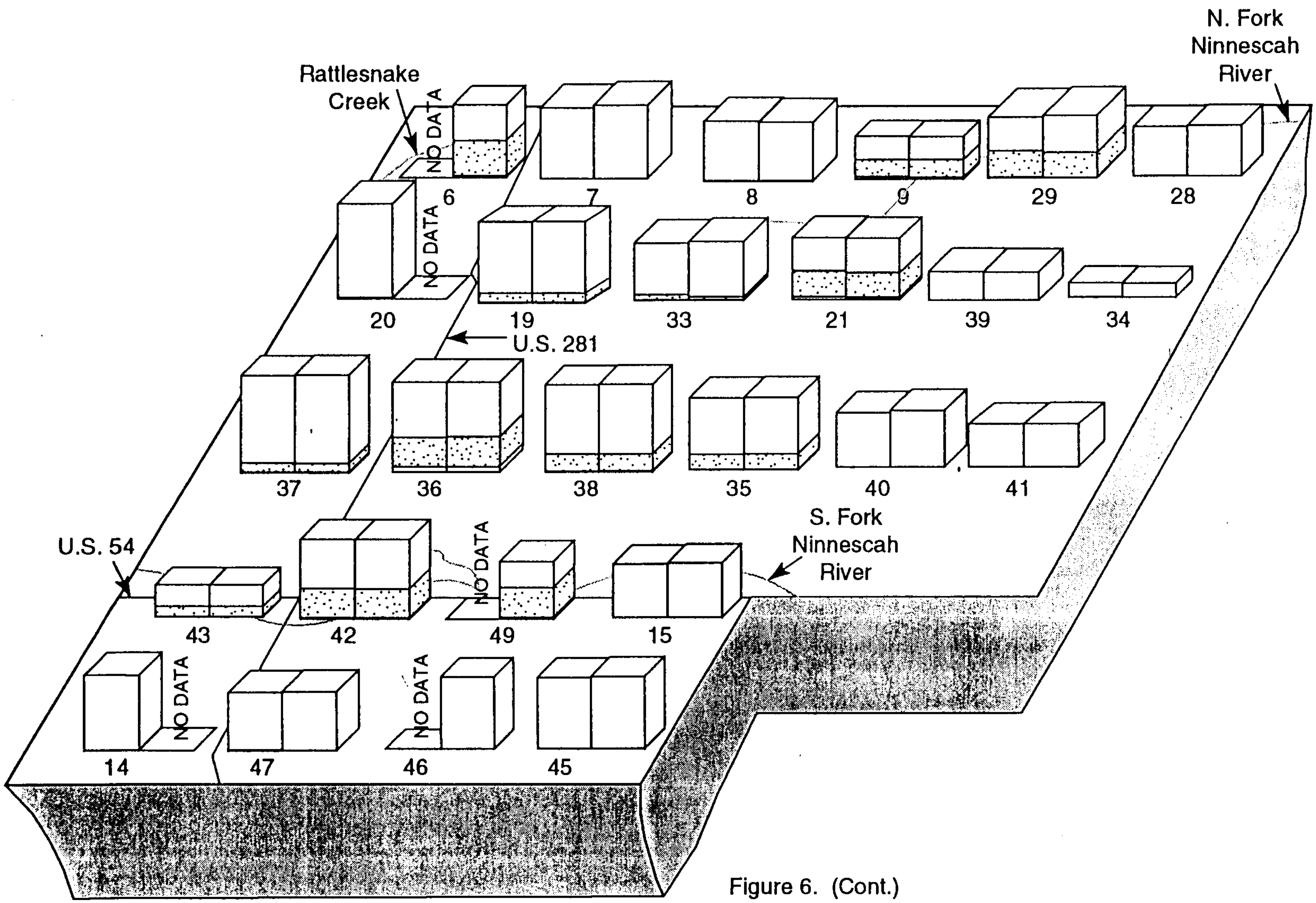


Figure 6. (Cont.)

II. GMD5 GROUNDWATER EFFLUENT -- A SIMPLE FLUX-BASED ESTIMATE

This section of the report summarizes an early attempt to develop an estimate of salt fluxes into the groundwater of eastern GMD2. In combination with the salt distribution observations described above, it provided the motivation and the starting point for the complete budget modeling described in Section III. The results described here are superseded by the results in Section III, so the following material is primarily tutorial and illustrative. Readers who are familiar with the concepts and methods of hydrology, geochemistry, and budget development may wish to go directly to Section III.

A. Surface water fluxes

In developing groundwater budgets for shallow alluvial aquifers, consideration of stream-aquifer interactions and other surface-water effects may be important. This is particularly true with respect to the linkages between salt budgets of regions such as eastern GMD5 and western GMD2. The apparent discrepancy between the salt inventories of eastern and western GMD5 (noted above), suggests that Rattlesnake Creek may divert a significant amount of salt out of the system. In addition, there are smaller creeks (e.g., Peace Creek and Salt Creek) that have the potential to act as "short-circuits" by transporting saline groundwater discharge into a region where the groundwater is fresher. As will be seen in Section III, surface flows are critical to budgetary balance in interactive groundwater systems.Although the example in this section addresses groundwater fluxes only, the importance of surface water fluxes developed in the following section makes it appropriate to lay out some general principles relating to surface water.

Water flow in streams is typically measured in cubic feet per second (cfs), which implies a nearly instantaneous determination. However, streamflows rarely change on time scales of seconds, so the results are usually reported as average values for hours, days, or longer periods. In the English system of measures, where surface water flux is measured in cfs, well pumping in gallons per minute (gpm) or millions of gallons per day (mgd), and groundwater flux in acre-feet/year (AF/yr), this makes for some frustrating interconversions. For this reason we develop our answers in the metric system (where a cubic meter contains 1,000 liters, a hectare is 10,000 square meters, and for almost all practical purposes a liter of water weighs one kilogram); the answers can be translated into English units after the arithmetic is done.

Water flow, whether in cfs or in m^3/day, is a volume flux. There is a related mass flux of the materials dissolved in water, which is commonly termed "load" (or sometimes "loading"). If a stream flows at an average of 1000 m^3/day and contains an average salt (NaCl) concentration of 100 mg/L (= 0.1 g/L), then the salt load or flux is 1000 m^3/day x 1000 L/m^3 x 0.1 g/L = 10^5 g/day or 100 kg/day (or 0.1 metric tons/day). This expresses the load as NaCl; if the composition is reasonably constant, it's usually more convenient to work in terms of one ion such as chloride (the weight of which is 35.5/58.5 times the weight of NaCl) and to express loads in those terms.

An important point with respect to surface water is that the load of salt is usually "conservative" whereas the volume of water may not be. Between two points in a flow system fresh water may be added by precipitation and runoff or removed by evaporation, but the amount of salt -- the load -- usually remains the same even though its concentration may change. This makes it important to consider both water quantity and water quality; if we simply see an increase in concentration we won't know whether that reflects addition of salt or removal of water, or some combination. Of course, in situations where there is significant discharge or recharge of saline stream water, the surface salt load will not be conservative.

Relationships among sources, sinks, and transport pathways can often be understood by examining the combination of water flux and dissolved constituent loads. In the case of south-central Kansas, salt discharge from the bedrock may behave quite differently from salt loads that originate from evaporative concentration of solids dissolved from the soil or bedrock. In particular, discharge and transport of bedrock-derived salt may be extremely sensitive to recharge, groundwater level and stream flow.

B. Groundwater fluxes

The area of interest for initial groundwater and salt flux estimation is the region along the NE border of GMD5 in Reno County. This is the area downgradient from the highest concentrations of salt in the groundwater (Figs 2, 5 and 6), and is also a potential source area for inflow to salt-affected portions of GMD2.

It should be pointed out that the development that follows is not strictly a budgetary model -- it demonstrates some approaches to the estimates of fluxes, which are key components of budgets. The outflow estimates can be transformed into a basic budget rather simply, by using water table and bedrock elevation maps, in conjunction with porosity estimates, to determine the approximate water inventory contributing to the effluent fluxes. Using an initial steady-state assumption, outflow and inventory determine inflow and residence time.

In order to estimate groundwater flux, we use the Darcy equation $Q = K\ dh/dl$, where Q is flux in units of m^3/m^2 day, K is the hydraulic conductivity in m/day, and dh/dl is the dimensionless hydraulic gradient. Combining this with an estimate of the cross sectional area of the saturated aquifer (m^2) provides the water flux; multiplying this by the average concentration provides a salt flux. In this case we use chloride ion as the salt indicator, since this is the chemical analysis on which concentrations are based; this can easily be transformed to actual salt (NaCl) or TDS if desired (Whittemore 1993).

1. Hydrologic gradients and hydrogeology

Groundwater flow in the region is predominantly eastward, with a slight northward component (Schloss et al. 1997, Garneau 1995 Figure 25). In order to estimate a regional gradient, the head and density-corrected head data presented by Garneau (1995, Table III) were used to estimate gradients between pairs of wells along the two sections shown in Figure 7. Both W-E and SW-NE well pairs were tested; as expected from the contoured elevations, the W-E gradients were higher and more consistent, and were used for the estimates. These values are presented in Table 1.

In order to assess variability, gradients were calculated for all of the well depths at the monitoring sites, and for both the "point" (measured, denoted by p) and "environmental" (density-corrected, denoted by "n") heads presented by Garneau (1995). The results were generally consistent (see Table 1), indicating that there are no major confined areas or density effects on the overall gradient.

For the initial estimates, a value of 0.002 was taken for dh/dl. Although individual values differ from this figure by 10-15%, the variations are small compared to the other sources of uncertainty in the overall estimates. This value is about 50% greater than the value commonly used for the eastern High Plains aquifer, but that is consistent with the relatively small values for saturated thickness in the vicinity of the cross-sections considered.

Sophocleous (pers. comm.) suggests that an appropriate value of K for the region in question is probably 80 $\pm$ 40 ft/day. We have used 30 m/day (91.5 ft/day) as an initial estimate.

2. Cross-sectional area

Vertical cross sections of the aquifer were prepared from Arc-Info land surface, water table and bedrock elevation coverages available at KGS. Sections were prepared along two N-S lines (Figure 7), with A-A' approximately on the boundary between Ranges 9W and 10W and B-B' between 8W and 9W. Both spanned Township 21S through all or most of T28S. However, for the purposes of this estimate, a much more limited area was used, corresponding to the portion of the sections between the Arkansas and the North Fork of the Ninnescah Rivers -- indicated as a-a' and b-b' on Figure 7.

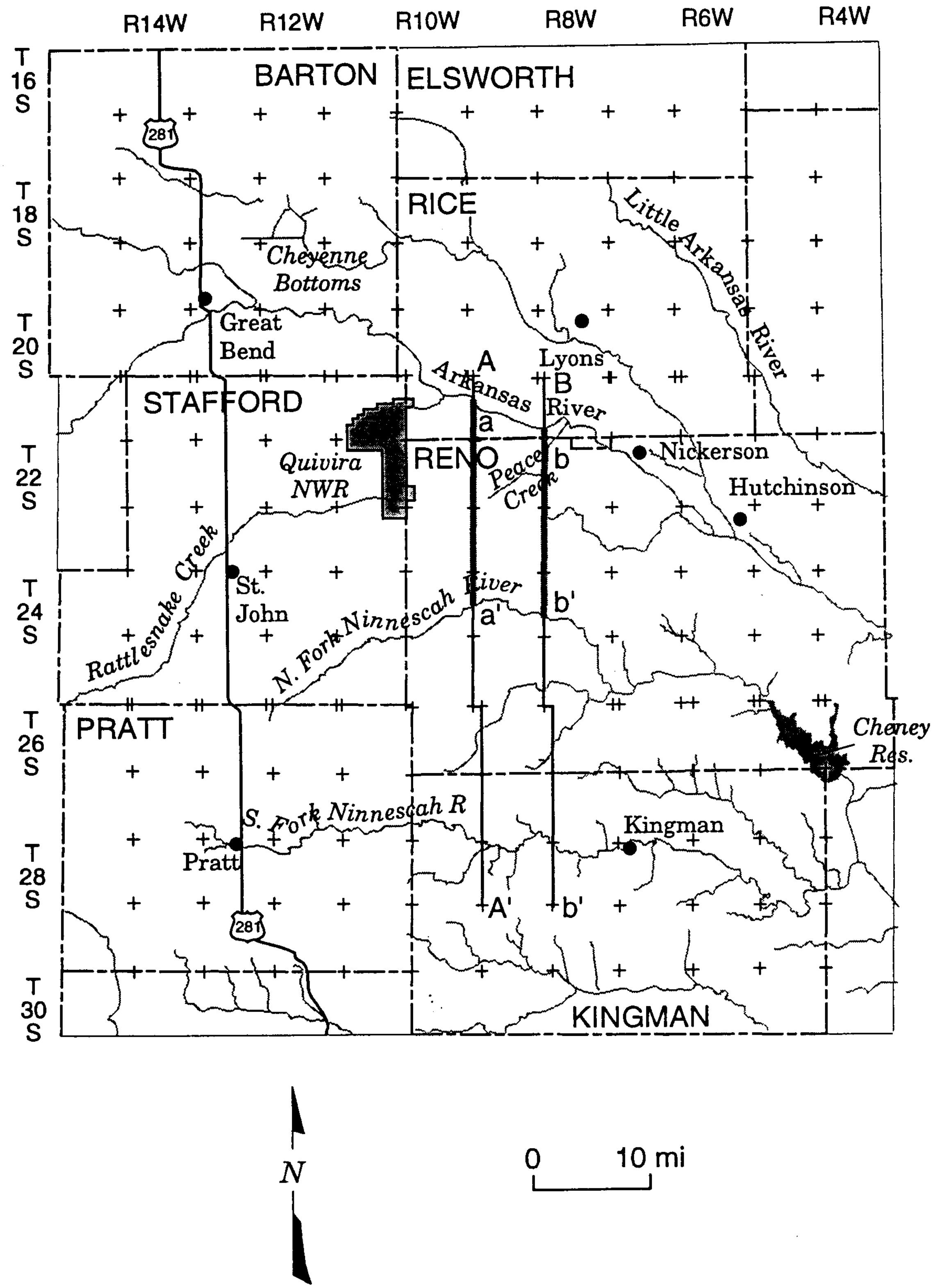


Figure 7. The larger (eastern GMD5 plus western GMD2) study areas, indicating the locations of the cross sections used for estimation of salt and water fluxes into the EBMI study area. The A-A' and a-a' transects are shown in vertical section in Figure 8; B-B' and b-b' are shown in Figure 9.

Table 1. Hydraulic gradients in the monitoring well network of eastern GMD5 head differences (dH) and inter-well distances (L) are in feet

E-W gradients

E well	W well	dH3p	dH3n	dH4p	dH4n	"L"	dH/dL3p	dHdL3n	dH/dL4p	dH/dL4n	dH3p	dH3n	dH4p	dH4n	"L"	dH/dL3p	dH/dL3n	dHdL4p	dH/dL4n
31-1	24-1	68.6	72.1	67.4	70.4	31700	2.16E-03	2.27E-03	2.13E-03	2.22E-03	68.6	72.1	67.4	70.4	31700	0.00216	0.00227	0.00213	0.00222
31-2	24-2	71.6	71.1	69.4	69.2	31700	2.26E-03	2.24E-03	2.19E-03	2.18E-03	71.6	71.1	69.4	69.2	31700	0.00226	0.00224	0.00219	0.00218
31-3	24-2	71.5	71	69.9	69.6	31700	2.26E-03	2.24E-03	2.21E-03	2.20E-03	71.5	71	69.9	69.6	31700	0.00226	0.00224	0.00221	0.0022
27-1	26-1	47.5	57.5	47.8	56.7	31700	1.50E-03	1.81E-03	1.51E-03	1.79E-03	47.5	57.5	47.8	56.7	31700	0.0015	0.00181	0.00151	0.00179
27-2	26-2	52	53.2	51.5	52.7	31700	1.64E-03	1.68E-03	1.62E-03	1.66E-03	52	53.2	51.5	52.7	31700	0.00164	0.00168	0.00162	0.00166
27-3	26-3	56.3	56.3	55.4	55.4	31700	1.78E-03	1.78E-03	1.75E-03	1.75E-03	56.3	56.3	55.4	55.4	31700	0.00178	0.00178	0.00175	0.00175
32-1	30-1	89.2	46.4	91	52.7	31700	2.81E-03	1.46E-03	2.87E-03	1.66E-03	89.2	46.4	91	52.7	31700	0.00281	0.00146	0.00287	0.00166
32-2																			
32-3	30-2	47.9	47.7	48.7	48.6	31700	1.51E-03	1.50E-03	1.54E-03	1.53E-03	47.9	47.7	48.7	48.6	31700	0.00151	0.0015	0.00154	0.00153
32-4	30-3	49.2	49	52.9	52.9	31700	1.55E-03	1.55E-03	1.67E-03	1.67E-03	49.2	49	52.9	52.9	31700	0.00155	0.00155	0.00167	0.00167
28-1	29-1	38.6	50.3	37.2	50.5	32200	1.20E-03	1.56E-03	1.16E-03	1.57E-03	38.6	50.3	37.2	50.5	32200	0.0012	0.00156	0.00116	0.00157
28-2	29-2	50.4	50.5	51.1	51.2	32200	1.57E-03	1.57E-03	1.59E-03	1.59E-03	50.4	50.5	51.1	51.2	32200	0.00157	0.00157	0.00159	0.00159
28-3	29-3	49.7	49.7	50.5	50.5	32200	1.54E-03	1.54E-03	1.57E-03	1.57E-03	49.7	49.7	50.5	50.5	32200	0.00154	0.00154	0.00157	0.00157

Note: Primary data from Garneau 1995; "3"=1993, "4" = 1994, "p" = point head, "n" = environmental head

Figures 8 and 9 show the sections used, with the index locations and the monitoring well locations shown. The N-S length of the section was calculated from the coordinates shown at the bottom; from a strict hydrologic standpoint the length of the water table contours approximating the map section lines would be more accurate, but the difference is almost certainly small compared to other sources of error. The average saturated thickness for the relevant portions was calculated by measuring 10-12 saturated thicknesses along the lengths of the a-a' and b-b' sections, averaging the results, and converting to meters. The figures show the 1993 and 1994 water tables, since these represent a rather extreme difference. However, because the difference is a small fraction of the total saturated thickness, a value intermediate between the two was used to make a single estimate of the cross sectional area.

Cross-sectional area results are given in Table 2.

Table 2: Areas of Groundwater Flux Cross-Sections a-a' and b-b' (Figs. 7-9)

Section:	a-a'	b-b'
Length:	2.99×10^4 m	2.83×10^4 m
mean satd. ht.:	34.0 m	30.3 m
Mean area:	1.02×10^6 m^2	8.56×10^5 m^2

3. Salt concentrations

Garneau (1995, Table II) used analysis of EM logs to estimate the amount of salt within the Great Bend Prairie aquifer at the various monitoring well sites. These estimates were expressed as the percentage of the total saturated thickness that would be occupied by a brine of 42,000 mg/L Cl if all of the salt were present in that form. Values were calculated from measurements made in 1993 and 1994; results are presented in Table 3.

Table 3: Brine inventories as % saturated thickness

Site	1993	1994	Mean
Section a-a'			
24	8.5	6.2	7.4
26	13	15	14
30	1.1	0.9	1.0
29	1.7	1.5	1.6
Section b-b'			
31	1.1	1.1	1.1
27	2.1	2.8	2.5
32	3.5	3.8	3.7
28	0.4	0.5	0.5

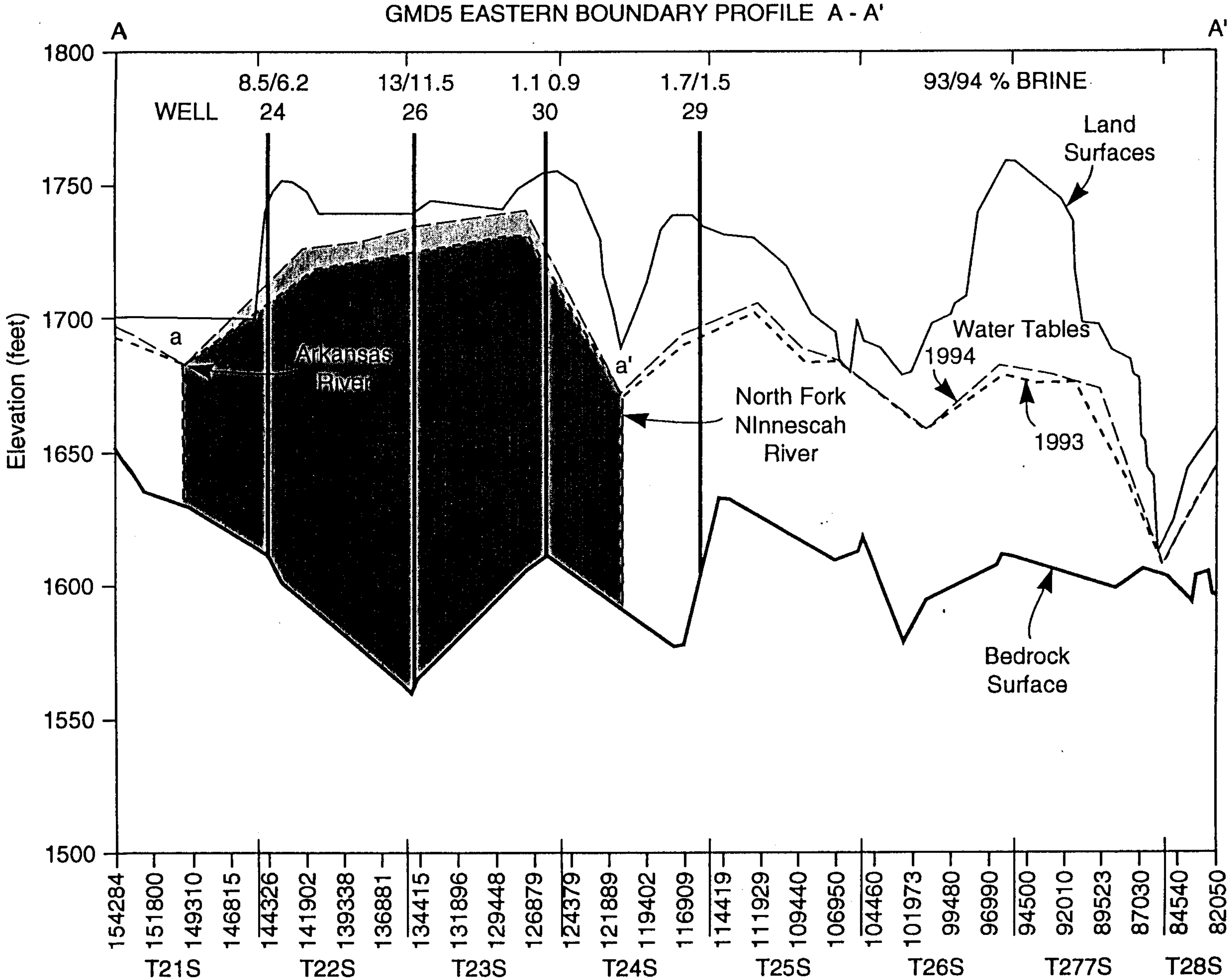


Figure 8. Vertical section along transect A-A' (Figure 7), showing bedrock, surface and water table elevations, the locations of monitoring wells, and the calculated percentage of Permian formation brine (42,000 mg/L Cl-) in the total saturated thickness at each well location. The sub-section a-a' (shaded area) was used for the flux estimates described in the text.

