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A Groundwater Model for the Central Sands of Wisconsin: Assessing the Environmental and Economic Impacts of Irrigated Agriculture

(Final Report)

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Introduction

Problem Overview

The central sand plain of Wisconsin (Hole and Germain, 1994) is 6,400 km^2 of predominantly sandy outwash soils, formed as the last glaciers retreated 10,000 years ago. The soils of this region have little inherent productivity, and early in the century barely supported agriculture. Research conducted in the 1940's by the (then) College of Agriculture of the (then) University of Wisconsin, however, demonstrated that these plains could in fact be very productive if the low water carrying capacity and fertility of the sandy soil was compensated for by irrigation and additional nitrogen inputs. A widespread irrigated vegetable industry soon grew in central Wisconsin, drawing several major vegetable processing plants to the region and enhancing the economy by providing jobs and demanding local goods and services. Today, the total economic impact of potato production alone in the Central Sands is on the order of $280 million annually.

The economic success in the Central Sands, however, has come at a cost to the environment. State and federal standards for drinking water are currently exceeded in more than 20% of wells in Portage County, and exceedence rates are as high as 70% in some regions where irrigation activities are particularly concentrated. Groundwater nitrate in excess of the drinking water standard forced closure of the Whiting municipal well from 1978 to 1991, until a $670,000 nitrate removal facility became operational. Wells in the city of Plover began exceeding the nitrate standard in 1993, forcing installation of a nitrate removal facility costing over $2 million. Plover now spends $6/lb to remove nitrate from its drinking water that was introduced at a cost of only 22 cents/lb as fertilizer.

So there are apparently conflicting interests in the Central Sands. Rising groundwater nitrate concentrations due to increased agricultural activity conflict with state and federal water quality standards. Compliance with these standards taxes municipal funds both through the costs of remediation efforts and through the erosion of farm and corporate incomes and associated revenues should agricultural regulation be required. Portage County is currently engaged in a groundwater management planning exercise to deal with the effects of agricultural pollution, but finds its efforts stymied by information gaps on the causes, effects, and economics of agriculture and groundwater pollution. This process is further complicated in that it requires building consensus between contentious groups of stakeholders; past attempts to bring these groups together have proven ineffectual, decaying into dispute and finger pointing.

GENERAL OBJECTIVES

Our long-term goal is to inform and facilitate current and future debates over off-site effects of irrigated agriculture in the Central Sands. We believe that wise decisions are more likely if we can find ways to bring to bear on the problem new and emerging concepts of the relationships among scientific knowledge, public policy, how farmers learn and adapt, and the democratization of environmental decision-making (Woodhill and Roling, 1998).

Toward this end we initiated the PIANO—Participatory Integrated Assessment of Nitrate Outcomes—project. The phrase "Nitrate Outcomes" looks to the future of the region's groundwater. How will nitrate levels respond under various land-use scenarios? Integrated Assessment (IA) is an emerging concept in decision-making related to complex environmental issues, discussed in greater detail below. Finally, the paradigm of community-based environmental management depends on broad participation by diverse stakeholders (USEPA, 1997; 1998).

The purpose of PIANO is to develop, between diverse stakeholder groups, a common understanding of the irrigated agricultural *system* at the heart of the conflict over groundwater contamination in the Central Sands. In our interactions with these groups, we have found that each is very well versed in scientific studies and findings supporting its own agenda. Beyond the spheres of these individual agenda, however, there are (perhaps conveniently) severe gaps in understanding that hinder communication and foster mistrust. Through PIANO, we seek to bridge some of these information and communication gaps; to engender a shared insight into how the system functions as a whole, and how changes to one part ripple out and affect the rest of the system. Insight of this type is crucial to well-informed and equitable policy deliberation.

At the heart of PIANO is collaborative development and exploration of an Integrated Assessment Model (IAM) – a computer model describing interactions between the environment, the economy, and human activity. IA modeling is "an interdisciplinary and participatory process of combining, interpreting and communicating knowledge from diverse scientific disciplines to allow a better understanding of complex phenomena" (Rotmans and van Asselt, 1996). Exercises of this type have proven useful for studying policy path impacts and building consensus between stakeholder groups in international environmental debates, as in the case of negotiations over acid rain deposition and emissions leading to global warming (Gough et al., 1998). IA appears well suited to the study of agricultural systems, but is not often used in this area (Bland, 1999).

The PIANO IAM consists of a spatially distributed model of land-use and crop-management practices overlying a numerical model of groundwater nitrate transport and linked with a regional economic analysis including both vegetable production and processing systems. With this model, users will be able to play out "what if?" type scenarios several decades into the future and study potential impacts of alternative policy paths. Possible scenarios that could be realized include the following:

- Turn off X % of pivots within a municipal wellhead capture zone. Does this bring the well into compliance? Over what timescales? What level of subsidy might be required to compensate for the loss in yield?
- Assume all growers adopt the University-recommended Best Management Practices. Does this affect nitrate levels or yields significantly?
- Explore alternative rotation strategies. Currently, approximately 30% of the agricultural land in the Central Sands is in potato (an N-intensive crop) on average over the growing season. What if rotations were changed to Y % potato? Would this be an economically viable strategy? Would it improve groundwater quality?
- What are the water treatment costs (public and private) that arise in various scenarios?

Unanticipated learning may also occur; in exercising the model, users will gain a greater appreciation for their own role in the system, and the constraints that other stakeholders operate under. A grower will be able to see if and when a plume of nitrate emanating from a pivot on his/her farm might reach a municipal or neighbor's well. An activist may gain some appreciation for how unpredictable rainfall can foil even the most well-intentioned fertilizer management program.

In our approach, the model creation – education processes are melded. Past experience with IA modeling has shown that a great deal of time must be spent listening carefully to potential users, incorporating their ideas, and teaching them about the system in order to build wide acceptance of the model (Schneider, 1997). "Black box" models are generally regarded skeptically by stakeholders, or used blindly; neither outcome is acceptable in our view. Collaborative development of models between scientists and stakeholders results in deeper understanding of the system on the part of all parties, and a greater sense of pride and ownership in the final product.

OBJECTIVES SPECIFIC TO THIS GRANT

The focus of work done under this grant was to develop a groundwater flow and nitrate transport submodel for a pilot study area in the Central Sands. This hydrologic submodel will be ultimately be integrated with crop growth and regional economics submodels, being developed in parallel under other funding resources. Progress on model integration and our plan for collaborative development are summarized briefly in the final section of this report.

Groundwater Model Development

STUDY AREA CHARACTERIZATION

The study area designated for the pilot PIANO project lies at the northernmost tip of the central sand plain and encompasses most of Portage County and parts of Adams, Waushara, and Wood Counties (Fig. 1a). The hydrogeology here consists primarily of glacial outwash sand and gravel lying atop bedrock of Precambrian igneous and metamorphic rock (northern part of study area) and Cambrian sandstone (south) (Clayton, 1986). Most of the outwash was deposited by melt-water streams stemming from the Green Bay Lobe during the Wisconsin Glaciation, which formed the Hancock and Almond end moraines running north-south through eastern Portage County. (The less well-defined Arnott moraine, west of the Hancock, likely formed during an earlier glaciation.). This depositional origin resulted in a gradient in mean particle size, with the Hancock moraine providing a rough dividing line between the coarser glacial deposits to east, and finer sandy outwash to the west. The groundwater divide also generally follows the Hancock moraine: from here, groundwater flows east to the Wolf River basin, and west to the Wisconsin River. The geological characteristics of Portage County and environs have been described in greater detail by Holt, et al., (1965), Weeks, et al. (1965), Weeks and Stangland (1971), Karnauskas (1977), Lippelt and Hennings (1981), Rothschild (1982), Bradbury and Rothschild (1985), Allen (1985), Stoertz (1985), Clayton (1986), Brownell (1986), Stoertz, et al. (1991), Bradbury, et al. (1992), and Mechenich and Kraft (1997).

The sand aquifer demarcated in Fig 1a, lying between the moraines and the Wisconsin River, is unconfined and relatively uniform in composition (Clayton, 1986). Because of its high projected water yield capacity (generally >1000 gpm), this region was targeted early on for irrigation (University of Wisconsin, 1964; Lippelt and Hennings, 1981) and today contains most of the irrigated acreage in Portage Co. East of the moraines, the aquifer is patchy and the water table is lower. While some irrigated agriculture is conducted there, these areas are part of the Wolf River drainage system and thus do not contribute nitrate to the aquifer in the study region. West of the Plover River, in northwestern Portage Co., the unconsolidated deposits are much thinner and thus less conducive to intensive irrigation.

Several smaller-scale modeling projects have been carried out within the current PIANO model domain (Fig. 2). These include a study of the Buena Vista Basin (Bradbury et al., 1992) and of the capture zone associated with municipal wells in the Stevens Point – Whiting – Plover area (Mechenich and Kraft, 1997). Results from these smaller-scale studies have been useful in quality-checking the larger model. Including the SWP wellhead capture zones within the PIANO domain will prove important from an economic modeling standpoint.

The PIANO model, as presently defined, is nested within a larger domain targeted for a modeling project headed by collaborator G. Kraft, focusing on source water protection for the Mississippi River (Fig 1b). Data collected for the project described here are being recycled and appended for the expanded domain, so they will serve a dual purpose. When the source water protection model is completed, the PIANO IAM domain will be expanded to the area delineated in Fig. 1b.

DATA COLLECTION

Water table database

Groundwater target elevations for model calibration were obtained from well geologic logs and construction reports collected from the Wisconsin Department of Natural Resources and the Wisconsin Geological and Natural History Survey, and from additional published reports (Weeks et al., 1965; Weeks and Stangland, 1971; Hickock and Associates, 1965; Hickock and Associates, 1981; Donohue and Associates, 1989; RUST Environment and Infrastructure, 1993). This information has been assembled into a database using dBase IV software (Borland International Inc., 1988; see table structure in Mechenich and Kraft, 1997). The spatial distribution of water table observations contained in the database is shown in Fig. 3.

While precise well locations are sometimes noted in construction logs, they are more often specified only to the nearest quarter section. To assign a specific latitude/longitude to each well, the quarter section was first identified on a USGS 7.5min topographic quad map. If a residence was indicated in the quarter section, the well was assigned the coordinates of the residence. Otherwise, coordinates were assigned by best judgement, for example by avoiding most topographically undulating part of the quarter section. Errors were assigned by assessing the average variation in elevation within the quarter section; therefore, targets in the moraines were assigned higher errors than targets in the sand plain. Well log observations that appeared to be in error, in comparison with neighboring observations or known local topographic elevations, were flagged in the database. Water table elevation was estimated by subtracting depth-to-water from the surface elevation, extracted from the quad map.

For calibration, one would ideally like to obtain synoptic target measurements spanning the entire model domain. This is rarely possible, especially with a domain of this size. In this case, the measurements span several decades (~1945-1990) and reflect a wide range in climatic and human-induced forcings. To effect some smoothing of temporal fluctuations and spatial well location errors, the point observations were averaged within 1km by 1km grid cells and contoured using Surfer (Golden Software Inc., 1990). The resulting plot, in Fig. 4, generally resembles an earlier water table map generated for Portage County by Lippelt and Henning (1981) based on sparser observational data.

Regional bedrock database

Several bedrock-mapping studies have been conducted in the Portage County area, with contour resolution ranging from 10-100 ft (Holt, 1965; Weeks et al., 1965; Weeks and Stangland, 1971; Hickock and Associates, 1981; Osborne, 1988; Brown et al., 1992). Additional bedrock data are available from well construction logs, although wells are typically finished short of the bedrock surface. In general, the bedrock surface slopes downward from north to south across the domain. Bedrock outcroppings, primarily sandstone bluffs in southern Portage Co., were mapped by Weeks, et al. (1965). The available data suggest a number of significant pre-glacial bedrock valleys lie buried beneath the sand outwash.

Existing depth-to-bedrock measurements made within the PIANO model domain have been collected into a database implemented in both dBASE and Excel format. The spatial distribution of measurements contained in the database is shown in Fig. 5. The database contains 1494 points, including 351 points representing 421 wells reporting a bedrock contact, 144 well bottom elevations that appear to be a good extension of the bedrock well data, 291 points added to clarify trends (i.e., extension of contour lines near the edges where data is sparse, and clarification of bedrock valleys based on the well data), and 708 points used to define sharp sandstone mounds based on the report of Weeks, et al. (1965) and surface expressions on topographic maps.

These point data have been interpolated to the model grid using a Natural Neighbor algorithm. Figure 6 shows the interpolated bedrock surface. Buried bedrock valleys, suggested by the well log data, are evidenced along the Plover River, and in the southern part of the domain.

Recharge estimates

Estimates of annual recharge rates in the Portage County region range between 8 and 13 inches (Holt, 1965; Weeks and Stangland, 1971; Stoertz, 1985; Bradbury et al., 1992); data from Weeks and Stangland (1971) indicate that 12 inches/year may be a reasonable basin-wide average. This study and others suggest that recharge rates vary spatially, depending in part on land-use patterns. Irrigation, for example, will reduce local recharge by increasing the potential for evapotranspiration. Based on a simple water balance model, Weeks and Stangland (1971) estimate recharge reductions of 5.4, 5.9 and 3.4 inches respectively for irrigated corn, potato and beans, compared with similar estimates for grassland.

Because irrigation and associated contaminant leaching is an integral component of the PIANO analysis, we have performed supporting analyses of the water budget associated with irrigated potato crops. Average annual recharge was estimated using a daily soil water balance model forced by regional climate data collected between 1970 and 1994. The model used daily measurements precipitation from the Cooperative Observer Network station at Hancock, WI, and estimates of daily ET extracted from a dataset generated by the Midwest Climate Center using weather data acquired at the Madison airport. (The ET estimates were increased by 15% to better match the shorter-term record available from the UW Automated Weather Observation Network station at the Hancock Agricultural Research Station.) Development of the potato canopy was modeled using a temperature-based empiricism. We assumed the soil holds 0.7 inches of water that is readily available for crop uptake; this is the allowable depletion typical of a Plainfield loamy sand (Curwen and Massie,). During full crop cover, daily ET was subtracted from this reservoir, while rain in excess of the available water-holding capacity drained through the soil. When canopy cover was incomplete, ET was taken as proportional to the cover fraction. Irrigation events were simulated by refilling the reservoir whenever the available soil water fell to zero. Evaporation directly from soil was considered while the crop cover was incomplete: following each soil wetting, a maximum of 3 mm of water was evaporated directly from the soil surface (Ritchie, 1973).