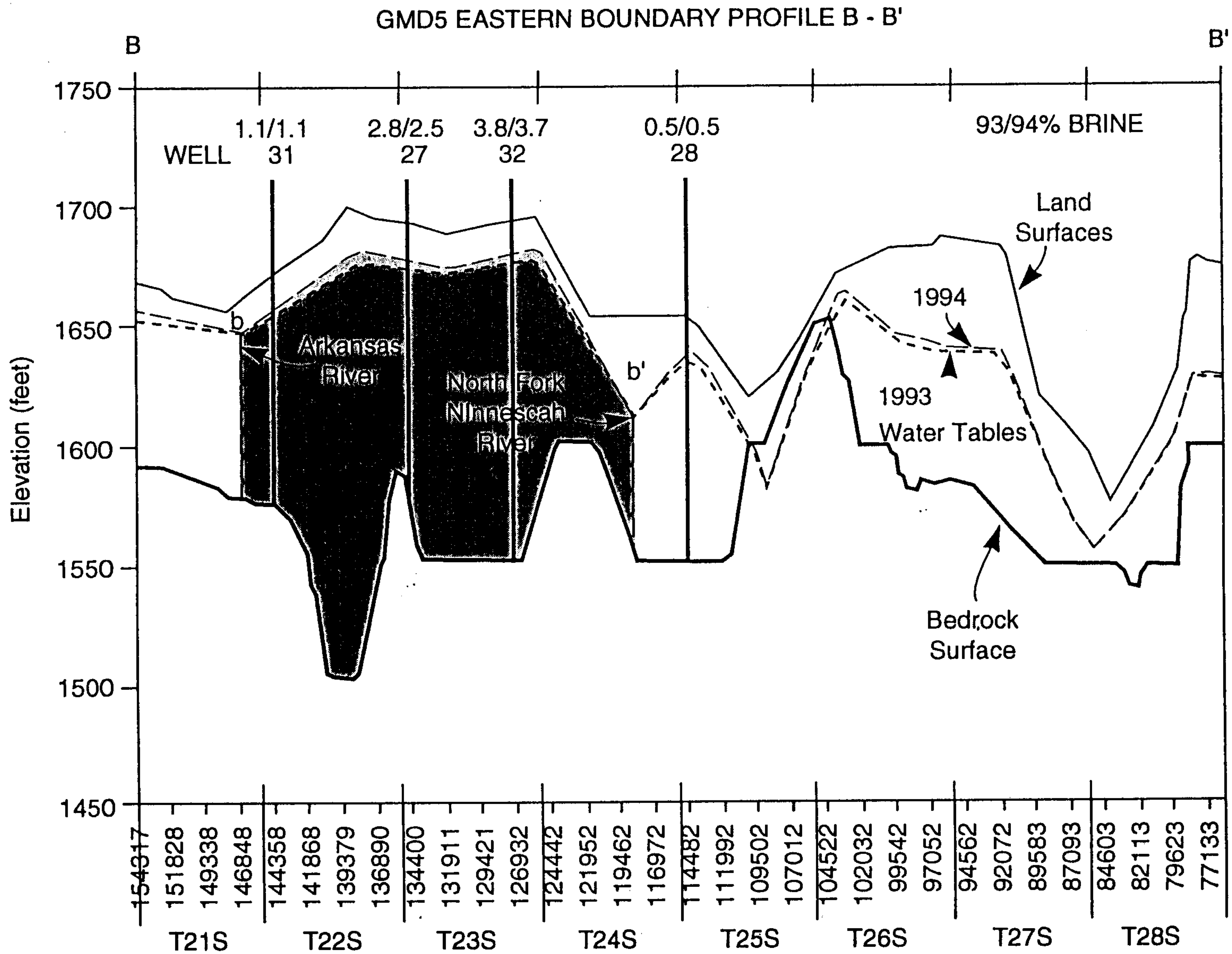


Figure 9. Vertical section along transect B-B' (Figure 7), showing bedrock, surface and water table elevations, the locations of monitoring wells, and the calculated percentage of Permian formation brine (42,000 mg/L Cl-) in the total saturated thickness at each well location. The sub-section b-b' (shaded area) was used for the flux estimates described in the text.

To obtain the mean salt composition applicable to section a-a' (Figures 7 and 8), we averaged the values for the three wells between the Arkansas and the North Fork (wells 28 and 29, south of the Ninnescah, were tabulated for information but were not used in the calculations). The result in this case was 7.5%. This appears to be a reasonable approach, since the wells used (Figure III-2) provide a representative sample of the bedrock profile.

Section b-b' (Figures 7 and 9) is more of a problem, however. A similar approach to averaging the three well values yields an estimate of 2.5%. It seems likely that this may underestimate the salt content, however, because none of these three wells is centered in the bedrock channels where the denser salt water may be expected to accumulate. In order to compensate for the possible effects for this, the average of the two saltier wells was used; this yields 3.6%. This issue will be considered further in the discussion below.

4. Salt and water fluxes

When the values selected are used in the Darcy Law calculation indicated above, the resulting water flux estimates are 6.1×10^4 and 5.1×10^4 m^3/day for flow through the vertical aquifer sections at a-a' and b-b' (Figure 7) respectively (or, 22 and 18 Mm^3/yr). These values are similar, and the difference is probably well within the uncertainties of the various estimates.

However, when the brine percentage values are applied, the results are 4.6×10^3 and 1.8×10^3 m^3/day for the flux of equivalent brine (concentration = 42,000 mg/L) through sections a-a' and b-b' respectively. The salt load of this flux is 75-190 metric tons of chloride (equivalent to roughly 125 to 315 metric tons of salt) per day. This budgetary imbalance, although not extreme for a preliminary estimate, suggests either an error in the input values or a pathway that has not been accounted for. Both are possible.

The average concentration values assigned to the sections are necessarily rather questionable because of the small number of sample points and the differences in monitoring well salinity values. For example, if the deep bedrock channel on the north side of transect b-b' had the same brine content as the similarly situated well 26 on transect a-a', the average salt concentrations across the two transects would be very similar. Recent field observations from new GMD2 monitoring wells suggest that this is likely to be the case (Young et al., 1997).

There is also the possibility of an additional pathway. In this case, surface discharge is a logical candidate. By using the river channels instead of the intervening groundwater "divides" to bound the transects, we have calculated flux based on groundwater only, when in fact we know that there is discharge to the Arkansas, the Rattlesnake, Peace Creek, and the Ninnescah in this region. If the average salinity of the discharged water that flows out on the surface is substantially higher than the salinity of the inflowing groundwater, it could account for a significant reduction in the groundwater salt load.

These two findings from a preliminary and very simple flux estimate emphasize two important advantages of this approach. In terms of experimental design, one of the criteria adopted for siting new monitoring wells for the GMD2 study was the need to get better sampling of the main bedrock channels. And, from the standpoint of refined calculations, it became clear that more rigorous budget modeling of the combined surface water and groundwater system was in order; results of these efforts are reported below.

III. ESTIMATION OF SALT AND WATER FLUXES WITH A BUDGET MODEL

In this section we develop and apply a rigorous balance models for salt and water in the combined stream-aquifer systems typical of the Great Bend Prairie-Equus Beds region. We demonstrate that developing this type of model is conceptually very simple, and that powerful results can be obtained based on available information. Our primary objective is to develop an understanding of how the combined stream-aquifer system works; we achieve this objective by means of developing a comprehensive hydrologic model. A host of practical questions can be addressed after the primary objective has been met. As an example, we estimate the total salt flux out of the GMD5 region.

The area of interest in GMD5 is limited by the Arkansas River to the north and the Medicine Lodge River to the south, as shown in Figure 10. In between these rivers we can define three natural regions: (a) the Northern region around Rattlesnake Creek (which includes Peace Creek); (b) the Central region around the North Fork of the Ninnescah River; and (c) the Southern region around the South Fork of the Ninnescah River. Each region corresponds to a surface watershed (Figure 11), but also includes the underlying aquifer, as shown in Figure 12. We defined the ground water subbasins shown in Figure 12 using the ground water flow lines that are closer to the boundaries between surface watersheds. It is apparent from parallel examination of Figures 11 and 12 that there is a large degree of overlap between the surface and groundwater "basins" for each of the three regions. Although it is impossible to obtain a perfect overlap between the surface and subsurface areas defined in this fashion, this is not important for modeling purposes. Given all the uncertainties in hydrologic fluxes and parameters, a small error in delineating hydrologic boundaries can be safely neglected. In particular, there is a rather small runoff contribution from the marginal areas of the surface watersheds, so streamflow is relatively insensitive to the exact position of these boundaries.

In seeking to understand the dynamics of flow and salinity transport in this system, we choose the boundaries of the study region based on both the groundwater quality data and the availability of surface water data. Figures 11 and 12 display two N-S lines that are the approximate western and eastern boundaries of the study area. These two lines correspond to the US 281 highway in the West and the R10W-R9W township line in the East. The exact boundaries follow properly chosen contour lines: topographic contours for watersheds and water level contours for ground water basins. We chose the areas to captures the transition zone from freshwater (West of the US 281 highway) to water with a much larger salt content.

Based on the available data we choose to develop separate models for the Northern, Central, and Southern regions. Modeling results confirm a very different qualitative behavior between the Northern and Southern regions, while the Central region shares characteristics of both. For this reason, we feel that the analysis of the Northern and Southern regions combined with an initial estimate for the Central region, reveals a clear conceptual picture of salt transport out of GMD5 and into areas of concern to GMD2.

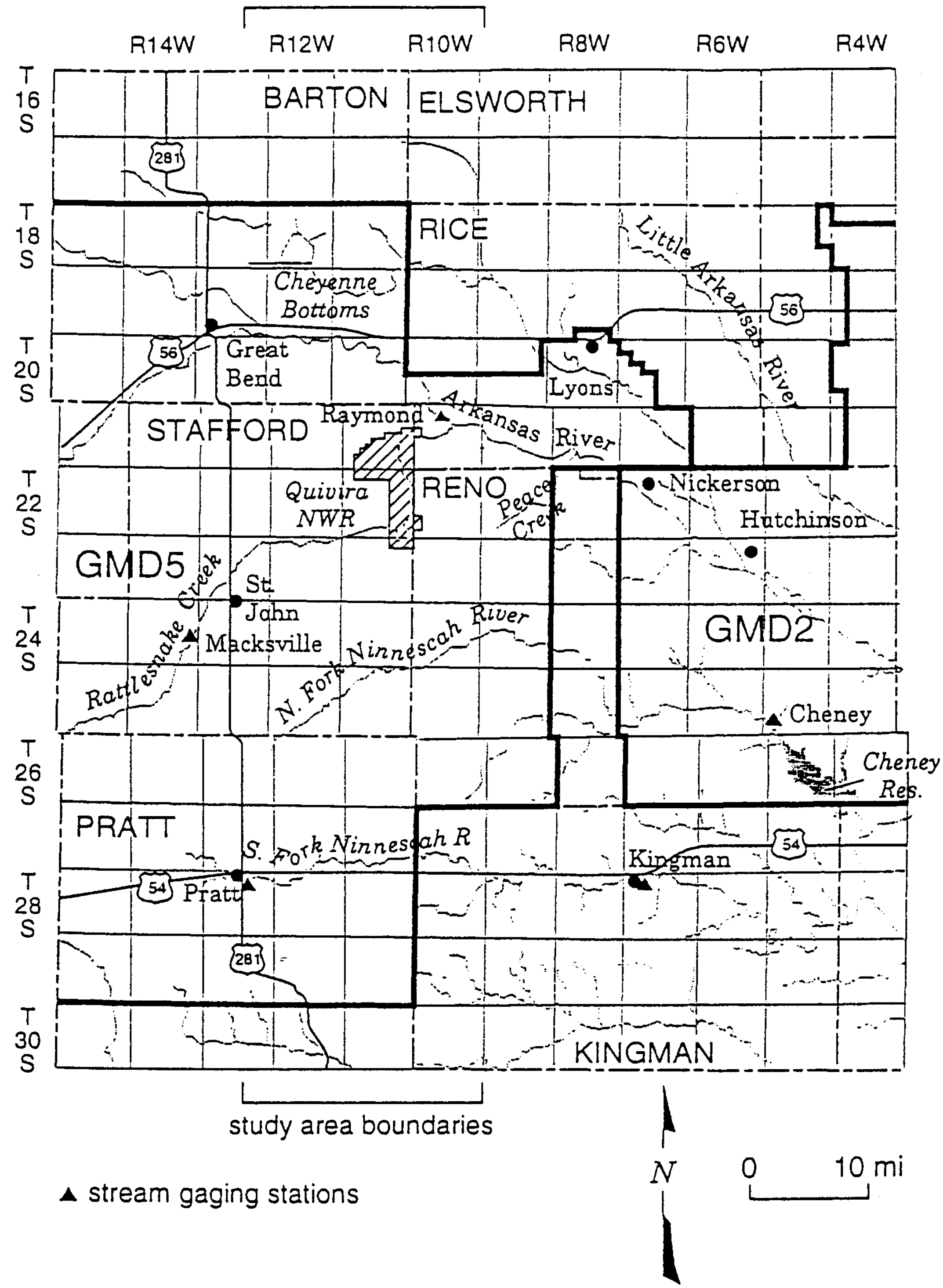


Figure 10: Surface features, including major streams, rivers, towns, roads, and political boundaries, of the larger mineral intrusion study area. Also shown are locations of the stream gauges used for model data input.

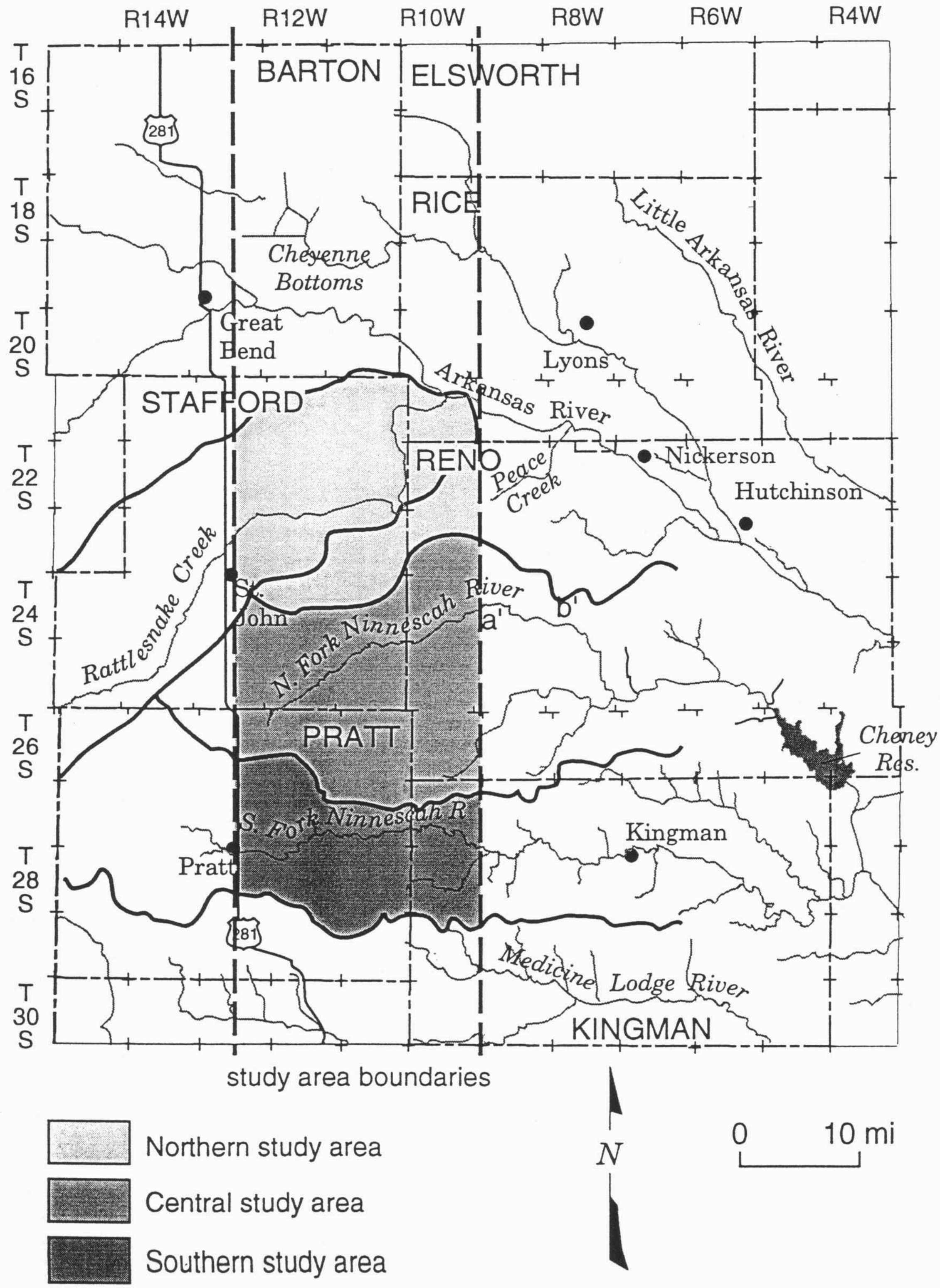


Figure 11. Map of the study area, showing watershed boundaries. The two dashed N-S lines are the approximate West and East boundaries of the study area. The exact N-S boundaries follow properly chosen topographic contour lines that define sub watersheds.

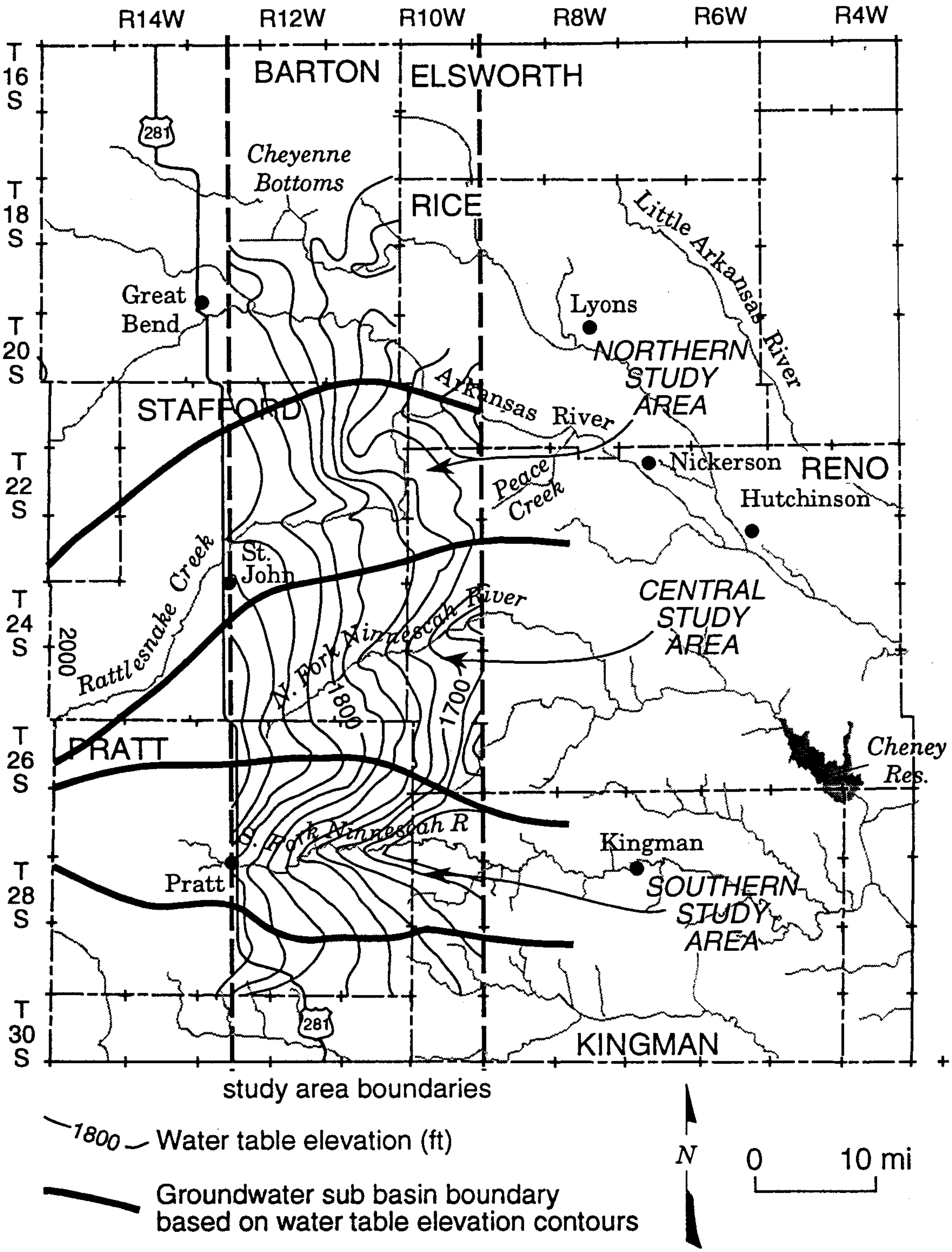


Figure 12. Map of the study area, showing boundaries of ground water sub-basins. The two N-S lines are the approximate West and East boundaries of the study area. The exact N-S boundaries follow properly chosen groundwater elevation contour lines that define sub basins.

A. General

In Section I we reviewed the basic ideas behind the budgetary approach to modeling. Here we develop them further in a step-by-step fashion to illustrate the main procedure. This is accomplished in four steps: (1) define a small number of reservoirs; (2) define all fluxes in and out of each reservoir; (3) estimate as many fluxes as possible using available data; and (4) calculate the remaining unknown fluxes using balance equations for salt and water. The only constraint in the last step is that the number of unknown fluxes has to equal the number of balance equations for the whole system.

All hydrologic models, no matter how sophisticated, are built using this four-step procedure to ensure conservation of mass (salt and water). However, different mass balance models can be developed for the same system, depending on the desired level of detail. More detail requires the evaluation of more fluxes and the estimation of more parameters. In this study we have deliberately chosen to use the smallest possible number of fluxes and parameters. The resulting models will be simple to understand and operate, while incorporating the main features of the chemistry and hydrology of the system.

1. Modeling Approach

Building a model requires making choices, depending on the type of results that are sought. For example, we might choose to focus on either steady or transient behavior. In the transient case, we need to choose the appropriate level of detail with which time processes are represented (e.g., daily, seasonal, year, multi-year).

Our strategy for model development is to build the simplest model first, and only add further detail if necessary (simple models are generally more robust than complex ones). For this reason we decided to develop a steady-state model that represents system behavior on a multi-year average basis. We believe that this model provides a solid basis for further refinement as the focus shifts from the big picture (natural system behavior, large-scale resource management) to the details required for operational purposes (fine-tuning water appropriations in a small region, predicting changes on a scale of a few months or years, etc.).

Thus, we visualize a hierarchy of models of the same system. Each model is developed to address questions at a different scale or resolution, and so it incorporates more or less detail as necessary. However, we start with the simplest conceptual model that explains overall behavior. Because it uses the least number of variables, it is the most robust model to which we can refer to time and again; this is not a pre-model that you discard later on. Although parameters of this model can and do change as more information is incorporated, these parameters change less than those of models at finer scale or those of subregions.

2. Modeling Tools

The conceptual models that we develop in this section are based on the budgetary approach explained earlier. This approach ensures conservation of mass in each area studied. In mathematical terms, the difference between system Inputs and Outputs is reflected in a change in Stock (or inventory), according to the equation

$$d[\text{Stock}]/dt = \text{Inputs} - \text{Outputs}.$$

The operator d[ ]/dt is the time derivative, which measures the rate of change with respect to time. We use the above equation for a full-fledged analysis of system dynamics (e.g., how long will it take for the system to adjust to a 50% decrease in aquifer recharge?). However,we usually start with the simpler steady-state version, where d[ ]/dt=0 and the sum of all Inputs is equal to the sum of all Outputs. Analyzing this condition of dynamic equilibrium provides a wealth of information and it can actually be done "on the back of an envelope." For example, a balance of Inputs and Outputs of both water and salt in a system with two reservoirs requires only four equations, which we can easily solve either by hand or with the help of a spreadsheet program (we used Microsoft Excel for the equilibrium calculations).

Analyzing changes in time is a little more elaborate, since we need to repetitively evaluate the same equation many times, advancing time in small increments. For this purpose it is best to use a computer program that simulates system dynamics. A number of such packages are commercially available, and they are suited for system dynamics of any quantity for which we can write a mass balance and can estimate the proper fluxes. We chose the STELLA package (Appendix A) because it has a simple and intuitive graphical interface that allows the user to draw a picture of the system in terms of Stocks and Fluxes (Inputs and Outputs); as you draw the picture, the corresponding balance equations are automatically written by the program. Running the program evaluates the missing terms (unknown Fluxes) and enforces mass balance. Other than Inputs and Outputs, each reservoir has two specific properties that define its response: a volume and a residence time. The volume is the value of the Stock at a given time; the residence time is the time required for the reservoir to be emptied of its contents (Stock).

3. Available Data

Developing simple balance models require the evaluation of a number of fluxes. Some fluxes, such as streamflow and precipitation, are directly measured; others, such as regional ground water flow, have to be estimated using other variables. Estimation introduces uncertainty because not all variables are accessible to measurement. For example, regional ground water flow can be estimated as we did earlier in Section II (in terms of hydraulic head gradient (measured), hydraulic conductivity (estimated), and aquifer cross-sectional area (estimated)). Because of the uncertainties in the component quantities, it is desirable to minimize the number of fluxes that have to estimated, if at all possible. Usually this can be accomplished by carefully choosing the boundaries of the study area. For example, we use natural hydrologic boundaries (e.g., no-flow) whenever possible because they reduce the total number of non-zero fluxes.

Salt fluxes are usually not accessible to measurement and have to be estimated as the product of a water flux and an average salt concentration. Again, by carefully choosing the model boundaries we can more accurately estimate these terms (e.g., where the average salt concentration is negligibly low, it can be assumed equal to zero, so that the corresponding salt flux is also zero). By proceeding in this fashion, we can maximize the number of fluxes that are relatively well-known. This is highly desirable to reduce the uncertainty of model outputs.

The quantity and quality of available data can sometimes define the scope of a modeling exercise. This applies to the number and distribution of measurement points when the corresponding variable is spatially distributed, and to the frequency of observations and record length for time-varying quantities. We have applied the simplest approach here, averaging out properties (in space) and measurements (in time). This choice can be relaxed later if deemed necessary.

In this study we have chosen to maximize the number of fluxes that are directly measured. The best example is stream discharge at a gauging station located in the neighborhood of a model boundary. Surface water data has two major advantages. First, good-quality data are usually available on most streams. Second and most important, in stream-aquifer systems, streamflow and concentration provide an integrated measure of system output and behavior. This is in contrast to ground water data, where a well provides information representative of a very small area surrounding it. Hence, it is both crucial and cost effective to gather the most information about the surface water system (quantity and quality).

4. Conceptual model choices

More or less complex models can be put together by linking a number of reservoirs. The basic building block is the well-mixed reservoir, which assumes a single value of salt concentration inside the reservoir. That is, the salt concentration in ground water is the same everywhere, regardless of depth and location, and the concentration in the surface water is the same in all ponds and marshes, and everywhere along the creek. This is only a convenient simplification; the equivalent well-mixed concentration represents the average value in each reservoir.

If further refinement is desired to accommodate regions of variable concentration, we can build a more detailed model by subdividing the study region in a larger number of reservoirs. For example, we might want the model to represent the vertical salinity gradients typical of the Great Bend Prairie (e.g., Garneau, 1995). However, more reservoirs imply that more fluxes need to be evaluated, and this is not always desirable. Instead, we have modified the basic model by allowing some vertical fluxes to have a concentration different than the average reservoir concentration. This accommodates the fact that the aquifer discharge to streams draws relatively more water from the shallow part of the aquifer, known to have a smaller salt concentration than the deeper parts. This is one exception to the rule - most fluxes can be assumed to be a mix of water from different parts of the reservoir, so that the average concentration is a representative value. The other exception corresponds to fluxes of known concentration, such as evaporation from marshes (freshwater by definition) and irrigation pumping (water with less than 100 mg/L of Chloride).

We have a wealth of information for fluxes that are measured on a regular basis, such as precipitation and streamflow. Examination of the corresponding records reveal significant variability at different time scales (daily, seasonal, and yearly). But the choice of whether to incorporate such variability into the model is not an obvious one. The modeler has to weigh the added complexity against the possibility of obtaining additional insight, and all this in light of the objectives of the study. Consistent with previous choices, we decided to build the simplest model, representing time-variable quantities with appropriate constant values. Thus, our model represents the steady-state or quasi-equilibrium situation where system inputs exactly balance system outputs -- an appropriate approximation in this first modeling stage.

We processed historical records of streamflow and precipitation to extract only the mean values, disregarding possible trends (this choice can be later revised as appropriate). The basic assumption (that to a first approximation he system is in quasi-equilibrium) is consistent with observations of the overall system response: measured ground water levels in the study area show little or no decline since records were first kept. This is true on average, not necessarily at all points in the study region (Sophocleous and Stern, 1993); there are declines in some places and increases in others.

5. Objective and Scope

The main objective of this study is the assessment of the natural regime in terms of flow and salt transport in the study area. The models will be used to address very simple questions such as the following:

- How much saltwater recharges the Great Bend Prairie aquifer?
- Where does the saltwater go, and how fast?
- How are the surface and ground water systems linked?
- How fast does the system respond to changes?

We will seek answers to these questions in quantitative terms, while probing their reliability. Because some key fluxes can only be estimated, we will examine how different estimates can change the answers. Simple uncertainty analyses can provide reliability bounds on key fluxes and associated predictions (e.g., what conclusions would remain the same regardless of whether groundwater recharge is 1, 2, or 3 inches?). The models that we develop can also be used to evaluate the anthropogenic impacts on the system, but we do not focus on these issues on this report.

B. Northern GMD5 Model

1. Selection of study area

With regard to water quality, the dominant feature of the northern section of GMD5 is the discharge of saltwater from the aquifer to Rattlesnake Creek and the Quivira Marsh system (roughly the area covered by the Quivira National Wildlife Refuge). Groundwater quality data displays a sharp increase in salt concentration along a N-S line that roughly coincides with the trace of the US 281 highway. Salt concentrations west of that line are the lowest in the region, being within the acceptable limits for human consumption; to the east both surface and ground water register high salt concentrations. The increase in concentration has been linked to salt water discharge from the underlying Cedar Hills formation, which subcrops just east of the US 281 highway. Since the Cheyenne and the lower part of the Kiowa formations are also known to be saline, it is likely that the lower Dakota formation is also a source of saltwater.

We constructed the simplest possible conceptual model of the combined surface water and groundwater system. The model conceptualizes the system as two interconnected reservoirs: one for groundwater and one for surface water. The output of the model is a set of internally consistent, order-of-magnitude estimates of water and salt fluxes. Figure 14 represents the two-reservoir model and the fluxes in and out of each reservoir. The surface water reservoir includes the Quivira Marsh system and Rattlesnake Creek, which provides both input and output to the marsh system. The groundwater reservoir corresponds to the part of the Great Bend Prairie aquifer that underlies the surface water reservoir, as discussed earlier in this section.

We have chosen the eastern boundary of the study area as the line that separates the townships R10W and R9W; this is the line a-a' used as a transect in Section II (see Fig. 7). This line approximates the eastern boundary of GMD5, which follows the line between R9W and R8W. Figures 11 and 12 delineate the boundaries of the study area. Note (see Figure 11) that we have included the upper part of the Peace Creek watershed in the northern study area. Because this section of the stream is not perennial (Dan Zehr, personal communication), we neglect Peace Creek as a surface water outlet. However, including Peace Creek in the area modeled significantly enlarges the area of the underlying aquifer. Thus, the north boundary of the study area is the water divide between the Arkansas River and the Rattlesnake Creek watersheds; the south limit runs mostly along the water divide between the Peace Creek and the North Fork Ninnescah River watersheds (Figure 11).

In more detail, all limits are hydrologic in nature, and because we deal with both a surface watershed and a section of the GBP aquifer, there are eight lines that define the surface and groundwater boundaries. The upgradient boundaries are the surface elevation contour and the groundwater level contour that run closest to the trace of the US 281 highway. The downgradient boundary of the groundwater system is the groundwater level contour that runs closest to the trace of the eastern boundary line; the downgradient boundary of the surface water system is the confluence of the Rattlesnake

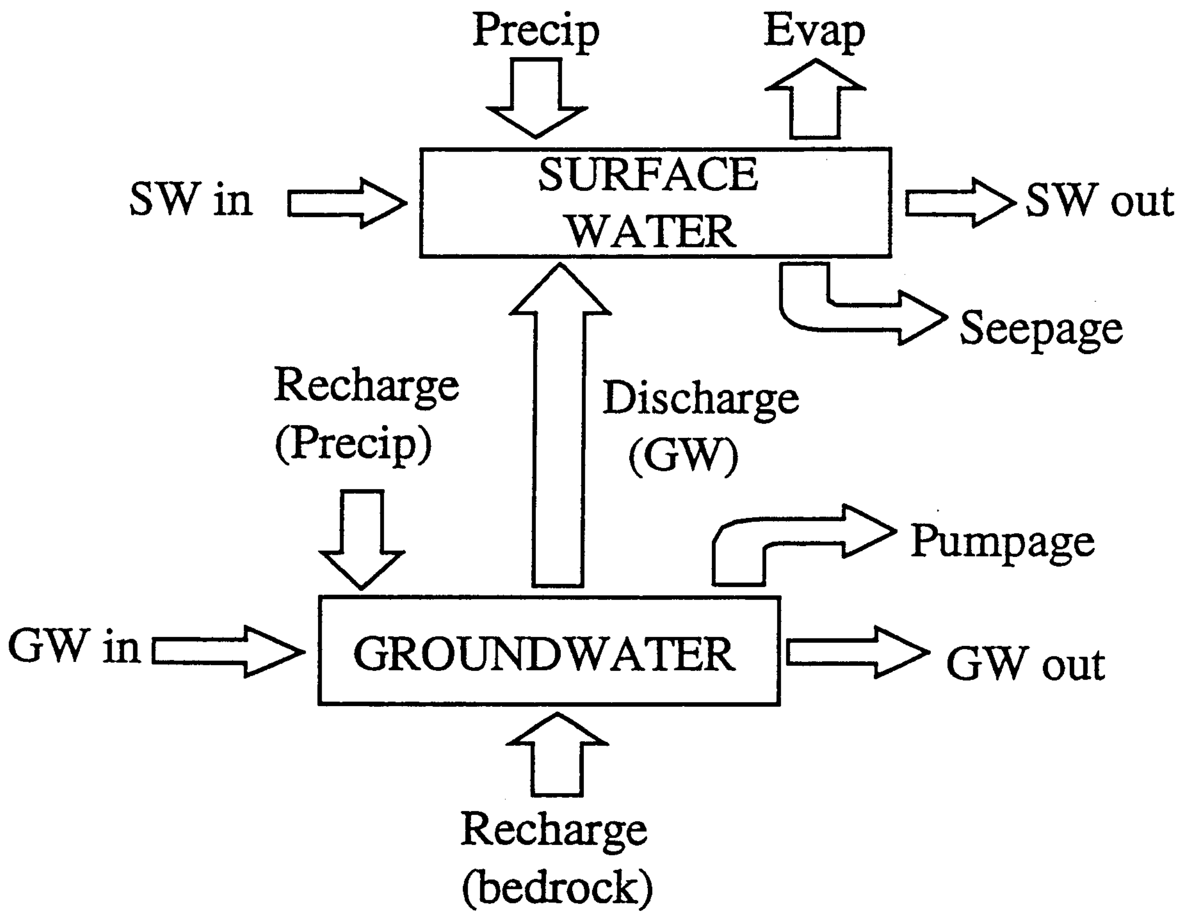


Figure 13. Schematic diagram with two reservoirs and all fluxes in and out of the northern study area (Rattlesnake Creek).

Creek with the Arkansas River. The north and south boundaries are water divides for the surface system, and flow lines representing groundwater flow divides for the groundwater system. The two areas defined by these boundaries overlap each other to a very large extent.

2. Review of available water quantity and quality data

Surface water data for major streams are available from the USGS. Gauging stations used in this study are shown in Figure 10. Each gauging station has a record of daily discharge values; these records are created by recording daily water level records and converting them to discharge with a stage-discharge relationship. Water quality measurements are sporadic, usually amounting to a few samples per year.In addition, water quantity and quality data have to be treated differently. We can run rigorous statistical procedures on regular and continuous series (daily discharges), but not so for a very irregular series (water quality data). For example, obtaining a duration curve is not possible when the information amounts to only a few days per year. Instead our best bet is to use all simultaneous measurements of discharge and a water quality parameter (e.g., chloride concentration) to develop a correlation, which can be used to generate a series of synthetic chloride values (corresponding to observed or generated discharges) and run statistics on that series to obtain the distribution.

Figure 14 shows the available chloride concentration and concurrent flow data for the Raymond gauging station, near the outflow of the Rattlesnake Creek (northern) section. The clear inverse relationship between flow and concentration strongly suggests that the salt load removed from the system is much more consistent than either the flow rate or the salinity of the effluent. These data are a reflection of the fact that the region of highest groundwater salinity is in the Quiviria marsh area, astride the flow path of Rattlesnake Creek (Figures 10 and 15). Data are from the USGS.

Figure 15 shows the discharge records for the Macksville and Raymond gauges (representative of the inflow and outflow to the northern salt-affected area) over their common period of record. The data clearly indicate that groundwater discharge results in an increase in streamflow within the region. It is apparent from Figure 15 that streamflows were relatively larger in the early part of the record, and relatively smaller in the latter part. We arbitrarily divide the record into two practical series: 1961-1980 and 1981-1995. The statistics of both partial series, displayed in Figures 16 and 17, confirm the large declines in mean streamflows at both stations (about 40% at Raymond, and 65% at Macksville).

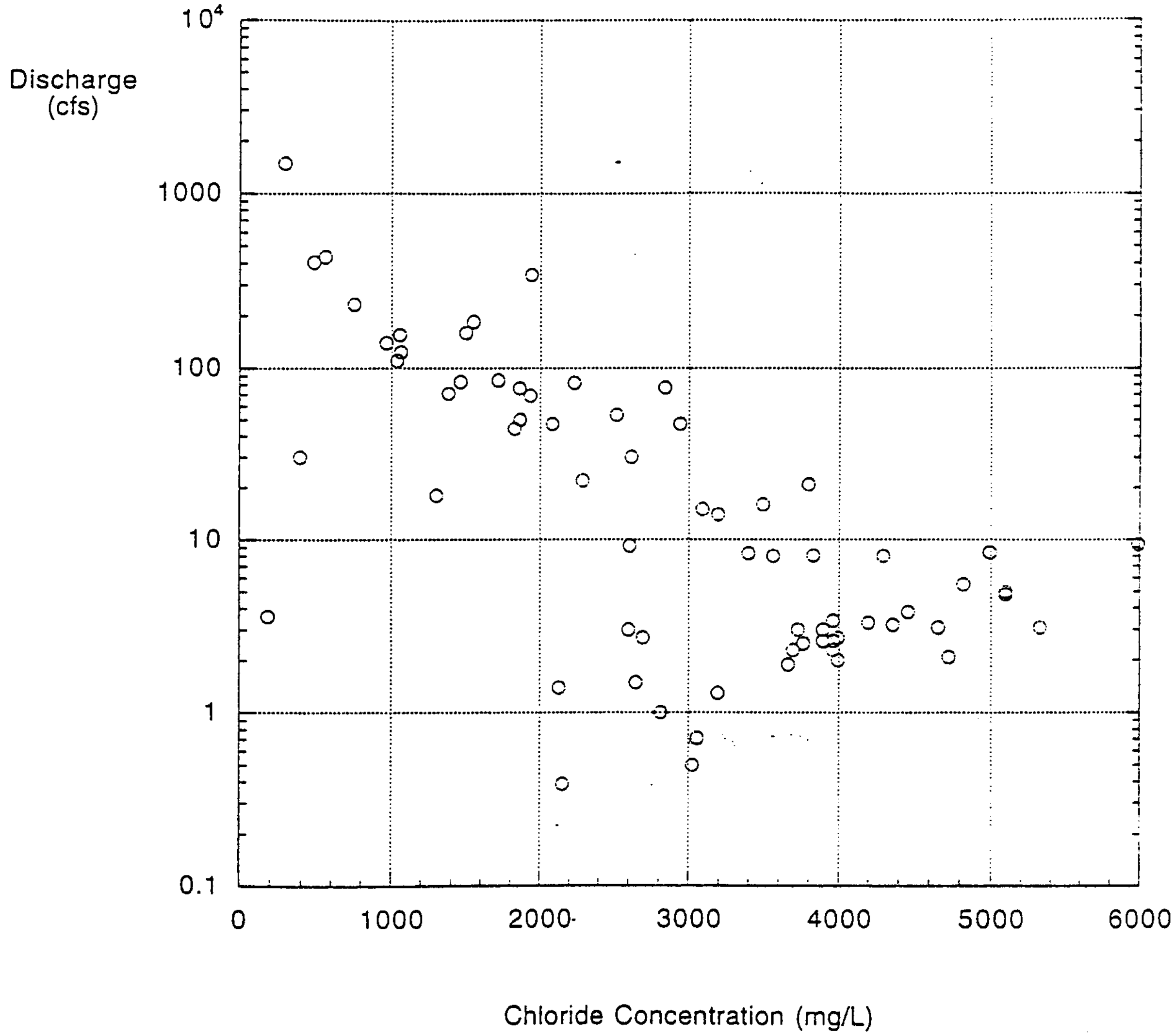


Figure 14. Surface water quality data at Raymond Station, Rattlesnake Creek. Discharge (cfs) versus Chloride (mg/L) .