An excerpt from the model output is shown is in Fig. 7. Recharge is estimated as the difference between annual precipitation and total (soil+crop) ET. On average over the 24-year climate record, the recharge rate generated by the model was 6 inches per year. Assuming a basin-wide average of 12 inches per year, this recharge reduction induced by irrigation agrees well with the estimates of Weeks and Stangland (1971).

GROUNDWATER FLOW MODEL CONSTRUCTION

Model Purpose

In designing and implementing any physical model, it is important to keep in mind the intended purpose so that appropriate accuracy can be obtained in the regions of importance.

In the context of PIANO, the purpose of the groundwater model is to estimate general timescales and pathways for the transport of nitrate introduced into the aquifer under irrigated fields. The user will explore 20-year simulations of system response to various temporal and spatial nitrate-loading patterns, driven by scenario land management choices.

This model is has been designed to be as simple as possible, but no simpler. It is intended for evaluation of gross cause/effect relationships, and for regional, rather than finescale, analyses, although subregions of model domain will be extracted and refined for more detailed studies in the future (see below). It will not be used to trace contaminant paths from isolated spills or leaks, but rather to study plume evolution from widespread areal sources, tracking chemicals that are used in large quantities years after year.

Conceptual model

Our conceptual model of the hydrogeology in Portage County stipulates that only flow in the Pleistocene aquifer is significant. The aquifer is unconfined, variably thick, and its base is defined by contact with bedrock or hillslope deposits. Vertical groundwater flow is insignificant at the scale of this analysis, and the aquifer can be adequately modeled as a vertically homogeneous hydrostratigraphic unit. Areal heterogeneity, however, must be considered (Mechenich and Kraft, 1997). We assume that groundwater recharge rates vary with landuse, and primarily as a function of irrigated vs. unirrigated management.

The domain for the current study is bounded on the west by the Wisconsin and Plover Rivers, and on the east, by the Tomorrow River. In the southeast, the boundary follows a chain of lakes along the Almond moraine, and then connects with a drainage ditch system running along the southern end of the domain and emptying into Fourteen Mile Creek (see Fig. 2). All boundaries are modeled as constant head boundaries. We believe that it is reasonable to expect that the river stages will remain relatively stable within the lifetime of the simulation (20 years). Water elevations within the ditch system will be somewhat more volatile (see e.g., Faustini, 1985; Zheng et al., 1988a; Zheng et al., 1988b); therefore, we will limit of our analyses to well north of the southern model boundary.

Numerical model

The conceptual model described above has been implemented numerically using the USGS MODFLOW code (McDonald and Harbaugh, 1988), embedded within the Groundwater Modeling System (GMS) user interface (Environmental Modeling Research Laboratory, 1999). GMS provides tools for geostatistical analysis, model construction and calibration, and data visualization. The numerical model, displayed schematically in Fig. 8, describes a single layer, unconfined aquifer in steady state. All coordinates have been converted to the WTM 83/91 georeferencing system, in concordance with WDNR standards.

Grid:
The model domain was discretized into 100x100 grid cells of roughly 0.3x0.3 km in area. In comparison, a typical center pivot covers approximately a quarter section, or 0.8x0.8 km. Nitrate loading in the contaminant transport-modeling phase will be implemented as areal sources coincident with pivots placed in the landscape by the user during scenario construction.

Boundaries:
All outer boundaries to the model domain have been modeled as constant head boundaries. Surface water features digitized from USGS 7.5 min topographic maps by the WI DNR were imported into GMS and used to delineate these boundaries. Surface water elevations were extracted from USGS 7.5 min topographic quad wherever plotted contours intersected a boundary water body. These elevations were assigned to corresponding model nodes – GMS then performs a linear interpolation between prescribed node elevations to complete the full boundary.

Hydraulic conductivity:
Measurements of aquifer hydraulic conductivity in Portage County range between orders of magnitude 10^{-5} to 10^{-3} m/s, with higher conductivities generally associated with the sand aquifer, and lower conductivities in the coarser moraine deposits (see Mechenich and Kraft, 1997, for a summary of observations). Mechenich and Kraft (1997) created a regional scale mapping of hydraulic conductivity for the SWP region based on specific capacity pump test data reported in well construction logs, following the method of Bradbury and Rothschild (1985). They found average conductivities of $\sim 10 \times 10^{-4}$ m/s in the flat outwash plain, and $2\text{-}5 \times 10^{-4}$ m/s in the moraine areas in the eastern part of their study area.

Based on these studies, we defined two general conductivity zones for the PIANO domain, with a zone division following the Hancock moraine (Fig. 9). For initial runs, the horizontal hydraulic conductivity was set to 10^{-3} m/s in the outwash plain zone, and 10^{-4} m/s in the moraine zone.

There is little information regarding vertical hydraulic conductivities in the central sand plain. Weeks (1969) reported a range in vertical to horizontal conductivity ratio of 1:2 to 1:20 for the Buena Vista Basin. Measurements of vertical conductivity made in the Plover River bed deposits range from 0.3 to 2.0×10^{-4} m/s with an average of 0.85×10^{-4} m/s (Osborne and Shaw, 1988), while measurements in drainage Ditch 4 vary from 0.08 to 0.85×10^{-4} m/s (Faustini, 1985). Here we assume that conductivity of river, stream and ditchbed sediments is an order of magnitude lower that that of the sand aquifer (10^{-4} m/s).

Sources/sinks:
Groundwater sources and sinks considered in the numerical model include recharge from rainfall and irrigation and discharge to lakes, rivers, streams and ditches. The surface water source/sink distribution was delineated using the WI DNR digitized "streams" GIS coverage. For model calibration, we neglect discharge to municipal, industrial or domestic wells, which will perturb local aquifer and streamflow but should not affect regional flow patterns. Sensitivity tests by Mechenich and Kraft (1997) showed that inclusion of wellfields in the SWP region had little effect on modeled heads near calibration targets.

Rivers, perennial streams, and lakes were simulated as variable sources/sinks using the MODFLOW river package. The stages/elevations of these sources were estimated from USGS 7.5 min topographic maps. We assumed rivers and perennial streams were 2 m wide, the depth of the bed material was 1 m, and the depth from stage to bed bottom was 2 m. As noted above, bed deposits were assigned a vertical conductivity of 10^{-4} m/s.

Ephemeral streams and drainage ditches interior to boundary were modeled with the MODFLOW drain package. Bed dimensions were set to 2 m wide by 1 m deep. The drain package requires specification of the elevation of the drain bottom. For streams, this was assumed to be 1 m below the stream stage as estimated from a USGS 7.5 min topographic map. Ditchbed elevations were assumed to be 2 m below the top of the ditch.