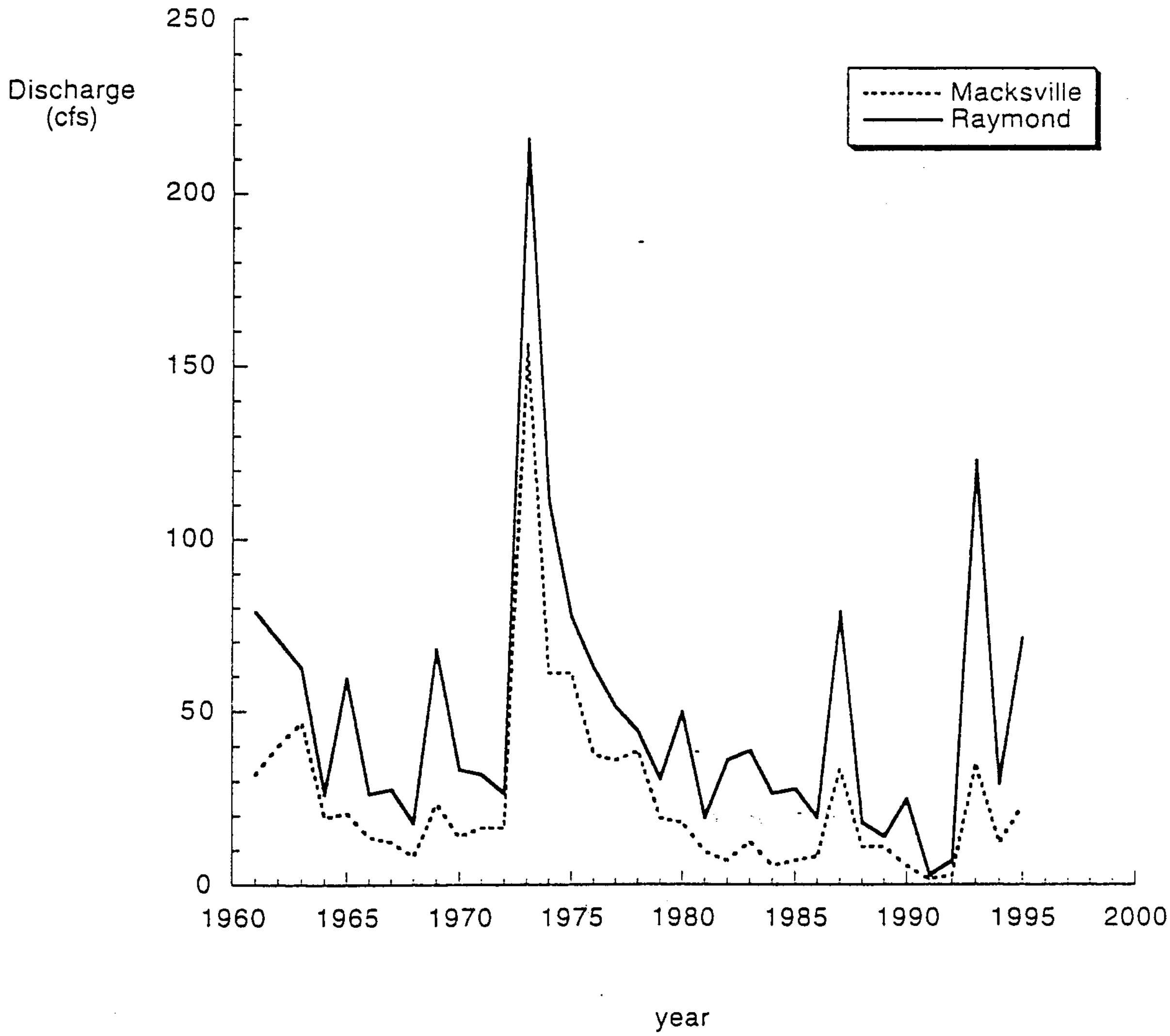


Figure 15. Annual mean streamflows in Rattlesnake Creek, at Macksville and Raymond gauging stations.

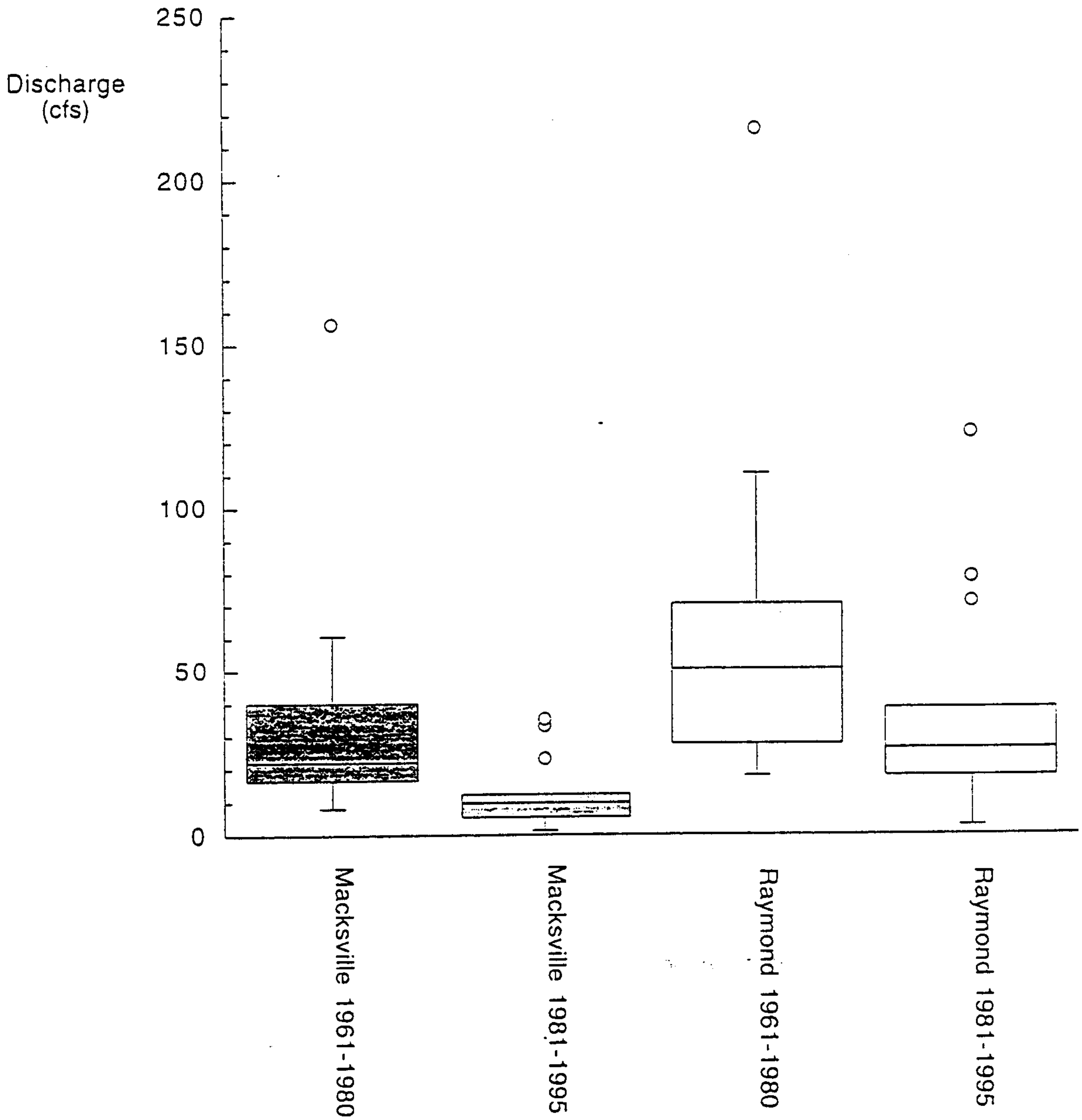


Figure 16. Statistics of streamflows in Rattlesnake Creek, at Macksville and Raymond gauging stations. Box plot analysis of annual discharge partial series 1961-1980 and 1981-1995.

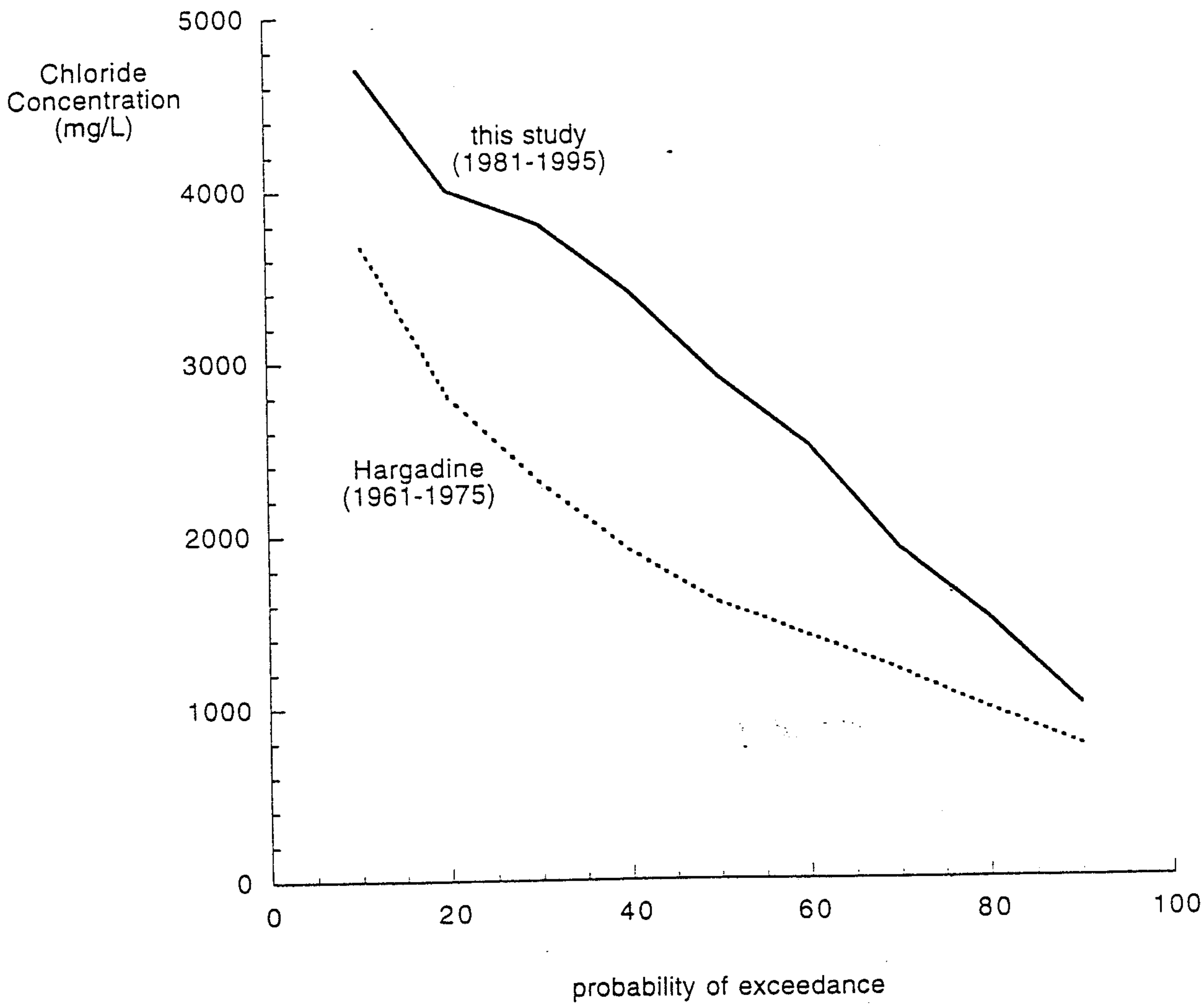


Figure 17. Statistics of Chloride concentration measurements in Rattlesnake Creek, at Raymond gauging station. The two curves correspond to two fifteen-year periods. Note the marked increase in concentrations in twenty years (1961-1975 and 1981-1995). Source: Hargadine et al. (1979) and Quinodoz (1996).

Figure 17 shows a summary of the chloride concentration data available at the Raymond gauging station. We found convenient to display the statistics of two 15-year records as a pseudo duration curve plot. Since measurements are very sporadic, there is no duration (e.g., daily) that can be attached to the concentrations displayed in Figure 17. However, it is apparent that chloride concentrations are significantly higher for the 1981-1995 partial series. This observation correlates well with the decrease observed in the streamflows at Raymond over the same time period (see Figure 15, suggesting that the total salt flux could be approximately constant.

The 1981-1995 series was retrieved from the STORET database, and the pseudo duration curve for the 1961-1975 series was taken from Hargadine et al. (1979). For our purposes, it suffices to estimate a single ratio between the chloride concentrations corresponding to both partial series. We consider only the values between the 50 and 80 percentiles, where the range of values for the 1981-1995 series coincides with the central range displayed in Figure 14. We average the ratios between values read from both curves for the same percentiles and obtain a mean of about 1.6. That is, concentrations in the 1981-1995 series are about 60% higher than those observed during 1961-1975.

3. Balance equations for salt and water

Conservation of water and salt requires two equations for each reservoir. Under steady-state, each equation has the form {Sum of Inputs} = {Sum of Outputs}. Figure 13 shows all fluxes in and out of each reservoir. Water and salt fluxes are labeled Qxxx and SFxxx, respectively (xxx is a descriptive index).

The following four equations express conservation of water and salt (Chloride):

Qprecip + Qswi + Qmix = Qevap + Qswo + Qseep

Qrech + Qgwi + Qbi = Qmix + Qgwo + Qpump

Qbi Cbi = Qgwo Cgw + Qmix Cmix + Qpump Cpump

Qmix Cmix = Qswo Csw + Qseep Csw.

We used the following notation for water fluxes and salt concentrations:
- Qprecip: rainfall input directly into surface water reservoir (ponds, streams, and marshes)
- Qevap: evapotranspiration output from surface water reservoir (ponds, streams, and marshes)
- Qswi: surface water input, measured at Macksville Station in Rattlesnake Creek
- Qswo: surface water output, measured at Raymond Station in Rattlesnake Creek
- Qmix: groundwater discharge into the surface water reservoir
- Qseep: seepage from the surface water reservoir back into the groundwater reservoir
- Qrech: fresh water recharge into the GBPA through overlying soil
- Qbi: salt water recharge from Permian bedrock/Cedar Hills formation

- Qgwi: regional groundwater flow into the GBPA through upgradient boundary
- Qgwo: regional groundwater flow out of the GBPA through downgradient boundary
- Qpump: irrigation pumping
- Cbi: chloride concentration in Permian bedrock/Cedar Hills formation porewater
- Cgw: chloride concentration in groundwater reservoir
- Csw: chloride concentration in surface water reservoir
- Cmix: chloride concentration of the flux Qmix (Csw < Cmix < Cgw)
- Cpump: chloride concentration of the flux Qpump

The first two equations express water balance, while the last two express salt balance. Note that not all the terms in the first two equations appear in the last two equations. This is due to some water fluxes carrying only freshwater, or a salt concentration so low that it can be approximated as zero. Then, all water fluxes that have an approximately zero concentration yield a negligible salt flux. The following water fluxes are in that category: Qprecip, Qevap, Qrech, Qgwi, Qpump, and Qswi. We used the following units: time in years, water volume in Mm^3 (where $M=10^6$), salt mass in Mkg of chloride, water fluxes in Mm^3/yr, and salt fluxes in Mkg/yr; salt concentrations (chloride) are in kg/m^3.

As previously discussed, we have modified the original formulation of the well-mixed reservoir by allowing some fluxes (Qmix and Qpump) to have concentrations that are different from the average reservoir concentration. This modification is based on the mechanics of groundwater flow, and allows more flexibility in fitting the model to the available field data.

4. Choosing the unknown variables of the model

The model defined by the four equations listed above contains 16 variables (fluxes and concentrations). To solve these four equations we need to reduce the number of variables to four. We can select any four variables as independent (to be calculated by the model), but all remaining variables have to be estimated in advance. Clearly there is more than one way to proceed at this point. We made our choice based on the available data: the four independent variables are those that we have little or no information about. Once the problem is reduced to four equations and four variables, it can be solved with pencil and paper in just four lines. The result is a set of water and salt fluxes that assure conservation of water and mass under the assumption of steady state.

We estimated the following variables: Qprecip, Qevap, Qswi, Qswo, Qgwo, Qpump, Qseep, Csw, Cgw, and Cbi. We also estimated a host of other secondary variables needed to calculate these fluxes (see Tables 4 and 5). The four variables calculated by the model are: Qmix, Qbi, Cmix, and the lumped term (Qrech+Qgwi). We lumped together two fluxes (Qrech and Qgwi) because we found insufficient information to produce independent estimates of each one. The details of the calculation are spelled out in Appendix B.

TABLE 4.
Model Inputs: Estimates of Invariant System Properties,
Northern Study Area

Surface Water Reservoir

The surface water reservoir includes the Big and Little Salt Marsh, and several other ponds inside the Quivira National Wildlife Refuge. The streams are considered part of the surface water reservoir, but their contribution to the surface area is negligible compared to the area of ponds and marshes. The following information was provided by Gregory Pouch (personal communication, 1996).

-- Volume of surface water reservoir = VOLsw = 10 Mm^3

-- Surface Area of surface water reservoir = AREAsw = 12.14 Mm^2 (3000 acres)

Ground Water Reservoir

The ground water reservoir is an appropriately defined region of the Great Bend Prairie Aquifer (GBPA). For each study area, the groundwater region is bounded by equipotential lines for the upgradient and downgradient boundaries, and by flow lines for the side boundaries. The limits of the ground water reservoir for the Northern GMD5 model are shown in Figure 102. Representative values for each parameter were selected as follows:

-- Volume of ground water reservoir = VOLgw = 4000 Mm^3

The volume VOLgw is the volume of void space in the aquifer, calculated as the product of: -- Surface Area of ground water reservoir: AREAgw = 650 Mm^2 (250 mi^2)
-- Saturated thickness of GBPA in study area. ST = 30.48 m (100 ft)
-- Porosity of GBPA in study area. n = 0.20

-- Area of cross-section along eastern boundary of study area = AREAxs = 0.49 Mm^2.
The vertical area AREAxs was calculated as the product of the saturated thickness ST (see above) and the

-- Length of the GBPA outflow cross section. Lxs = 16090 m (10 mi)
(See Figure 12)

-- Hydraulic conductivity in the GBPA. K = 24 m/day (80 ft/day)
Estimated realistic low and high values: 12 and 36 m/day
(Source: Sophocleous et al., 1993, OFR 93-21, statistics of 68 drillers' logs)

TABLE 5.

Model Inputs: Estimates for single record [1961-1995], Northern Study Area

Qswo Flux

Taken as the mean value of the 1961-1995 series of yearly mean discharge records at the Raymond gauging station operated by the US Geological Survey.

Qswo = 43 Mm^3/yr

In addition, the 95% confidence limits about the mean are: 31 and 56 Mm^3/yr

Qswi Flux

Taken as the mean value of the 1961-1995 series of yearly mean discharge records at the Macksville gauging station operated by the US Geological Survey.

Qswo = 22 Mm^3/yr

In addition, the 95% confidence limits about the mean are: 14 and 31 Mm^3/yr

Qprecip Flux

Calculated as the product of the surface area AREAsw (see Table 4) and the mean annual precipitation rate of 0.635 m/yr (25 in/yr), taken from the Climate and Weather Atlas of Kansas (KGS, Educational Series 12).

Qprecip = 7.7 Mm^3/yr

Qevap Flux

Calculated as the product of the surface area AREAsw (see above) and the mean annual evaporation rate of 1.4 m/yr (55 in/yr), taken from Viessman et al. (1977), "Introduction to Hydrology", p. 45.

Qevap = 17.0 Mm^3/yr

Qgwo Flux

Calculated as the product of the cross-sectional area AREAxs (see above), a representative hydraulic head gradient (0.002), and representative values of the GBPA hydraulic conductivity K (see above). This hydraulic head gradient is the same value used in Section II to develop flux estimates. For consistency we keep the same value here, although it might slightly overestimate the regional gradient over the whole Northern Study Area.

Qgwo = 10 Mm^3/yr

In addition, the low and high estimates are: 5 and 15 Mm^3/yr

Qseep Flux

No information is available. We set it to 1/3 of the value of Qmix, whenever Qseep was assumed nonzero.

Cgw Salt Concentration

Representative range of values taken from available measurements along the N-S section that runs along the boundary between townships R. 10 W. and R. 9 W. (Eastern boundary of the study area). Cgw range = [3; 4; 5 kg/m^3].

Csw Salt Concentration

Representative range of values taken at the Raymond gauging Station on Rattlesanke Creek. Csw range = [1.5; 2; 2.5 kg/m^3].

Cbi Salt Concentration

Assumed equal to representative value of brine concentration = 42 kg/m^3

5. Results obtained

We solved the four balance equations as explained above. We analyzed a number of cases, making different assumptions for some of the key fluxes. We made an effort to identify qualitative changes in the streamflow and concentration time series, and used that insight to define four different cases to analyze in detail. The "baseline case" is the simplest of all: each complete record (streamflow and chloride concentration) is processed as a single entity and the resulting long-term averages are assumed representative of predevelopment conditions (prior to the onset of significant irrigation pumping). Other cases differentiate between predevelopment and development conditions.

We analyzed four cases, which differ in how we process the available records of surface water discharge [1961-1995] and all sporadic salt concentration measurements (references to the "time series" below apply to both discharge and concentration records). The four cases are:

(n1). Assume the whole time series [1961-1995] to be representative of steady-state pre-development conditions.

(n2). Assume that only the first 20 years in the time series [1961-1980] are representative of steady-state pre-development conditions.

(n3). Same as (n2) but assuming that there is no seepage back to the groundwater (this assumption provides a lower limit for the ground water discharge term Qmix).

(n4). Assume that the last 15 years in the series of surface water discharge [1981-1995] are representative of steady-state development conditions. Here we use a value of the Qpump flux estimated from irrigation records (see Table 6).

The results for all four cases are shown in Table 7 and Figures 18 to 21. Although in principle each case yields different results, they also have some similarities that are worth noting. There are features that change remarkably little across different cases; they can be assumed to be characteristic features of the natural system, not affected by human activities. For example, the total saltwater recharge from bedrock (Qbi) is remarkably constant across all four cases, ranging from 2.5 to 3 Mkg/yr. The same is true for the ratio of surface to ground water salt fluxes, which ranges from 2 to 3.25. Since in steady-state Inputs balance Outputs, the total saltwater flux leaving the study area is equal to the incoming flux from bedrock (Qbi); the importance of this result is that the total salt outflow from GMD5 is controlled primarily by natural factors and not greatly affected by human activities. However, human activities can change the way in which this total is distributed along two main outlets: surface and ground water.

A reasonable conceptual model is given by the pair of scenarios (n2) and (n4), which together show the consequences of development. Because of the way that we structured the model, the extra water needed to balance pumping comes from the lumped term (Qrech + Qgwi). This term increases by about 2/3 of its predevelopment value; such a large increase requires both an increase in recharge (reasonable under irrigation) and an increase in regional ground water inflow. This situation can only be sustained by

TABLE 6.
Model Inputs: Estimates for two partial series, early [1961-1980] and late [1981-1995] parts of the available record, Northern Study Area

Here we list only those variables that display marked changes between the early and late parts of the data records.

Qswo Flux
Taken as the mean yearly mean discharge at the Raymond gauging station operated by the US Geological Survey. Listed below are the values for the two partial series, indicating the years included in each record.
Qswo = 52 Mm^3/yr [1961-1980]
Qswo = 32 Mm^3/yr [1981-1995]
In addition, the 95% confidence limits about the mean are: 35 and 70 Mm^3/yr [1961-1980], and 17 and 47 Mm^3/yr [1981-1995].

Qswi Flux
Taken as the mean yearly mean discharge at the Macksville gauging station operated by the US Geological Survey. Listed below are the values for the two partial series, indicating the years included in each record.
Qswo = 31 Mm^3/yr [1961-1980]
Qswo = 11 Mm^3/yr [1981-1995]
In addition, the 95% confidence limits about the mean are: 18 and 44 Mm^3/yr [1961-1980], and 6 and 16 Mm^3/yr [1981-1995].

Csw Salt Concentrations
Estimates for the two partial series were developed based on the information available at the Raymond gauging Station on Rattlesnake Creek (see Figure 18).
Csw = 1.5 kg/m^3 [1961-1975], expressed in terms of chloride ion (Cl^-)
Csw = 2.5 kg/m^3 [1981-1995], expressed in terms of chloride ion (Cl^-)

Cgw Salt Concentration
Using our previous estimate for overall average (Cgw = 4 kg/m^3), assuming it to be representative of the conditions of the [1981-1995] partial series, and using the corresponding surface water concentration (Csw = 2.5 kg/m^3, see above), we calculate the ratio Cgw/Csw = 1.6. Assuming that this ratio holds for the [1961-1975] partial series as well, we can use the corresponding estimate of Csw (1.5 kg/m^3, see above) to estimate an average value for Cgw. In summary:
Cgw = 2.5 kg/m^3 [1961-1975], expressed in terms of chloride ion (Cl^-)
Cgw = 4.0 kg/m^3 [1981-1995], expressed in terms of chloride ion (Cl^-)
Ranges of values were developed using our previous estimates for the overall record, and assuming that the relative ranges RR remain the same (RR=(maximum-minimum)/mean). The corresponding ranges for Csw are calculated using the ratio Cgw/Csw = 1.6.

Qpump Flux
The total irrigation pumpage in the study area was estimated using the actual figures published in the 1991 Irrigation Water Use Report (Kansas Water Office). The report contains annual totals per township. We simply added these figures for all townships included in the study area. For those townships that are partially included, the water use figure was adjusted by multiplying it by the percent of the total township area that is included in the Northern Study Area.
Qpump = 40 Mm^3/yr [1991]

CASE	Qswo	Qswi	Qgwo	Cgw	Qmix - Qseep	Qmix	Qseep	Csw	Cmix	Qpump	SUMgwo	SUMswi	Qbi	Qrech+Qgwi	SFbi	SFgwo	SFmix	SFseep	SFswo	SF_gw_OUT	SF-sw/SF-gw	Tgw (yr)	Tsw (yr)
n1	43	22	10	4	30	30	0	2.0	2.9	0	40	60	3.0	37	126	40	86	0	86	40	2.15	100	0.17
n2	52	31	10	2.5	30	40	10	1.6	2.4	0	50	79	2.9	47	122	25	97	16	81	41	2.00	80	0.13
n3	52	31	10	2.5	30	30	0	1.6	2.7	0	40	69	2.5	37	106	25	81	0	81	25	3.25	100	0.14
n4	32	11	10	4	30	30	0	2.5	2.7	40	80	49	2.9	77	120	40	80	0	80	40	2.00	50	0.20

NOTES:

(a) units for WATER fluxes are MCM/yr; for SALT fluxes are MKg/yr; forChloride Concentration are Kg/CM (CM=m^3)

(b) the four cases represent the following scenarios:

n1: [61-95] series
n2: [61-80] series
n3: [61-80] - no Qseep
n4: [80-95] series

Table 7: Budget model results for the four selected cases, northern GMD5 study area.

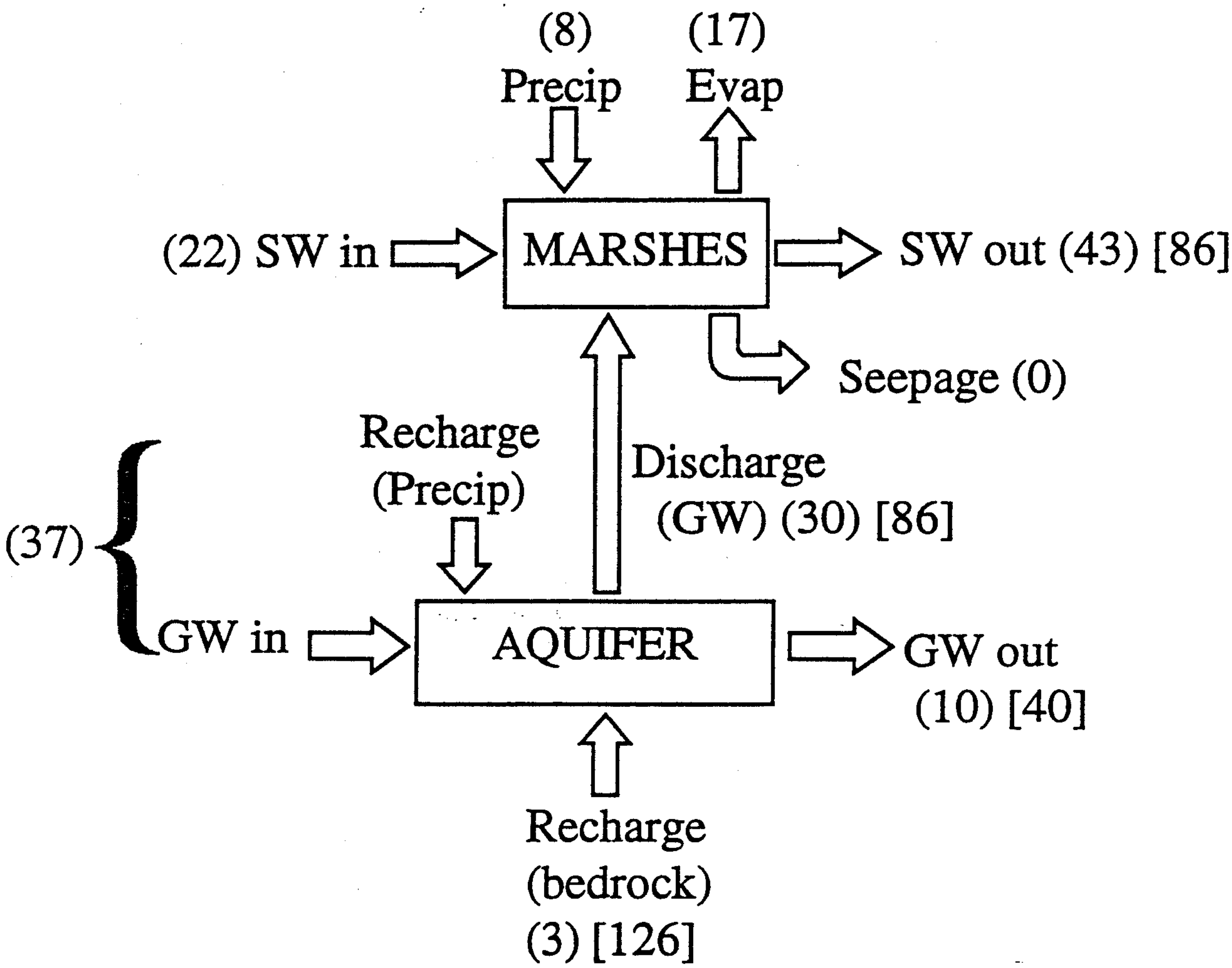


Figure 18. Modeling results for water and salt fluxes under scenario (n1) for northern study area. Water fluxes in Mm^3/yr are shown in parenthesis; salt fluxes (as Cl) in Mkg/yr are shown in brackets.

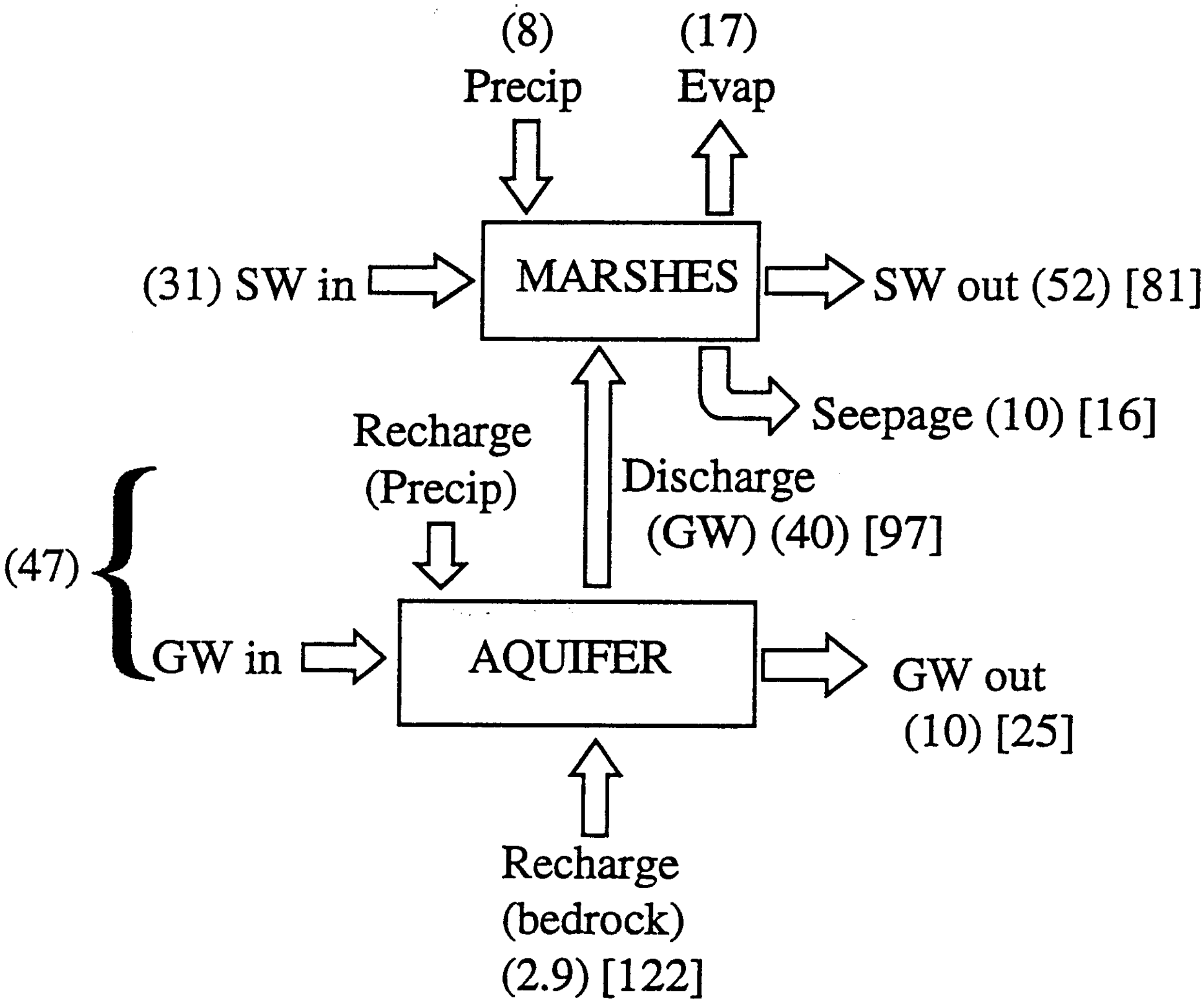


Figure 19. Modeling results for water and salt fluxes under scenario (n2) for northern study area. Water fluxes in Mm^3/yr are shown in parenthesis; salt fluxes (as Cl) in Mkg/yr are shown in brackets.

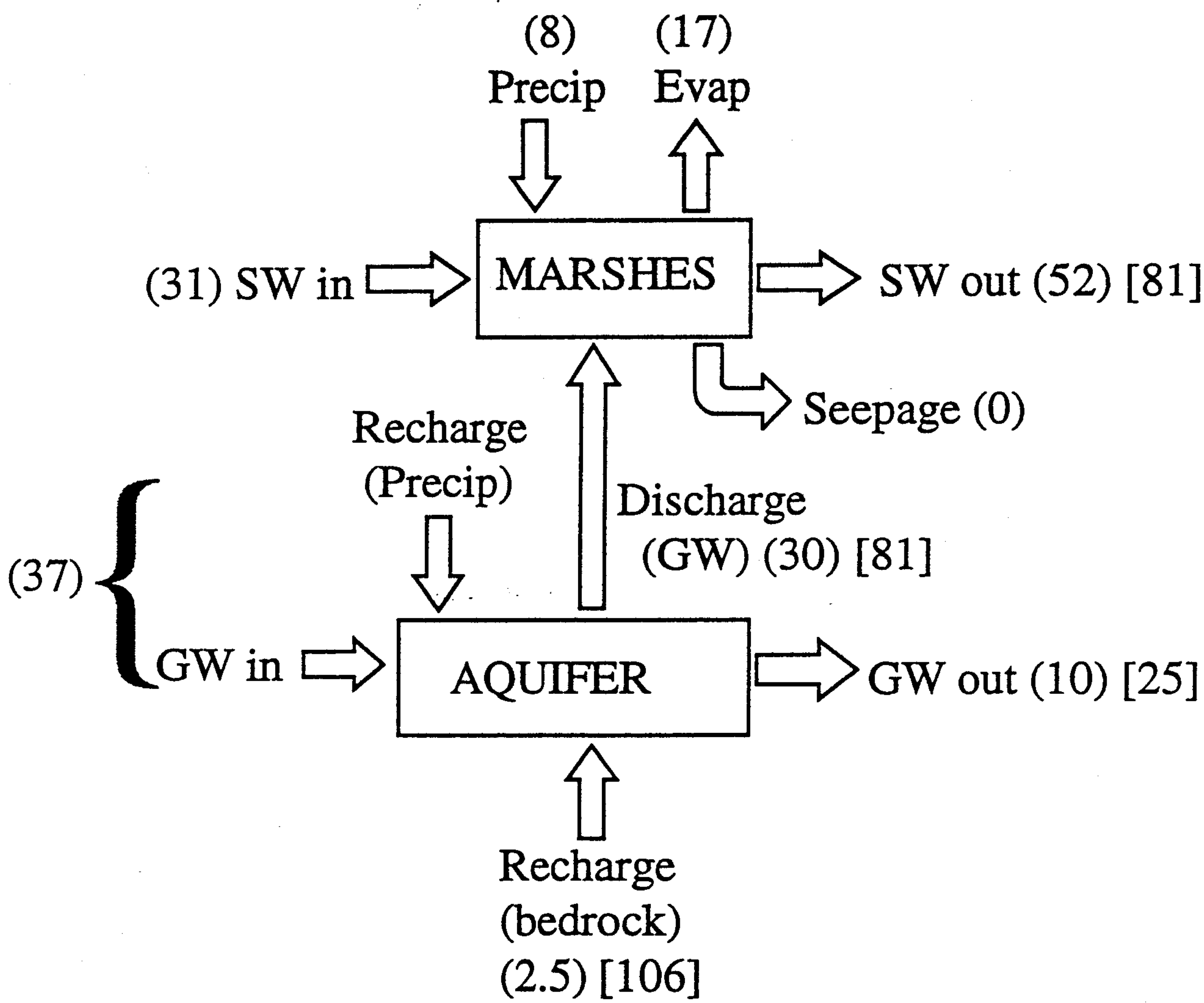


Figure 20. Modeling results for water and salt fluxes under scenario (n3) for northern study area. Water fluxes in Mm^3/yr are shown in parenthesis; salt fluxes (as Cl) in Mkg/yr are shown in brackets.