Recharge distribution:
During calibration, we experimented with two recharge assignment strategies. First, we used a uniform recharge rate of 12 inches/year across the entire domain. In a second test, we defined two recharge zone categories tied to irrigated and unirrigated landuse. General zones were delineated based on a landuse map generated in 1992 by the Portage Co. Planning and Zoning Dept, and on a 1992 WISCLAND landcover classification created jointly between the University of Wisconsin and the WI DNR (see Fig. 10). Polygons associated with regions of intense irrigation were assigned an annual recharge rate of 6 inches/year, with 12 inches/year assigned to all other parts of the domain.

Solver package:
The Preconditioned Conjugate-Gradient 2 solver package (Hill, 1990) in MODFLOW was used to iteratively compute a two-dimensional hydraulic head distribution solution consistent with the prescribed model boundaries and source/sink features described above, with specified error criteria of 10^{-4} m for maximum change in hydraulic head and 10^{-3} m^3 for maximum iteration residual.

<u>*Model calibration*</u>
Water table targets:
Steady state water table levels predicted by model were compared with the cell-averaged observation data set (Fig 4) to assess the suitability of model input assignments, particularly for inputs with large uncertainties such as hydraulic conductivity and recharge. A comparison by eye with the contoured observations revealed large residuals along boundary the between the outwash plain and moraine conductivity zones, clearly an artifact of the strong discontinuity imposed along that surface. Increasing the conductivity in the moraine zone from 10^{-4} to $5x10^{-3}$ m/s reduced these residuals to reasonable levels. A few odd groundwater mounds were detected in the model head contours. Closer examination revealed these to be gravel pits or glacial kettle lakes – these were removed from the model source/sink distribution.

Model contours representing the final calibration using uniform recharge are shown in Fig. 11, overlaid on the observation contours, while Figs. 12a-b show point-by-point comparisons of modeled and observed heads and model residuals. The largest residuals occur in areas where the gradient in the water table is large, primarily on the edges of the northern neck of the study domain. Model errors in these areas are likely exacerbated by spatial uncertainties in the specification of well locations, where small errors in location translate into large apparent errors in model agreement. The model appears to underestimate the north-south gradient along the moraines; however, the observational errors are large here due to the highly undulating terrain. The root mean square error (RMSE) between modeled and measured heads is 1.54 m, or about 2% of the full range in head variation across the domain. In comparison, the average error assigned to the target head measurements was 1m (see Fig. 12b).

Modeled heads generated assuming non-uniform recharge are displayed in Fig. 13. Here, recharge in irrigated zones demarcated in Fig. 10 was reduced from 12 inches/year to 6 inches/year. This degrades model agreement slightly, increasing the RMSE to 1.6 m; see particularly the recharge region just south of Plover, where heads are now underestimated. Apparently, a blanket 6-inch reduction in recharge due to irrigation is too drastic over the spatial scales defined here. A thorough assessment of landuse within these targeted recharge zones would reveal that less than 50% of the total acreage is actually under irrigation at any given time; thus, recharge associated with irrigated and unirrigated landuse should be weighted appropriately.

Stream flow targets:
Historical records starting in the 1960's are available for two USGS gauging stations operating on the Little Plover River: near Arnott WI (Station #5400600) and near Hoover Road (Station #5400650). The historical average discharge at Arnott (1959-1976) was 4.0 cfs with a standard deviation of 2.7 cfs. At Hoover Road, the average discharge between 1960-1987 was 10.6 cfs with a standard deviation of 4.6 cfs. Holt (1965) attributes 90% of the flow in the Little Plover to baseflow, or 3.6 ± 2.4 cfs and 9.5 ± 4.1 cfs for the Arnott and Hoover Road stations, respectively. The model predicts 3.2 and 8.4 cfs integrated baseflows at these points, respectively. Modeled flows are somewhat higher (3.5 and 8.9 cfs, respectively) if recharge in the irrigated zone north of the Little Plover is increased to 12", consistent with the assumed recharge for unirrigated areas.

In September of 1997, Browne et al. (2000) collected streamflow measurements at 200 ft intervals in the stretch of the Little Plover River between the Hoover Road and Arnott gauging stations. These measurements are compared with modeled cumulative baseflow in Fig 14 – the modeled gradient follows the measurements well.

Stream flow calibration in the central part of the domain is rather difficult due to the extensive ditching system that has been developed for agricultural drainage – point observations reflect an integrated response to contributions over the entire up-gradient ditch network. Further validation of stream flows predicted by the numerical model in this part of the domain will be ongoing. Flow measurements made at 25 locations along the ditch system in central and southern Portage County during 1998 and 1999 are currently being cataloged and quality controlled (B. Browne, personal communication). This database should be accessible by late August, and will be compared with model predictions at that time.

Nitrate Transport Model Construction

N-Loading model

For this study, we are concentrating on N-loading from irrigated agricultural fields; however, additional sources, such as septic system, feedlots, lawn fertilizers, etc. could be added in the future, distributed spatially on the basis of land-use. The N-loading model we use here is described further below. Briefly, it provides N-leaching and crop uptake estimates which respond dynamically to precipitation patterns and user-specified fertilizer application schedules. In the integrated model, crop uptake is mapped to yield and thence to income, but for the purposes of the groundwater model component we are interested only in the time-dependent injection of N into the saturated zone.

Technically there is a time lag on the order of 40-120 days between the exiting of nitrate from the root zone (during a leaching event) and entrance into the saturated zone (S. Kung, personal communication). Over the life of a 20-year simulation, and given typical groundwater velocities of 100 m/year, this lag is insignificant and will not considered here.

In the IAM, users will start with a default landuse map, which they can modify at will. A time-series of loading values will be generated with the agronomic model for every model cell occupied by a center pivot. Currently, the model is specifically tuned for potato, but modifications to simulate corn, beans, soybean, and alfalfa are in the works (see below).

Transport model

MT3D, a widely used, three-dimensional, transport code (Zheng and Wang, 1998), will be used to simulate the transport of nitrate in our IAM. The head solution from MODFLOW will be input to MT3D and used to generate a groundwater velocity distribution. This distribution, together with groundwater recharge rates and nitrate loading data provided by the agronomic model, and estimates of dispersivity and porosity, will be used to simulate nitrate transport subject to advection and dispersion. Denitrification rates are expected to be low in the sandy soils of the study area (Kraft et al., 1995), so nitrate will be modeled as a chemically conservative contaminant. Model output will consist of a time-series of nitrate concentrations at each grid cell.

Some simple test loading scenarios have been simulated with this transport model. Historical measurements of NO_3-N concentrations in the well in the Village of Whiting show an overall increase from 4 mg/l in 1965 to around 18 mg/l in 1995. Similarly, NO_3-N concentrations in the Little Plover River near the Hoover Road gauging station increased from approximately 2 mg/l to 8 mg/l between 1967 and 1994 (see Mechenich and Kraft, 1997). (Kraft et al., 1999) identify non-point source loading from agricultural fertilizers as the main cause for elevated groundwater nitrate concentrations in this part of the central sand plain.