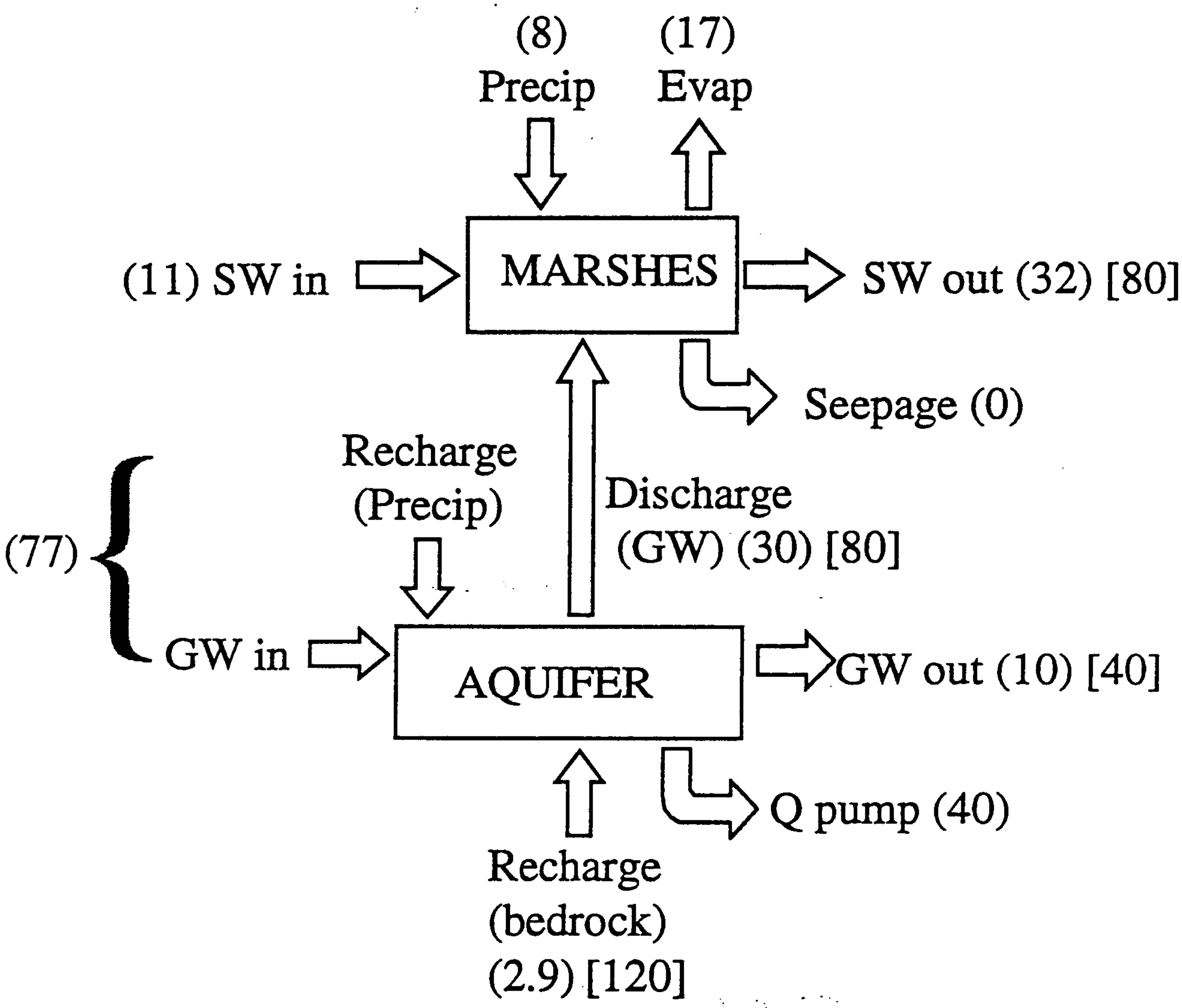


Figure 21. Modeling results for water and salt fluxes under scenario (n4) for northern study area. Water fluxes in Mm^3/yr are shown in parenthesis; salt fluxes (as Cl) in Mkg/yr are shown in brackets.

drawing water from the region immediately upgradient, not included in our model; groundwater declines can result in that area because of this large water transfer. (Water level declines are less likely near the creek and marshes; because that area is a regional groundwater discharge zone; water levels are stable as long as the creek and marshes are full of water.)

However, analyzing the consequences of development is not as simple as we made it appear. We made a number of assumptions (e.g., evaporation remains the same under irrigation); changing these assumptions will produce different results. Hence, our results provide one possible comprehensive picture in terms of all fluxes and concentrations. However, if we are interested in the broad picture, our model yields valuable insights in terms of the few variables that appear to remain the same under both predevelopment and development conditions.

An important caveat is to note that scenarios n2 and n4 both have significant stream outflow, although the volume is reduced in the development case. If streamflow were dramatically reduced or eliminated, the large fraction of the total salt load currently discharged by surface water implies some major changes in the salinity of the groundwater system.

6. Robustness of model predictions

It is important to recognize that the values used as model inputs are estimates subject to uncertainty. Even variables such as the mean annual discharge at Raymond Station vary considerably from year to year, and so does the long-term average, depending on the particular record considered. When we have abundant data, this uncertainty can be measured by the standard error of the mean, a function of the record length and the variance of the observed values. In other cases, we may only have a range of values corresponding to different scenarios or hypotheses. In any case, uncertainty in model inputs causes uncertainty in model outputs and predictions.

No modeling study is complete without assessing the uncertainty in model predictions. There are several ways to assess uncertainty and here we chose the simplest one for illustration purposes. The results of this exercise will provide an estimate of the order of magnitude of the uncertainty in predictions for the two-reservoir model of the Northern part of GMD5. Preliminary analyses indicate that three variables carry the most uncertainty: the two main water fluxes out of the system (Qswo and Qgwo), and the salt concentration in the groundwater reservoir (Cgw) - note that the product of Cgw and Qgwo define the groundwater salt flux out of the system (SFgwo). For this reason, and to keep the analysis simple, we will assume that only these three variables can contribute to the uncertainty of the model results. By comparison, a complete uncertainty analysis would include the uncertainties in all variables of the model. Therefore, our results probably somewhat underestimate the total uncertainty.

To simplify the mathematics, we conduct a discrete uncertainty analysis using three points for each variable (a total of 27 cases). The results are presented in Table 8.

Qswo	Qswi	Qgwo	Cgw	Qmix - Qseep	Qmix	Qseep	Csw	Cmix	SUMgwo	SUMswi	Qbi	Qrech+Qgwi	SFbi	SFgwo	SFmix	SFseep	SFswo	SF_gw_OUT	SF-sw/SF-gw	Tgw (yr)	Tsw (yr)
43	22	10	4	30	30	0	2.0	2.9	40	60	3.0	37	126	40	86	0	86	40	2.2	100	0.17
43	22	10	3	30	30	0	1.5	2.2	40	60	2.3	38	95	30	65	0	65	30	2.2	100	0.17
43	22	10	5	30	30	0	2.5	3.6	40	60	3.8	36	158	50	108	0	108	50	2.2	100	0.17
43	22	5	4	30	30	0	2.0	2.9	35	60	2.5	32	106	20	86	0	86	20	4.3	114	0.17
43	22	5	3	30	30	0	1.5	2.2	35	60	1.9	33	80	15	65	0	65	15	4.3	114	0.17
43	22	5	5	30	30	0	2.5	3.6	35	60	3.2	32	133	25	108	0	108	25	4.3	114	0.17
43	22	15	4	30	30	0	2.0	2.9	45	60	3.5	42	146	60	86	0	86	60	1.4	89	0.17
43	22	15	3	30	30	0	1.5	2.2	45	60	2.6	42	110	45	65	0	65	45	1.4	89	0.17
43	22	15	5	30	30	0	2.5	3.6	45	60	4.3	41	183	75	108	0	108	75	1.4	89	0.17
31	14	10	4	26	26	0	2.0	2.4	36	48	2.4	34	102	40	62	0	62	40	1.6	111	0.21
31	14	10	3	26	26	0	1.5	1.8	36	48	1.8	34	77	30	47	0	47	30	1.6	111	0.21
31	14	10	5	26	26	0	2.5	3.0	36	48	3.0	33	128	50	78	0	78	50	1.6	111	0.21
31	14	5	4	26	26	0	2.0	2.4	31	48	2.0	29	82	20	62	0	62	20	3.1	129	0.21
31	14	5	3	26	26	0	1.5	1.8	31	48	1.5	30	62	15	47	0	47	15	3.1	129	0.21
31	14	5	5	26	26	0	2.5	3.0	31	48	2.4	29	103	25	78	0	78	25	3.1	129	0.21
31	14	15	4	26	26	0	2.0	2.4	41	48	2.9	38	122	60	62	0	62	60	1.0	98	0.21
31	14	15	3	26	26	0	1.5	1.8	41	48	2.2	39	92	45	47	0	47	45	1.0	98	0.21
31	14	15	5	26	26	0	2.5	3.0	41	48	3.6	37	153	75	78	0	78	75	1.0	98	0.21
56	31	10	4	34	34	0	2.0	3.3	44	73	3.6	40	152	40	112	0	112	40	2.8	91	0.14
56	31	10	3	34	34	0	1.5	2.5	44	73	2.7	41	114	30	84	0	84	30	2.8	91	0.14
56	31	10	5	34	34	0	2.5	4.1	44	73	4.5	39	190	50	140	0	140	50	2.8	91	0.14
56	31	5	4	34	34	0	2.0	3.3	39	73	3.1	36	132	20	112	0	112	20	5.6	103	0.14
56	31	5	3	34	34	0	1.5	2.5	39	73	2.4	37	99	15	84	0	84	15	5.6	103	0.14
56	31	5	5	34	34	0	2.5	4.1	39	73	3.9	35	165	25	140	0	140	25	5.6	103	0.14
56	31	15	4	34	34	0	2.0	3.3	49	73	4.1	45	172	60	112	0	112	60	1.9	82	0.14
56	31	15	3	34	34	0	1.5	2.5	49	73	3.1	46	129	45	84	0	84	45	1.9	82	0.14
56	31	15	5	34	34	0	2.5	4.1	49	73	5.1	44	215	75	140	0	140	75	1.9	82	0.14

UNITS: for WATER fluxes are Mm^3/yr; for SALT fluxes are MKg/yr; for Chloride Concentration are Kg/m^3

Table 8: Discrete uncertainty analysis, budget model results for northern GMD5.

The three points used are the mean (used in the baseline case), and low and high values; these extreme values correspond to the 95% confidence limits about the mean for streamflows, and to reasonable high and low bounds for salt concentrations. The 27 different cases are calculated as in the baseline case, and the results are listed in Table 8. Note that the first three columns in the table contain the uncertain inputs, each described by three points [minimum; mean; maximum] as follows: Qswo =[31; 43; 56], Qgwo =[5; 10; 15], Cgw =[3; 4; 5]. The remaining columns contain other inputs and all outputs, calculated following the steps detailed in Appendix B.

TABLE 9 – UNCERTAINTY ANALYSIS SUMMARY FOR BASELINE CASE (n1)

INPUTS	Min	Max	Mean	Rel. Range
Qswi	14	31	22	0.77
Qswo	31	56	43	0.58
Qgwo	5	15	10	1.0
Cgw	3	5	4	0.5
OUTPUTS				
Qmix	26	34	30	0.27
SUMgwi	31	49	40	0.45
SUMswi	48	73	60	0.42
Qbi	1.5	5.1	3.0	1.20
Qrech + Qgwi	29	46	37	0.46
SFbi	62	215	126	1.21
SFgwo	15	75	40	1.50
SFmix=SFswo	47	140	86	1.08
Tgw	82	129	100	0.47
Tsw	0.14	0.21	0.17	0.41

A summary of the uncertainty analysis is given in Table 9, listing the minimum and maximum values for each variable. Table 9 also lists the relative range, defined as the range [maximum - minimum] divided by the mean value; this is a dimensionless measure of uncertainty that can be used to compare all variables and see which ones carry more uncertainty. Using the comprehensive information in Table 8 we can plot all possible values of selected variables, to identify a confidence region for each variable (or combination of variables). Figure 22 illustrates such a region for the salt fluxes out of the study region, SFswo and SFgwo.

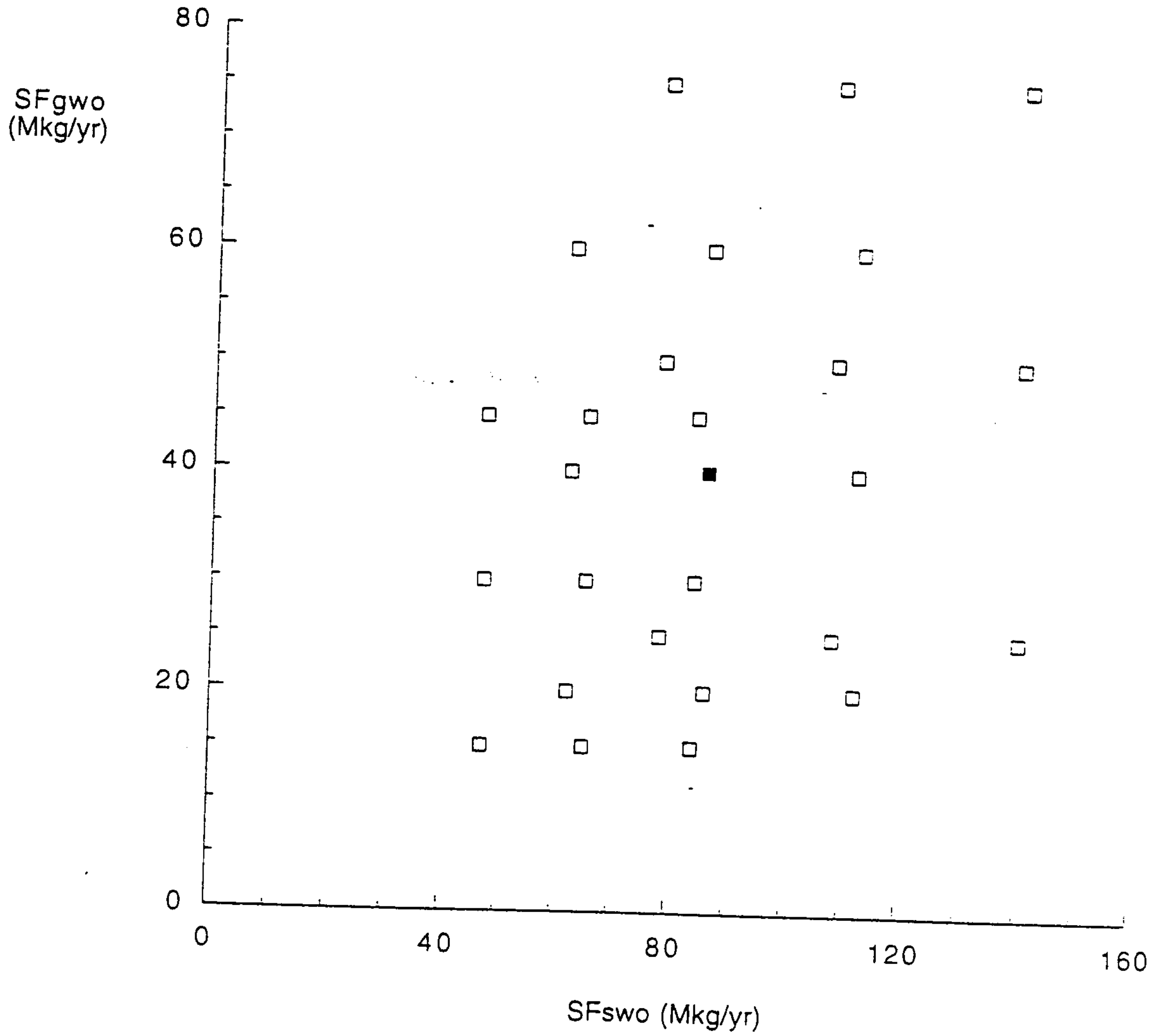


Figure 22. Uncertainty in salt fluxes out of Quivira-Rattlesnake Creek region, due to uncertainty in mean values of selected inputs, under scenario (n1).

Figure 22 has a simple interpretation. There is a single most likely point (specially marked) that correspond to the reference case. All other points around it define a region which for practical purposes will contain most values that are likely to occur. But they are not equally likely. As a general rule, their likelihood decreases with their distance from the reference point. Because of this "central point with a cloud" interpretation, one should not attempt to extract more complex interpretations out of this plot (e.g., linear regression and other functional relationships).

We chose this simple discrete method for uncertainty analysis to introduce the main concepts. There are more sophisticated methods that will yield a continuous probability distribution instead of a small number of points. We applied one of these methods (Monte Carlo simulations) to the reference case and obtained results comparable to those of the three-point discrete method. However, continuous distributions are the most appropriate to describe physical variables (e.g., discharge, flux, concentration) that can take on any value inside a given range; their major advantage is that they provide a complete probabilistic description that can be used to calculate the risk associated with particular values.

Figure 23 depicts the distribution of the input salt flux from bedrock SFbi. We have marked three points in that figure to show typical probability statements that can be extracted from the plot. The mean value is also shown for reference, although in general we are interested in the probability of extreme values. For example, a manager might have to define the value that has a small probability (say 5%) of being exceeded. Using Figure 23 we determine the answer to be a salt flux of about 165 Mkg/yr of chloride. The risk is the probability of an undesirable event, in this case having a large salt flux. We can lower the risk if we can accept larger fluxes: a value of 185 Mkg/yr has a risk of only 1%. One can also readily obtain ranges (confidence intervals) from this type of plot. By reading the 5% and 95% values, we determine that there is a 90% probability that the total Cl flux will be in the range [90-165] Mkg/yr.

7. Implications for water management

Results indicate that the well-mixed reservoir concept provides an adequate model for the northern study area of GMD5. This is because Qmix is more than 50% of the total ground water output, so that the surface water outlet (Rattlesnake Creek at Raymond Station) actually measures the bulk of the system's response.

Management policies are usually developed for a given planning horizon (e.g., 20 years), often using model predictions to aid in the required analyses. This requires an understanding of the dynamics of the system, both in terms of fluxes and of residence times on each reservoir. Even a simple model like the one developed for this study can be useful, since the key parameters have been determined. In our model the controlling factor is the groundwater residence time, which ranges from 100 yr. in the baseline case to 50 yr. in the development case. This is the time it would take for all the water in the Great Bend Prairie aquifer in the study area to be replaced by new water in the absence of mixing (plug flow analogy). This parameter is the key to define system dynamics, and

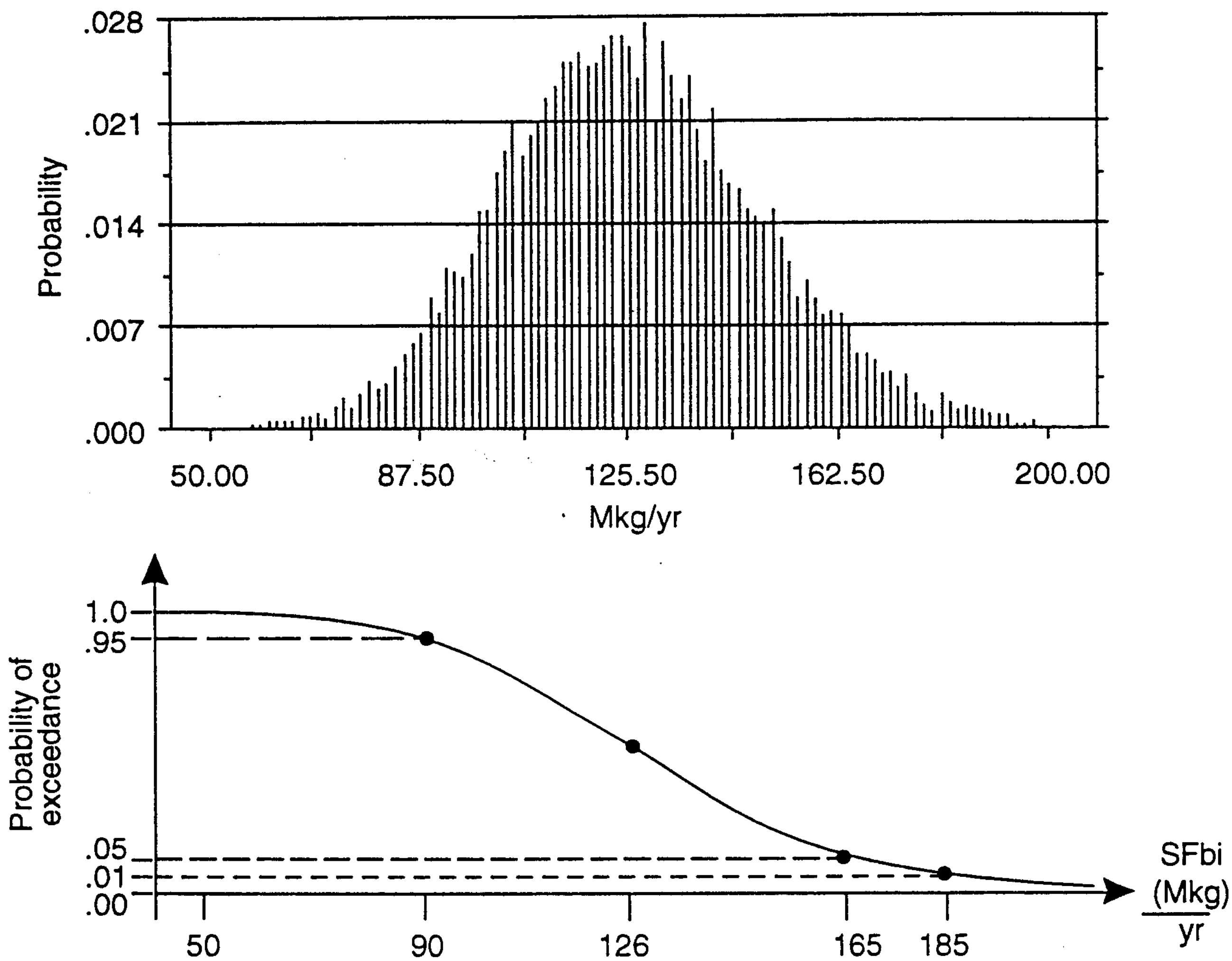


Figure 23. Results of uncertainty analysis with the Monte Carlo method, under scenario (n1). Probability density and probability distribution functions for the input salt flux from bedrock, SFbi.

therefore the one that can have the largest impact on the analysis of management alternatives.

System dynamics is best analyzed with software specifically designed for this purpose, such as STELLA. We developed a STELLA model for the system shown in Figure 13, using the equations and parameter values listed in Appendix B. The mechanics of transferring a steady-state balance model to the STELLA framework are very simple; (see Appendix A). Essentially, after we enter all the fluxes into the STELLA program, we can evaluate the system response as a function of time, for different possible scenarios. These "what-if" analyses can provide valuable insight on the system behavior. For example, consider the hypothetical situation where freshwater recharge to the aquifer is increased by 50% (e.g., by importing water from other basins). The STELLA model predicts the change in fluxes and concentration as a function of time, as illustrated in Figure 24. Note that because the residence time is 100 years (baseline case), it takes a few hundred years for the concentration in both reservoirs to achieve a new equilibrium.