We ran a 30-year transport simulation assuming a constant NO_3-N loading rate of 100 lbs/acre in the recharge zones associated with current intensive irrigation activity (Fig. 10). This loading rate represents an average of typical loadings for the principal crops grown in the sands, weighted by fractional acreage determined from a cropping census conducted in the SWP region

(Mechenich and Kraft, 1997). Initial N concentration was set to 4 mg/l everywhere in the model domain and aquifer porosity was set to 0.32 (Mechenich and Kraft, 1997). After approximately 20 years, the modeled nitrate concentrations in the grid cells closest to the Whiting and Hoover Rd sampling sites came into equilibrium at values of approximately 15 and 8 mg/l, respectively, close to the current measurement levels (see Fig. 15). Clearly these simulations need to be taken with a large grain of salt; the distribution of irrigated fields has not defined with precision, nor have changes in land-use or N-sources other than irrigated agriculture been taken into account. Still, it is encouraging that the model generates reasonable asymptotic N-concentration estimates. As more realistic land-use scenarios are explored, predictions from the transport model will be further scrutinized for reasonability.

Pending Applications of Model and Supporting Databases

The numerical groundwater model and supporting databases developed under this grant will also be utilized in projects beyond of the scope of PIANO.

As mentioned above, the model domain and databases are currently being expanded to encompass a larger portion of the WI central sand plain (Fig. 1b) under a proposal focused on source water protection and associated groundwater resource management. This work is being conducted at the Central Wisconsin Groundwater Center under direction of co-PI G. Kraft. The project timeline predicts model completion by June 2001. At this point, we should have accumulated some experience in working with stakeholders in running simulations within the smaller subdomain in Fig. 1a, and will be ready to absorb this larger modeling region into PIANO. This larger domain will include important agricultural regions in Waushara County, home to many of the grower stakeholders that we will be working with.

Plans are also in place to take the PIANO model and optimize the calibration for the Little Plover region (Kraft and Browne, personal communication). Then, using particle tracking, the model will be used to determine what parts of the watershed feed what stretches of stream. This will help interpret the chemical signature detected in groundwater inflow along different reaches of the stream.

Collaborative Development of Integrated Model

Much of the groundwork for the integrated model has already been established under other funding resources. The economic and agronomic sub-components of the IAM are nearing a first stage phase of completion. We have also established contact with several stakeholder groups in the Central Sands and have held a pilot series of small-group meetings.

Current status of agronomic and economic model components

The agronomic model must predict the relationships among N fertilization, N leaching and yield for the crops grown in the region (see Fig 16). We have developed a potato and soil nitrogen model specifically tailored for the Central Sands; potato is, by far, the most economically important crop in this region. The model was developed by Mr. Seth Wilner and Dr. Bland, building on Wilner's M.Sc. thesis research (Wilner, 1998) and several years of field trials conducted at the Hancock Agricultural Experiment Station (in the Central Sands) and on irrigated sands in Minnesota. It successfully predicts when heavy rains cause enough leaching of fertilizer nitrate to reduce yield. A Ph.D. student is working on further validation in the Central Sands and expansion to other crops. We are also running the ALMANAC and DSSAT models to evaluate its ability to predict N uptake and leaching relations for soybean, alfalfa, sweet corn, and field corn.

This research was funded by the WI Fertilizer Research Council, the WI Potato and Vegetable Growers Association, and the UW System. First approximations for the yield-leaching-fertilizer relationships are available for the needed crops.

Socioeconomic Submodel

The economic modeling effort compares the benefits of improved water, or the avoided remediation costs of contaminated groundwater, with the costs of changing the farmer's production patterns: crop rotation and nitrogen fertilizer use. Farmers' crop and fertilizer use choices provide inputs to the agronomic and hydrologic model components; their outcomes can then be compared to the profits derived from the farming operations (see Fig. 17). An expanded version of the profit maximization side of the model can include linkages beyond the farm level to processors, other input businesses, and government.

The work done to date on this model component was supported by USDA-Hatch funds administered by the College of Agricultural and Life Sciences at UW-Madison.

MODEL INTEGRATION PLAN

To create the IAM, which will be the focus of the proposed stakeholder interactions, the agronomic, hydrologic and economic submodels must be joined within an integrated framework. The IAM will be constructed in a modular format, so individual components can undergo ongoing refinement as the project progresses.

To make the simulation results as accessible and comprehensible as we can, we will publish them as interactive visualizations on the World-Wide Web. Stakeholders will be able to set up regulation and land management scenarios via controls in a Web applet, execute the model, then visualize economic and contaminant futures out to 20 or 30 years from their browser. Full visualization of model input/output will include 1D (time-evolution at a point), 2D (GIS, spatial distributions) and 3D (contaminant plume evolution) representations. To provide these visual data exploration tools through the Web, we will use a scientific visualization package called VisAD (Hibbard, 1998; 1999), which has been developed at the University of Wisconsin and is used widely in meteorological applications. The latest version of VisAD is implemented in Java and has been tailored specifically for web-based applications (Hibbard et al., 1997).

COLLABORATIVE IMPLEMENTATION

We have experimented with the idea of collaborative model development in the context of PIANO with a series of small group meetings with two stakeholder communities during the winter of 2000. Two groups of five participants each were recruited from the potato grower community and from the Portage County Groundwater Citizens Advisory Committee. Previous discussions with members of both communities revealed distrust with the other and recollections of previous acrimonious meetings. Thus we decided that a comfortable, collaborative environment required segregation, at least at early stages.

Our objective with this series of meetings was to develop rapport with a few members of each community and to see what collaborative model building might mean. We chose to focus on the agronomic model since, at the time, it was the most advanced. At the first meeting we introduced the idea of an "agricultural system" and found this was a new way of thinking for many of the participants. Gaps in systems understanding were often substituted with unsubstantiated assumptions about how things worked and why other stakeholders do what they do. In subsequent meetings, we worked together to iteratively construct a picture of nitrogen and water flows in an irrigated field that was acceptable to the group as a whole. A spreadsheet version of the model was presented at the last meeting.

Overall, the response to these sessions was quite positive. We observed new vocabulary integrating into the group discussions, and were impressed with the insights and connections that the group members were developing as they struggled to understand the complexities of the N-cycling system. This experience has underscored for us the value of self-discovery and active participation as an effective learning technique.

However, assessing these pilot sessions in hindsight, we are led to revise our full-participation model development paradigm. We now believe that a fully-integrated and operational prototype IAM must be in place before formal collaboration commences, to help potential users envision how such a tool might be of use to them. This initial version must be presented carefully, emphasizing that it is incomplete until users peer deeply inside it and we explore and modify it together.

Our revised stakeholder interaction plan will be manifested through three types of meetings. *Focus groups* will be utilized to gather reactions from specific stakeholder communities about specific portions of the model. *Study groups* will be organized from stakeholder communities to allow interested members to spend a series of meetings exploring the integrated model with us. Finally, a *Summit Meeting* (or meetings) of all interested stakeholders will be held in the final months of the project. In a daylong session we will present the model and scenario results. Participants will include at least some of the people who attended focus and study groups, as well as others new to PIANO. This phase may coincide with debate by the County Board over adoption of the revised Portage County Groundwater Management Plan, in which case the summit meetings would be a valuable learning opportunity for Board members.

We continue to seek funds from the USDA, WI state agencies and CALS to support development of the PIANO IAM.

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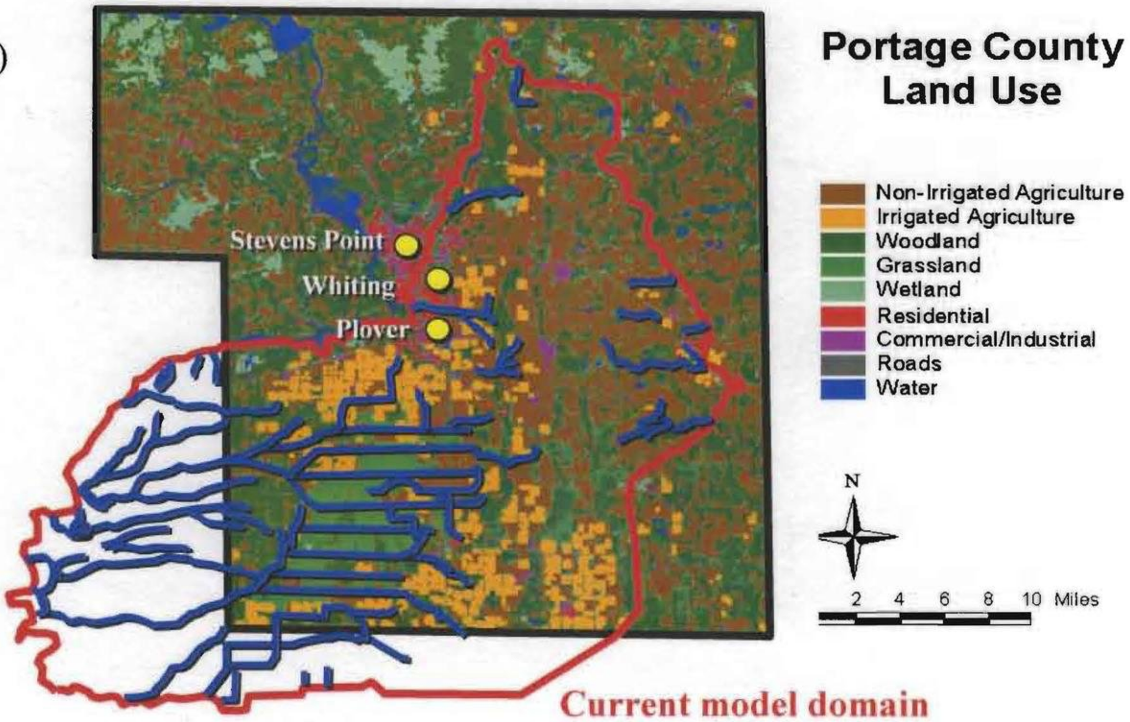
a)



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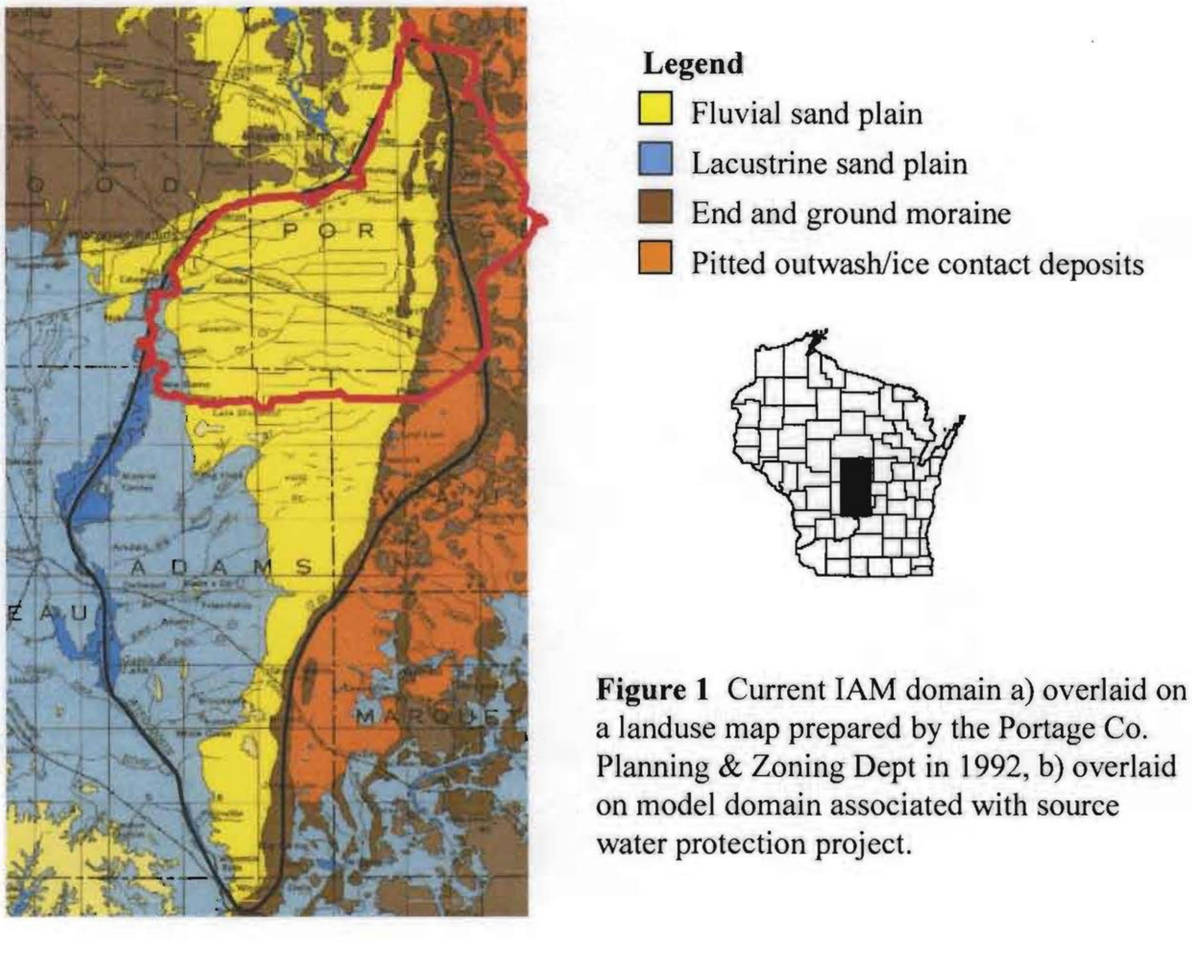
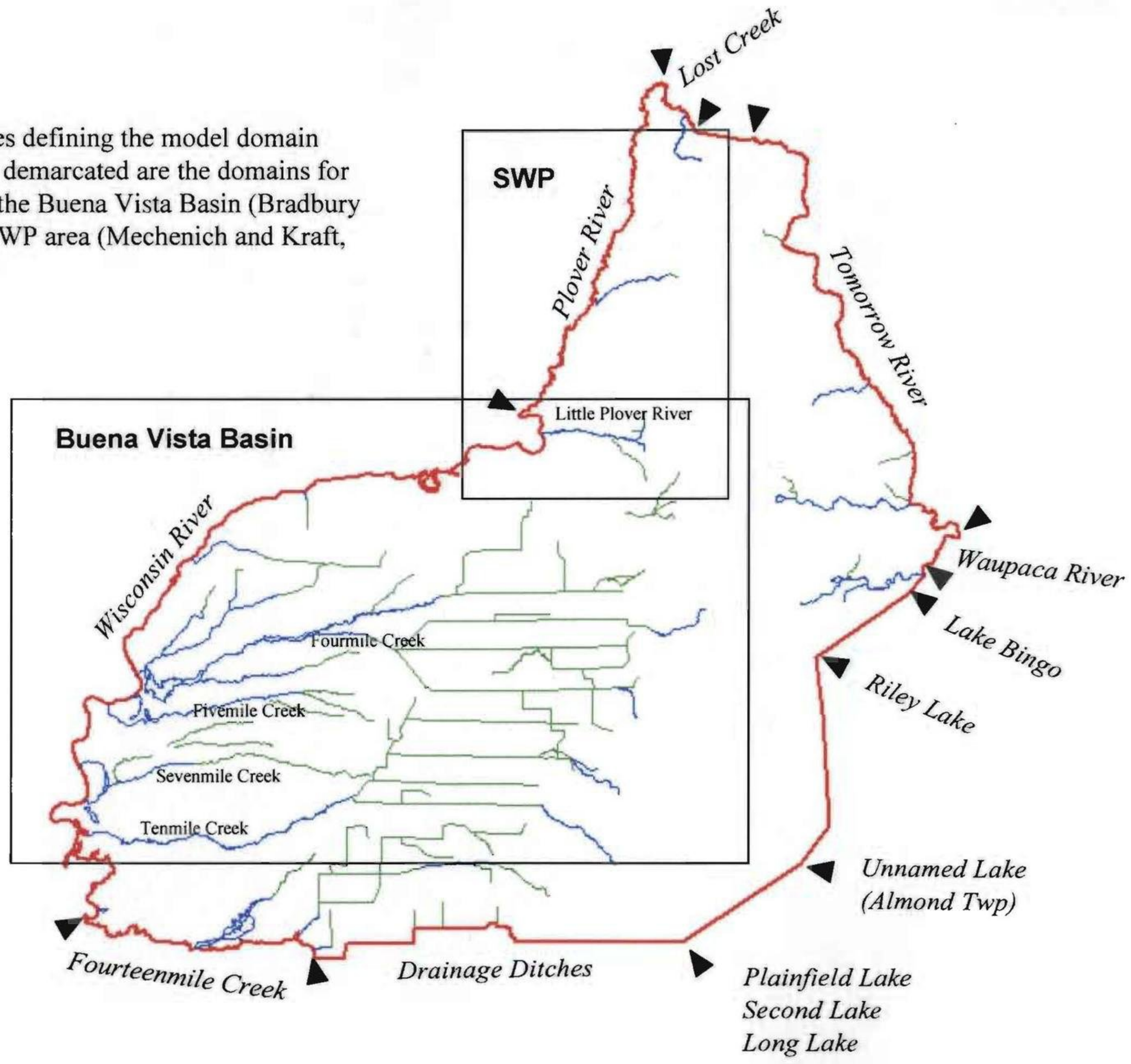