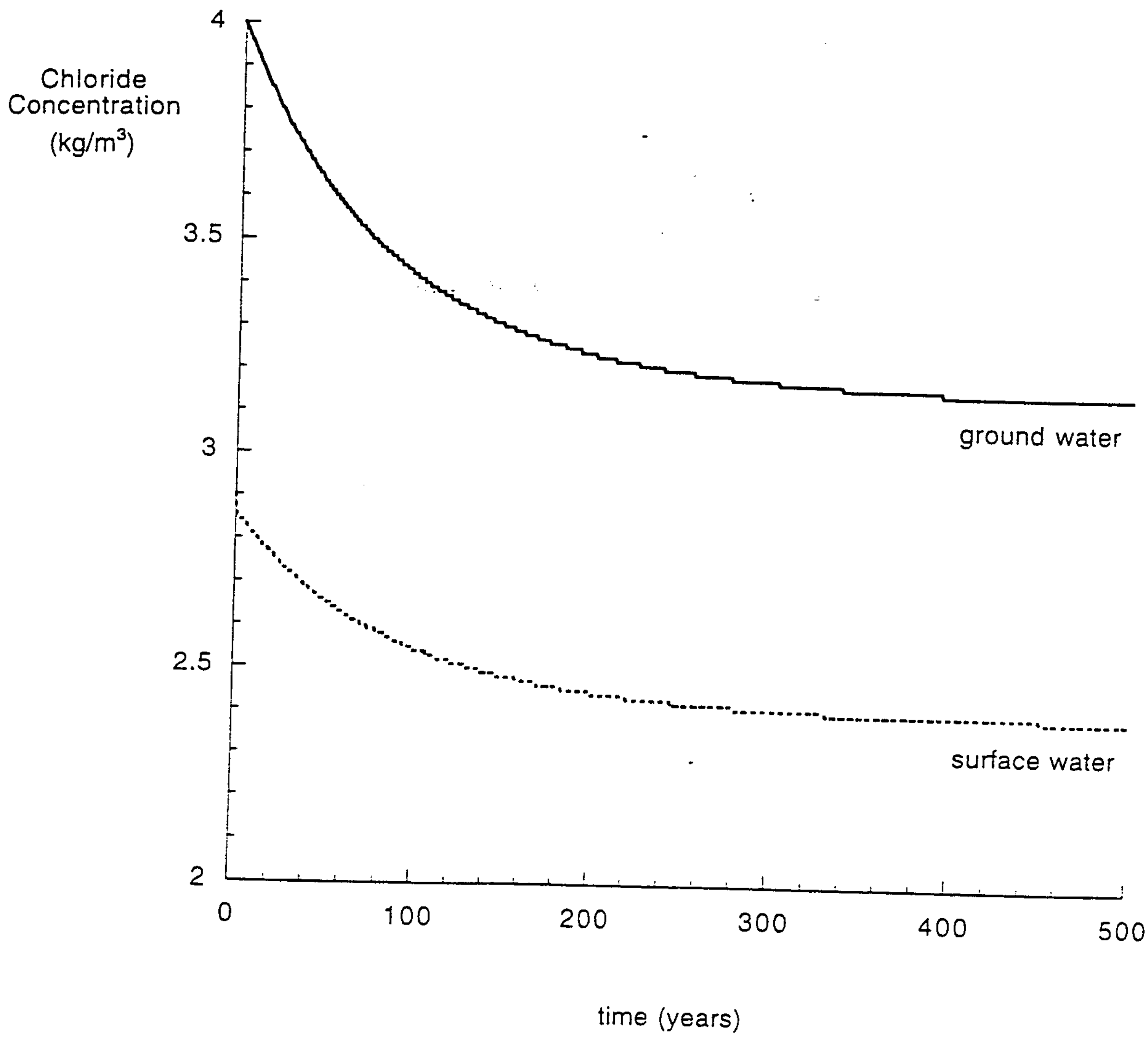


Figure 24. Analysis of system dynamics using the STELLA software package, for the baseline case (n1), with a hypothetical 50% increase in groundwater input.

C. Southern GMD5 Model

1. Selection of study area

The southern study area is the fraction of the South Fork Ninnescah River between the US 281 Highway (west boundary) and the R10W-R9W Township line (eastern boundary), as shown in Figure 11. These lines are the approximate boundaries; in reality we use the surface elevation contours and the groundwater level contours that run closest to the trace of each line. Similarly to the delimitation of the northern study area, we choose the north and south boundaries based on surface and ground water hydrology. The north boundary is the water divide between the North and South Forks of the Ninnescah River; the south boundary is the water divide between the South Fork Ninnescah River and the Medicine Lodge River. For the aquifer we use the flow lines that run closest to the surface water divides, as explained for the northern study area (see Figure 12).

2. Review available water quantity and quality data

There are fewer data available for this region than for the Rattlesnake Creek basin. This is partly a consequence of saltwater intrusion being less severe in this region. Salt concentrations in both surface and ground water west of the US 281 Highway (near Pratt) are only about 50 mg/L; groundwater concentrations East of the R10W-R9W Township Line have only increased to about 100 mg/L (Whittemore, 1993). These values are well below the threshold of 250 mg/L that makes water unsuitable for human consumption. However, in the intervening 20 miles salt concentrations in ground water are very high, because of the influx of saltwater from the Permian bedrock. Gillespie and Hargadine (1993) studied a region similar to our southern study area and identified the Ninnescah Shale formation as the source of saltwater. Their mapping shows an excellent correlation between its spatial extent and the onset of high ground water concentrations. Saltwater concentrations in groundwater show a high degree of variability in the area of interest, being as high as 14,000 mg/L at some points near the base of the aquifer.

The USGS has two permanent gauging stations near the West and East boundaries of the study area, at Pratt and Murdock (see Figure 10). Discharge statistics are given in Table 10. There are also sporadic measurements of discharge and water quality at two intermediate stations at Calista and Kingman. Salt concentrations in the river water are highest in the eastern part of the study area, just east of Cairo; progressively lower values are registered at Calista, Kingman, and Murdock (e.g., Gillespie and Hargadine, 1993). Concentrations decrease from 350 to about 250 mg/L in this river reach, and are lower further east. This decrease in concentrations is due to a steady increase in discharge, from 17 cfs at Pratt to 207 cfs at Murdock (daily averages of multi-year series). These two opposite trends cancel out to yield a constant salt flux (the product of discharge and concentration), as sketched in Figure 25.

TABLE 10.
Discharge Statistics for USGS gauging stations at Pratt and Murdock, South Fork Ninnescah River

The following discharge statistics for the complete series up to 1995 were obtained from the USGS database (yearly averages in cfs):

station name	no. of years in sample	annual mean	highest annual mean	lowest annual mean
Pratt	15	17.1	30.4	10
Murdock	45	207	371	89

A partial series analysis at Murdock station reveals that the mean annual discharge has remained practically unchanged in the last twenty years. Hargadine et al. (1979) reported a mean annual discharge of 202 cfs for the series up to 1975. This series contains twenty years of daily observations, taken from August 1950 to September 1959, and from June 1964 to September 1975. Twenty years later (up to 1995), the average annual discharge is essentialy the same (207 cfs, see above). This finding suggests that the hydrologic system is in equilibrium. Hence, its long term behavior can be modeled assuming steady-state.

The field data summarized above are consistent with a rather simple conceptual picture. There is a plume of saline water that originates in the bedrock and ends in the river. The total salt flux carried by the river is approximately constant when it crosses the eastern boundary of the study area, near Calista. The river in all of the study area, and at least up to Murdock, receives groundwater discharge with lower salt concentrations that dilute the average concentration in the river. The combined stream-aquifer system seems to be in a state of equilibrium: Table 10 shows that the mean annual discharge at Murdock has remained the same in the last 40 years of record.

3. Balance equations for salt and water

We constructed a model for this system that is even simpler than the one designed for the northern study area. Because of the absence of a major surface water body, we need only one reservoir to model water and salt fluxes in and out of the aquifer. Figure 26 shows a sketch of the reservoir and the corresponding fluxes. The two balance equations are:

$$Qrech + Qgwi + Qbi = Qloss + Qgwo$$

$$Qbi\ Cbi + Qgwi\ Cgwi = Qgwo\ Cgwo + Qloss\ Csw$$

where:

- Qrech: fresh water recharge into the GBPA through overlying soil
- Qgwi: regional groundwater flow into the GBPA through upgradient boundary
- Qgwo: regional groundwater flow out of the GBPA through downgradient boundary
- Qbi: salt water recharge from Permian bedrock
- Qloss: discharge from groundwater to river
- Cbi: salt concentration in Permian bedrock/Cedar Hills formation
- Cgwi: Chloride concentration in groundwater at west boundary
- Cgwo: Chloride concentration in groundwater at east boundary
- Csw: Chloride concentration of groundwater discharge to the river (Qloss)

4. Choosing the unknown variables of the model

The model defined by the above two equations contains nine variables (fluxes and concentrations). To solve these two equations we need to reduce the number of variables to two, by estimating the remaining seven. As with the northern study area, we chose to calculate the variable that we know less about, Qbi, and an additional one, Qgwi. All other variables were estimated, as detailed in Table 11. Calculations are shown in Appendix C.

5. Results obtained

As discussed earlier in this section, we can reasonably assume that this system is in equilibrium (steady state). Hence, we analyzed a single case deemed representative of those conditions. Alternative assumptions were tried for some of the unknown variables to define a range of values for the main estimates. The results are shown in Table 12 and Figure 27.

As in the northern study area, most of the saltwater is carried by the river. But the imbalance is much more pronounced here, where the ratio of surface to groundwater salt fluxes is about 4:1.

6. Implications for water management

The southern region has a completely different behavior than the northern region. Here dilution plays a dominant effect, and the spike of salt water from the bedrock is slowly diluted as both ground water and surface water travel downgradient and mix with freshwater from recharge.

It is interesting to compare the results of both study areas in terms of the input salt flux from bedrock (SFbi), or its equivalent, the total salt flux through the system. In absolute terms, the salt flux in the southern study region is about 20% of that in the northern study area.

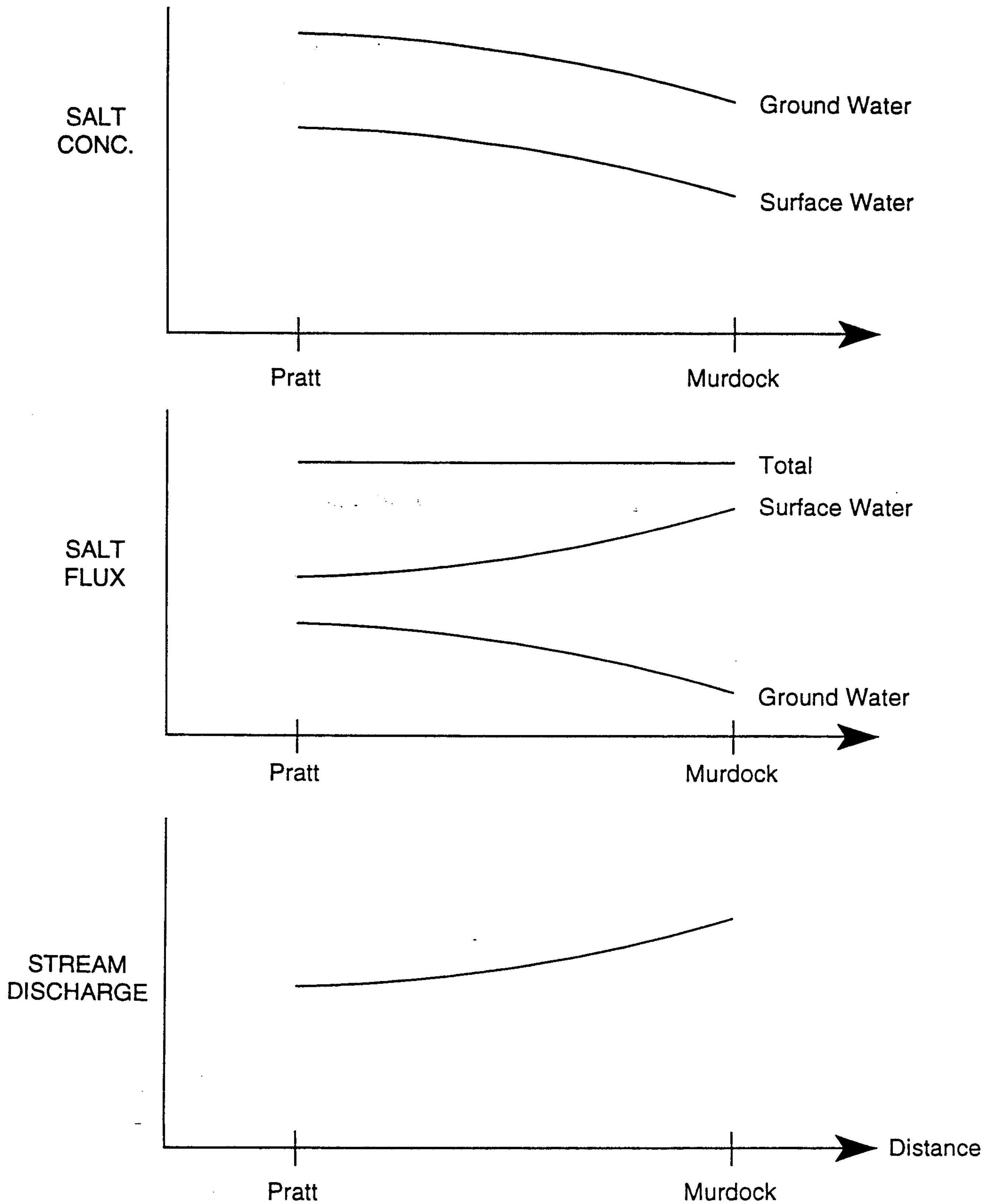


Figure 25. Qualitative trends in water quantity and quality parameters along the South fork Ninnescah River, approximately between Pratt and Calista. Sketch is a composite of data from different sources.

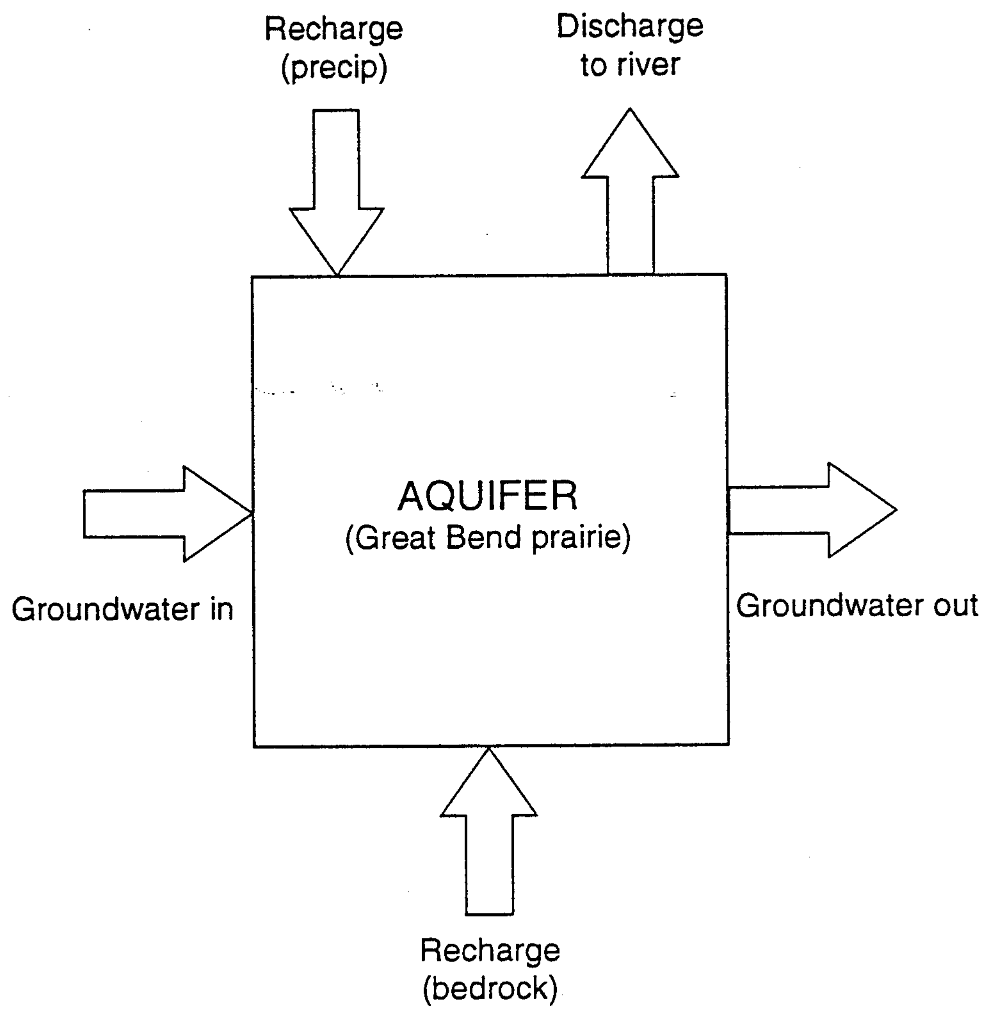


Figure 26. Schematic diagram with a single reservoir (aquifer) and all fluses in and out of the southern study area (South Fork Ninnescah River).

TABLE 11.

Model Inputs: Estimates for Steady State Model, Southern Study Area

<u>Qrech Flux</u>

Estimated as the product of the area covered by the model (800 Mm^2), and a representative value of the recharge rate (0.05 m). This recharge rate of about 2 in is well within the range of values deemed acceptable for this region (Sophocleous, 19xx).

Qrech = 40 Mm^3/yr

<u>Qloss Flux</u>

The discharge from the aquifer to the river was calculated as the difference between the annual mean discharge at Calista (60 Mm^3/yr) and Pratt (15 Mm^3/yr) stations.

Qloss = 45 Mm^3/yr

<u>Qgwo Flux</u>

Estimated with a simple mass balance model between Pratt and Murdock, allowing for the total groundwater discharge to the river. The resulting value applies to a vertical cross section at Pratt.

Qgwo = 80 Mm^3/yr

Based on the mass balance between Pratt and Calista, a slightly smaller value is estimated for the cross section at the Eastern boundary of the study area.

Qgwi = 75 Mm^3/yr

<u>CgwE Salt Concentration</u>

Estimate based on the range of values spanned by available measurements near the Eastern boundary of the study area (R.10W.-R.9W. township line).

Cgw = 0.1 kg/m^3, expressed as chloride ion (Cl^-).

<u>CgwW Salt Concentration</u>

Estimate based on the range of values spanned by available measurements near the Western boundary of the study area (US 281 highway).

Cgw = 0.05 kg/m^3, expressed as chloride ion (Cl^-).

<u>Csw Salt Concentration</u>

Representative average value of concentration measured at several points in the South Fork Ninnescah River, between Pratt and Murdock stations.

Csw = 0.4 kg/m^3, expressed as chloride ion (Cl^-).

Using this value, we can estimate the concentration of the aquifer discharge to the river, by multiplying by the ratio [Qcalista/Qloss] = 60/45 = 1.33

Closs = 0.53 kg/m^3, expressed as Chloride ion (Cl^-).

<u>Cbi Salt Concentration</u>

Representative value of brine concentration.

Cbi = 42 kg/m^3 Cl.

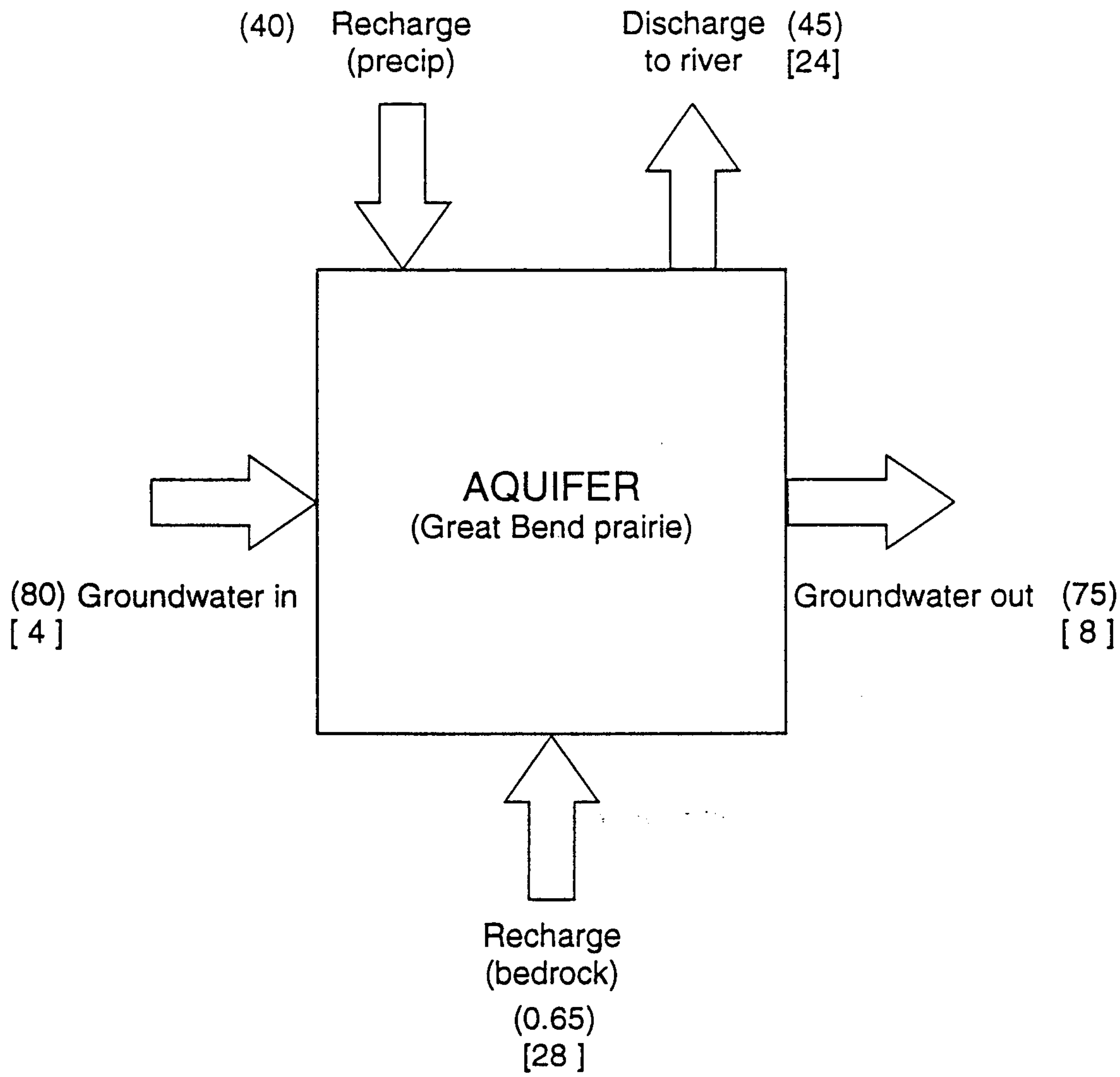


Figure 27. Modeling results for southern study area. Water fluxes in Mm^3/yr are shown in parenthesis; salt fluxes in Mkg/yr are shown in brackets.

D. Central GMD5 model

Hydrologic information is very sparse in the central study area, especially regarding surface water. There are no operating streamgauges in the North Fork Ninnescah River, and only sporadic measurements of water quality parameters are available in the STORET database. The only operating streamgauge is near Castleton, immediate upstream of Cheney reservoir (this gauge is identified as ÒAbove CheneyÓ). However, based on the qualitative relationships observed in the Southern study area, it is reasonable to assume that the total salt flux in the river becomes constant before crossing the Eastern boundary of the Central study area. Then this constant flux is what we would observe at the gauge near Castleton.

Given the paucity of data in this region, we decided not to formulate a budget model, but instead to obtain flux-based estimates, much as in section II of this report. The main objective is to have an order of magnitude estimate for the fluxes out of the Central study area, so that we can paint a complete picture of the water and salt fluxes out of GMD5.

For the surface water system, we use the mean annual stream discharge at the gauge near Castleton (30-yr average, from 1965 to 1995). We obtained a representative value for the chloride concentration by inspection of the corresponding data in the STORET database.
Multiplying these figures we obtain the total salt flux. The figures are:

Qswo = 137 Mm3/yr

Csw = 0.3 kg/m3

SFswo = 41 Mkg/yr

For the groundwater system, we obtained a representative value of chloride concentration from the monitoring of water qualityin GMD5 conducted by KGS in the last few years (Whittemore, 1993). The groundwater flux is estimated as equal to the (incoming) groundwater flow into the northern region - this is an order of magnitude estimate. The figures are:

Qgwo = 20 Mm3/yr

Cgw = 0.6 kg/m3

SFswo = 12 Mkg/yr

IV. DISCUSSION AND SUMMARY

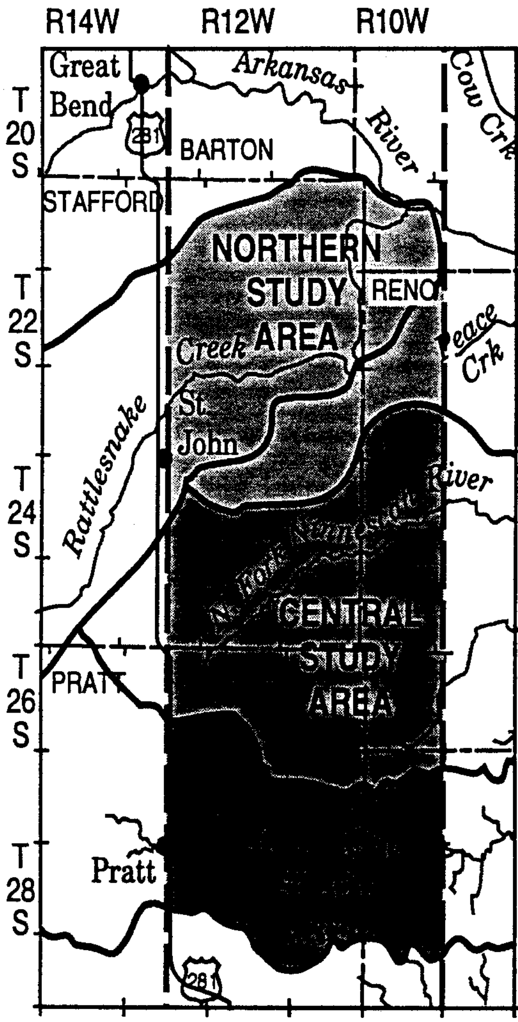
The hydrologic systems in all study areas have a common feature: saltwater discharges from the bedrock into the aquifer, followed by mixing in the aquifer, and discharge to the stream. Because the streams gain a large percentage of their discharge in these regions, they also carry most of the salt load. Figure 28 summarizes the water and salt outflows from the three GMD5 study areas.

Perhaps the most important finding of this study is that the total salt flux can be accurately estimated. This is a direct result of analyzing the combined stream-aquifer system with simultaneous budgets for salt and water. We found that, regardless of the values assumed for other fluxes, the total salt input from the Permian bedrock was rather well constrained (our estimates have relative uncertainties in the order of plus or minus 50%). Total fluxes (expressed as mass of chloride ion) corresponding to average conditions are about 12 Mkg/yr for the Rattlesnake Creek area, 53 Mkg/yr for the North Fork Ninnescah River, and 30 Mkg/yr for the South Fork Ninnescah River area.

There is a physical explanation for the very small variability observed in the model predictions of the saltwater discharge from bedrock. Measurable changes in water levels will affect the discharge from ground water to the streams (and the relative partition between outbound fluxes), but it will not substantially change the boundary conditions that control the saltwater input from bedrock. Also, because this term represents less than 1% of the total volumetric flux in each system, changes in the other larger fluxes do not necessarily affect its magnitude.

We believe these results are particularly important for the analysis of future management alternatives. We can argue as to how the total salt load is distributed between surface water and ground water, but not about its combined magnitude. However, the relative partition of outbound salt fluxes between surface and groundwater can change as a result of changes in resource utilization (both ground and surface water).

This issue is particularly important to the application of this approach to water and salt balance issues in the more narrowly defined EBMI study area. Here, we have demonstrated that there is a significant salt input in the form of groundwater flux, but we have not yet assessed the data to determine whether surface water input (e.g., via Salt Creek) is significant, or the possible magnitude of bedrock discharge within the region. The suggestion is strong that surface water and groundwater management practices, both within the study area and upgradient from it, will be important factors in determination of long-term salinity fluxes and distributions.



Water and Salt Fluxes Out of the GMD5 Areas

PATH	Water (Mm3/yr)	Salt (MkgCl/yr)
GW	10	40
SW	43	86
GW	20	12
SW	137	41
GW	75	8
SW	60	24

Figure 28. Summary of water and salt outflow estimates developed in this study. SFsw is the surface water salt flux, SFgw is the ground water salt flux; all in M kg/yr.

Analyses are only as good as the data on which they are based, and this study is no exception. Application of the combined water and salt budget model requires more data than a hydrologic model that focuses only on volumetric fluxes. Salt concentrations are a crucial piece of information to make realistic predictions of salt fluxes. Unfortunately, water quality data are far less available than discharge measurements. Model predictions can be updated when more data become available, but an increase in the reliability of predictions requires more "density" of information. In this type of stream-aquifer systems, it means that water quality data should be gathered at more frequent intervals (e.g., weekly) at selected points. A small investment in gathering this type of information will reap large benefits in the form of improved model predictions.

Further refinements and applications of this approach can be anticipated as a result of the ongoing EBMI study, and as a result of additional data on bedrock elevation and deep aquifer water quality that is being collected both in that study and as part of the GMD5 water rights application program. These new data sources, plus further investigation of some of the modelling avenues outlined in this preliminary report, should substantially improve our understanding of the regional system.

Overall, the most important general points derived from the study can be summarized as follows:

- Usefulness of simple models

We demonstrated in this study that simple balance models are useful in three ways. First, they provide quantitative answers to questions regarding the overall system behavior, and so facilitate our understanding of complex systems. Second, they can be valuable tools to aid water managers in establishing policies dealing with resource allocation. In particular, these models can easily be set up to provide not only an estimate, but also attach a measure of reliability to it. Thus, managers can make decisions based on acceptable levels of risk for different situations. Finally, these simple models can be a valuable aid in developing more detailed models that are embedded into them. For example, results can be used to constrain parameter values and scope out a range of boundary conditions for more complex situations.

- Dealing with complexity -- embedded models, hierarchies, and information transfer

Different mass balance models can be developed for the same system, depending on the desired level of detail. More detail requires subdividing the study region in a larger number of reservoirs; this in turn requires the evaluation of more fluxes and the estimation of more parameters. This approach is discussed, but not fully demonstrated, in this report.

A given system can be represented with a hierarchy of models, depending on the questions to be addressed. Each model in the hierarchy can address questions at a different scale or resolution, by incorporating more or less detail as necessary. In this report we start with the simplest conceptual model that explains overall behavior.

Because it uses the least number of variables, it is the most robust model to which we can refer to time and again; this is not a pre-model that you discard later on. Although parameters of this model can and do change as more information is incorporated, these parameters change less than those of models at finer scale or those of subregions because of the effects of averaging over both time and space.

- Steady-state versus system dynamics - residence time

Developing management policies requires an understanding of the dynamics of the system, both in terms of fluxes, and of residence (or response) times in each reservoir. In our model the controlling factor is the groundwater residence time, which ranges from 100 yr. in the baseline case to 50 yr. in the development case. While equilibrium models can be calculated on a spreadsheet, the software package STELLA is well adapted for modeling dynamics and transient responses in a time-dependent budget model.

- Uncertainty and risk analysis

Estimation introduces uncertainty because not all variables are accessible to measurement. For the northern study area, we illustrated how to deal with uncertain quantities (e.g., key fluxes) by using simple uncertainty analyses, which can provide reliability bounds on key fluxes and associated predictions.

Uncertainty also affects some of the variables that are measured on a regular basis, such as daily streamflows. This uncertainty is caused by the intrinsic variability, and can only be reduced by averaging. Thus, daily streamflows are highly variable, and their prediction carries a large uncertainty. Even mean annual streamflows can be highly variable (e.g. Rattlesnake Creek), and this affects the estimation of the average of the whole time series. In this report we only considered the uncertainty in the mean values, and its impact on model predictions.

The effects of uncertainty and natural variability on management policy and practice can be assessed by linking sensitivity analysis of the dynamic budget model with economic or regulatory criteria (e.g., the effects of maximum or average salt concentrations).

- Data limitations and possible improvements

Application of the combined water and salt budget model requires more data than a hydrologic model that focuses only on volumetric fluxes. Salt concentrations are a crucial piece of information to make realistic predictions of salt fluxes. Unfortunately, water quality data are far less available than discharge measurements. Model predictions can be updated when more data becomes available, but an increase in the reliability of predictions requires more "density" of information.

The model is a convenient tool for assessing the management benefits of collecting more data, compared with cost. In the type of stream-aquifer system studied here, there is a clear indication that water quality data should be gathered at more frequent intervals (e.g., weekly) at selected points. A small investment in gathering this type of information will reap large benefits in the form of improved model predictions.

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<u>Appendix A. STELLA software</u>

[Adapted in part from the supplier's literature]

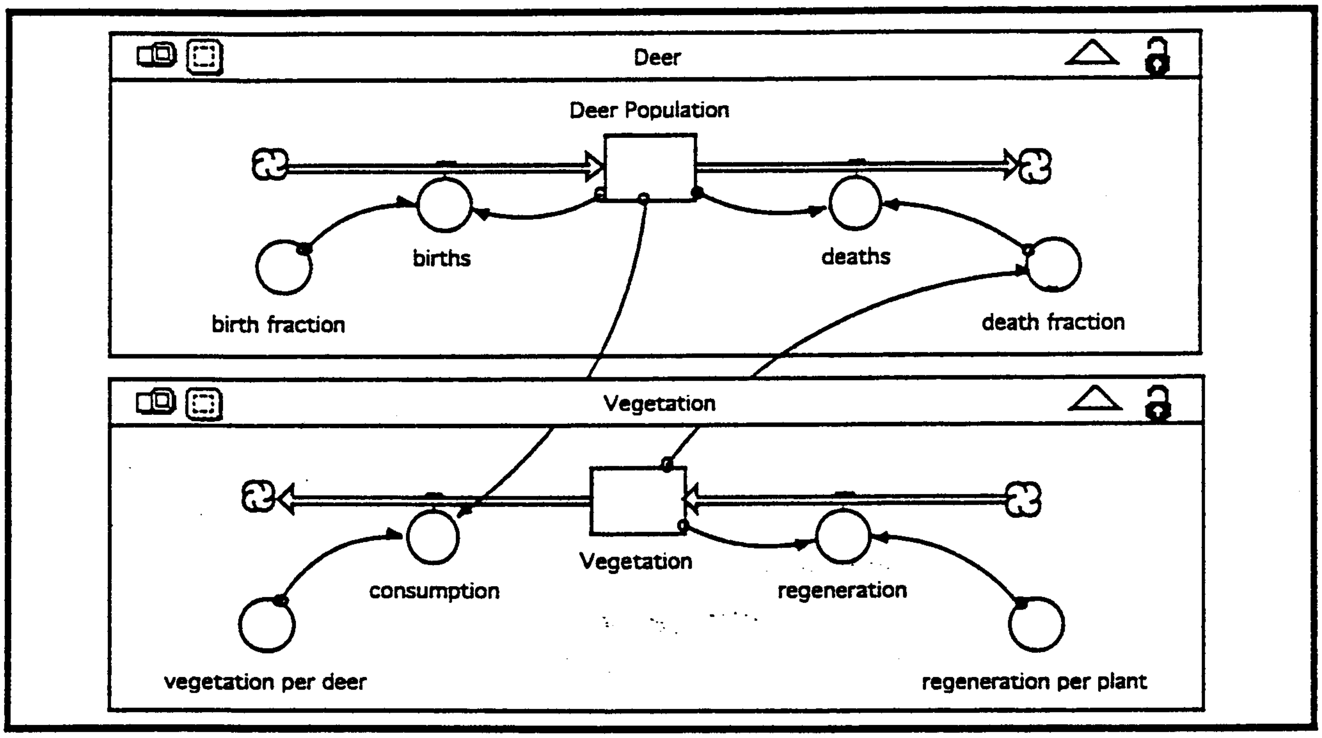
STELLA II is a commercially available software package developed by High Performance Systems (Hanover, New Hampshire). This package is especially designed to model system dynamics in a very general framework. A major advantage is that it is not discipline-specific; applications span many different fields, including biology, environmental science, mathematics, chemistry, among others.

STELLA II has a well-designed graphical user interface that lets the user build models without writing equations. Instead, the user builds a pictorial representation of the system as combinations of Stocks and Flows. Any variable (a stock or flow) can be defined in terms of other variables already defined in the model, thus allowing for both empirical and mechanistic models suited to each situation. The software automatically writes balance equations for each Stock in terms of the Flows in and out of that reservoir. The user can review and edit the balance equations if so inclined, or can leave the details to the software package.

The most powerful feature of STELLA is that once a model has been developed, it is both fast and straightforward to analyze the dynamic behavior of the system under conditions chosen by the user. Furthermore, the complexity of the model is chosen by the user and can be modified at any time. More detail can be added by connecting a sequence of Stocks and Flows, or building a hierarchy of embedded models that incorporate processes at different scales.

This package lends itself naturally to information transfer, since run-time versions can be developed and distributed without need for additional licenses. Thus, a scientist can develop models and distribute the results to the end users as a STELLA model. A simple example is shown in the figure below, which displays a STELLA sample model for the size of a deer population, as a function of births, deaths, and availability of food. The square symbols are Stocks, and a balance equation is written for each one of them. Flows in and out of each reservoir affect the value of the Stock at a given time; Flows are represented by a circle with a spigot, indicating that the user can control its value (e.g.,. births in the figure); circles without spigots (e.g., vegetation per deer) are other variables that affect Flows; arrows are connectors that transfer information to the appropriate Flows or Stocks.

This example could be transformed into a water resources model by substituting water rights (the consumers) for deer population, available water for vegetation, and recharge for regeneration. The model would then permit exploration of the sustainability of the resource as a function of both appropriations and recharge variations.


Deer
Deer Population
births
deaths
birth fraction
death fraction
Vegetation
Vegetation
consumption
regeneration
vegetation per deer
regeneration per plant

Appendix B. Model of Northern study area

Here we illustrate the calculations for only one of the four cases analyzed in this report. This is the case labeled as (n1), which assumes that the complete record [1961-1995] represents dynamic equilibrium under predevelopment conditions. However, the equations below are written in a general form that accomodates all four cases (only selected variables change values from one case to another).

With the information listed in Table 5, we can solve the model by using the four conservation equations. The calculations proceed in the following sequence:

step 1: $Qmix - Qseep = Qevap + Qswo - Precip - Qswi = 30\ Mm^3/yr$

step 2: $Cmix = (Qswo + Qseep)\ Csw\ /\ Qmix = 2.9\ kg/m^3$

step 3: $Qbi = (Qgwo\ Cgw + Qmix\ Cmix + Qpump\ Cpump)\ /\ Cbi = 3.0\ Mm^3/yr$

step 4: $(Qrech + Qgwi) = Qmix + Qgwo + Qpump - Qbi = 37\ Mm^3/yr$

In step 1, we assumed that Qseep=0, so that Qmix=30 Mm^3/yr. In step 3, Cpump was assumed to be zero (this is a good approximation, since Cpump is two orders of magnitude smaller than Cgw). In steps 3 and 4, we assumed that Qpump was zero as well. The values for all other variables are taken from Tables 101 and 102.

The information generated in the above four steps completely define the stream-aquifer system. Additional variables and fluxes can be directly calculated as follows:

$SFbi = Qbi\ Cbi = 126\ Mkg/yr$

$SFgwo = Qgwo\ Cgw = 40\ Mkg/yr$

$SFmix = Qmix\ Cmix = 86\ Mkg/yr$

$SFswo = Qswo\ Csw = 86\ Mkg/yr$

$SFseep = Qseep\ Csw = 0$

$SFgw\_OUT = SFgwo + SFseep = 40\ Mkg/yr$

$Tgw = VOLgw\ /\ (Qgwo + Qmix + Qpump) = 100\ yr$

$Tsw = VOLsw\ /\ (Qswo + Qevap + Qseep) = 0.17\ yr$

In the last two steps we calculated the residence time in each reservoir (Tgw, Tsw) using the total volume of water contained in each one: VOLsw = 10 Mm^3 (estimated volume in ponds and marshes), and VOLgw = 4000 Mm^3 (estimated pore space volume in the GBPA in the study region). Figure 4 contains a diagram with all the fluxes corresponding to the baseline case. The nomenclature is the same used in the main text of the report. Q denotes volume fluxes, SF denotes mass fluxes, and C denotes chloride concentrations.

<u>Appendix C. Model of Southern study area</u>

Here we provide the detail of the calculations carried out with a single box model of the Southern study area, as depicted in Figure 26. With the information listed in Table 11, we can solve the model by using two conservation equations, one for water and one for salt. Since Table 11 contains estimates for all water fluxes, except Qbi, we use the salt balance equation to obtain that term:

$$Qbi = (Qgwo\ Cgwo + Qloss\ Closs - Qgwi\ Cgwi) / Cbi = 0.65\ Mm3/yr$$

The water balance equation is not strictly needed in this case, but we can use it to confirm the magnitude of particular terms, or combination of terms. Here we calculate the difference between incoming and outgoing ground water fluxes:

$$Qgwi - Qgwo = Qloss - Qbi - Qrech = 4.35\ Mm3/yr$$

The information generated in the above four steps completely define the combined surface-groundwater system. Additional variables and fluxes can be directly calculated as follows:

$$SFbi = Qbi\ Cbi = 28\ Mkg/yr$$

$$SFgwo = Qgwo\ Cgwo = 8\ Mkg/yr$$

$$SFgwi = Qgwi\ Cgwi = 4\ Mkg/yr$$

$$SFloss = Qloss\ Csw = 24\ Mkg/yr$$

Figure 27 contains a diagram with all the water and salt fluxes corresponding to this case.

Appendix D: Recent publications on mineral intrusion issues in south-central Kansas

Project reports and publications

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[Note: the KWO-funded data base and research program in place in GMD5 was a key element in obtaining this NSF research grant]

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