Figure 1 Current IAM domain a) overlaid on a landuse map prepared by the Portage Co. Planning & Zoning Dept in 1992, b) overlaid on model domain associated with source water protection project.

Figure 2 Features defining the model domain boundaries. Also demarcated are the domains for earlier models of the Buena Vista Basin (Bradbury et al, 1992) and SWP area (Mechenich and Kraft, 1997).



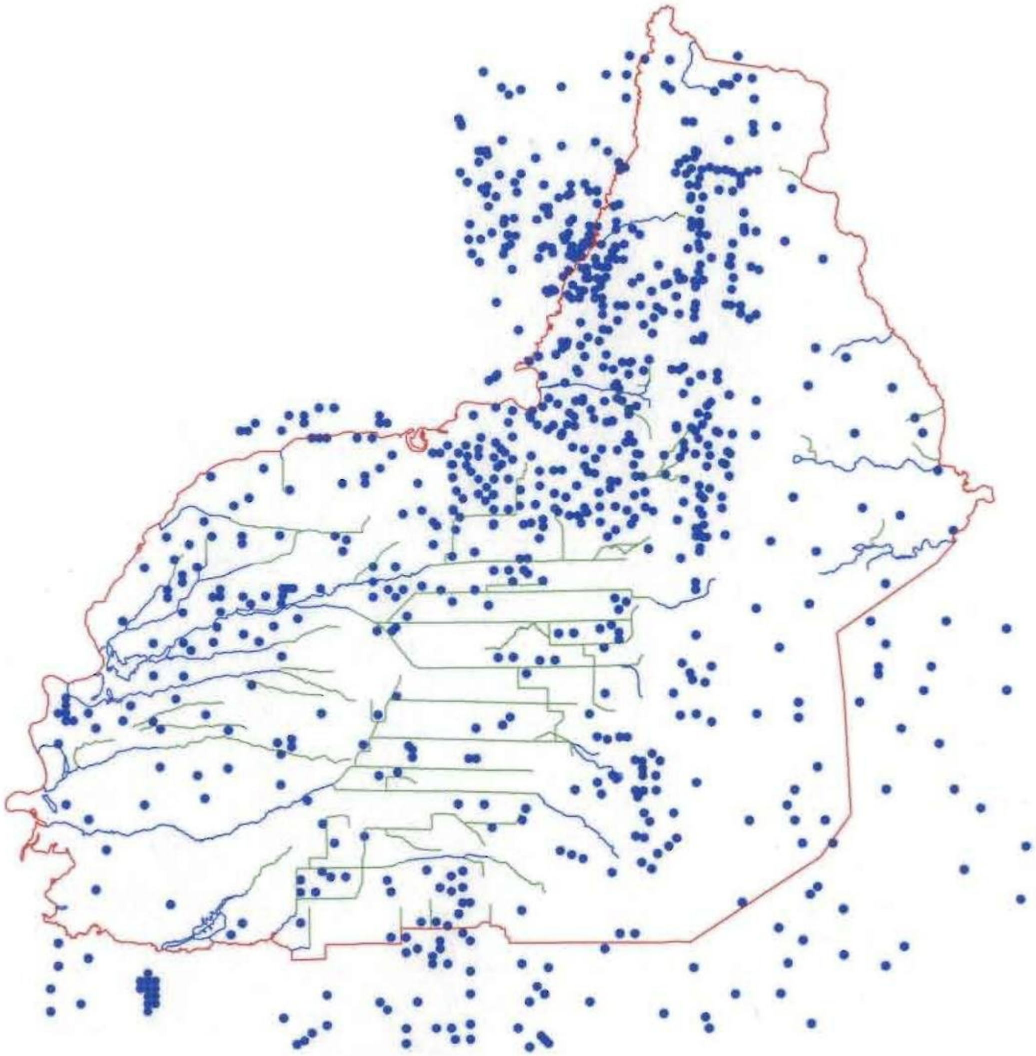


Figure 3 Locations of water table data points

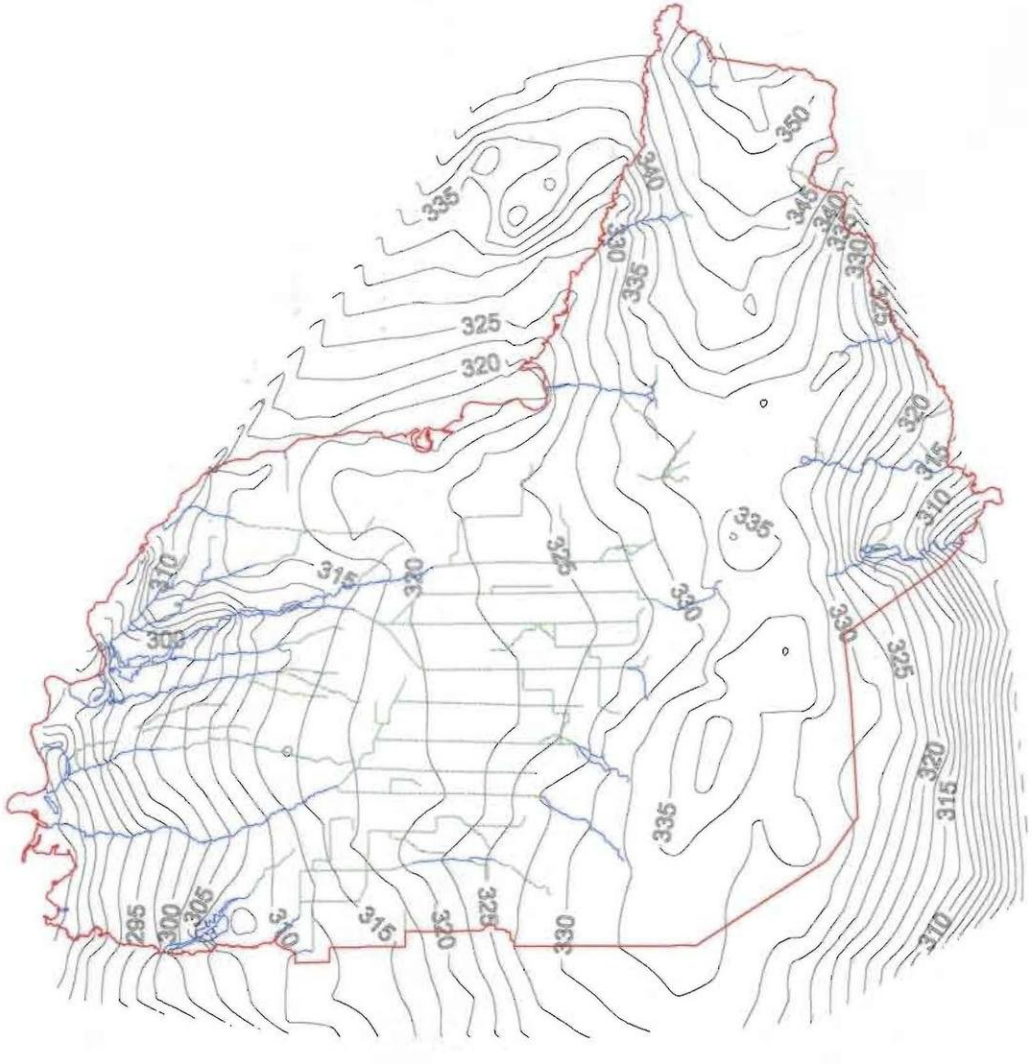


Figure 4 Contour plot of cell-averaged water table data set (in meters)

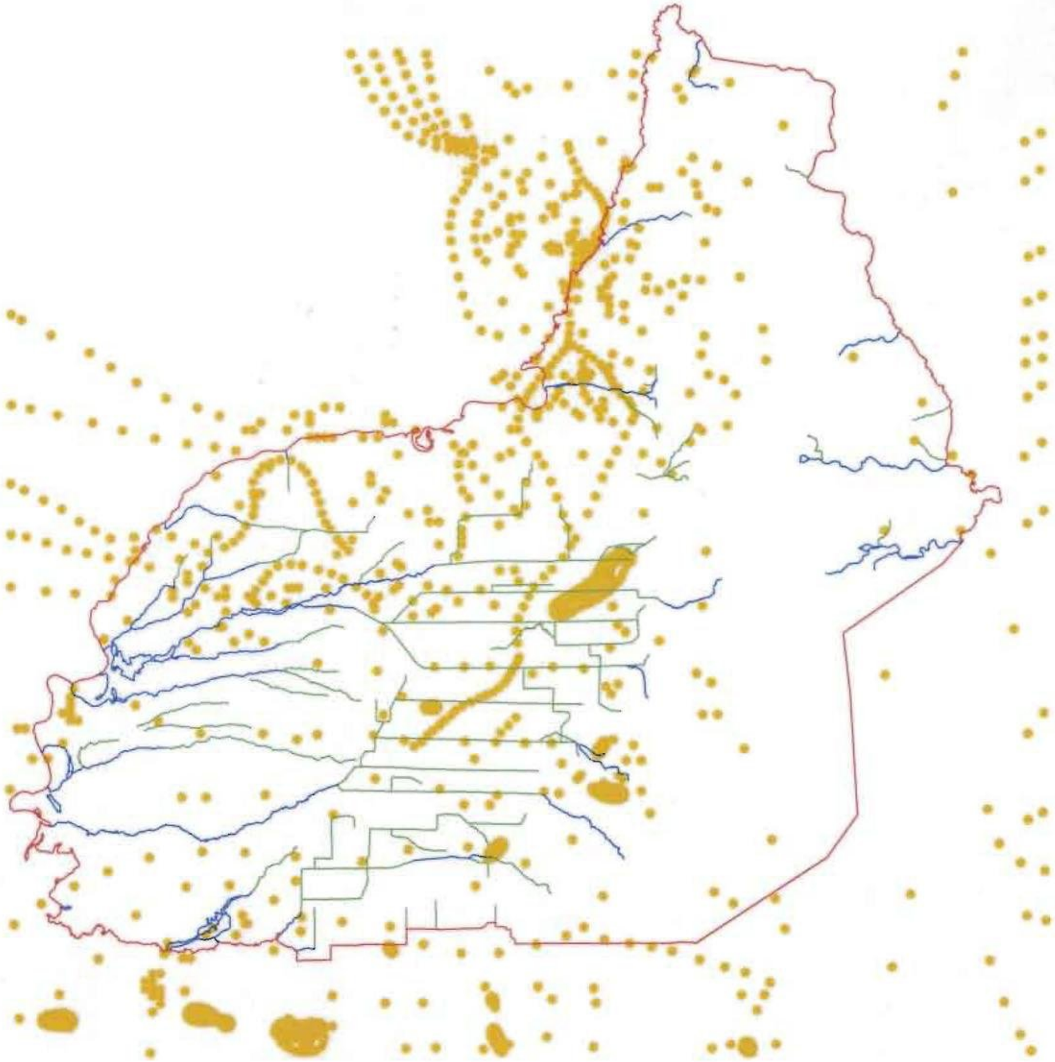


Figure 5 Locations of depth-to-bedrock data points

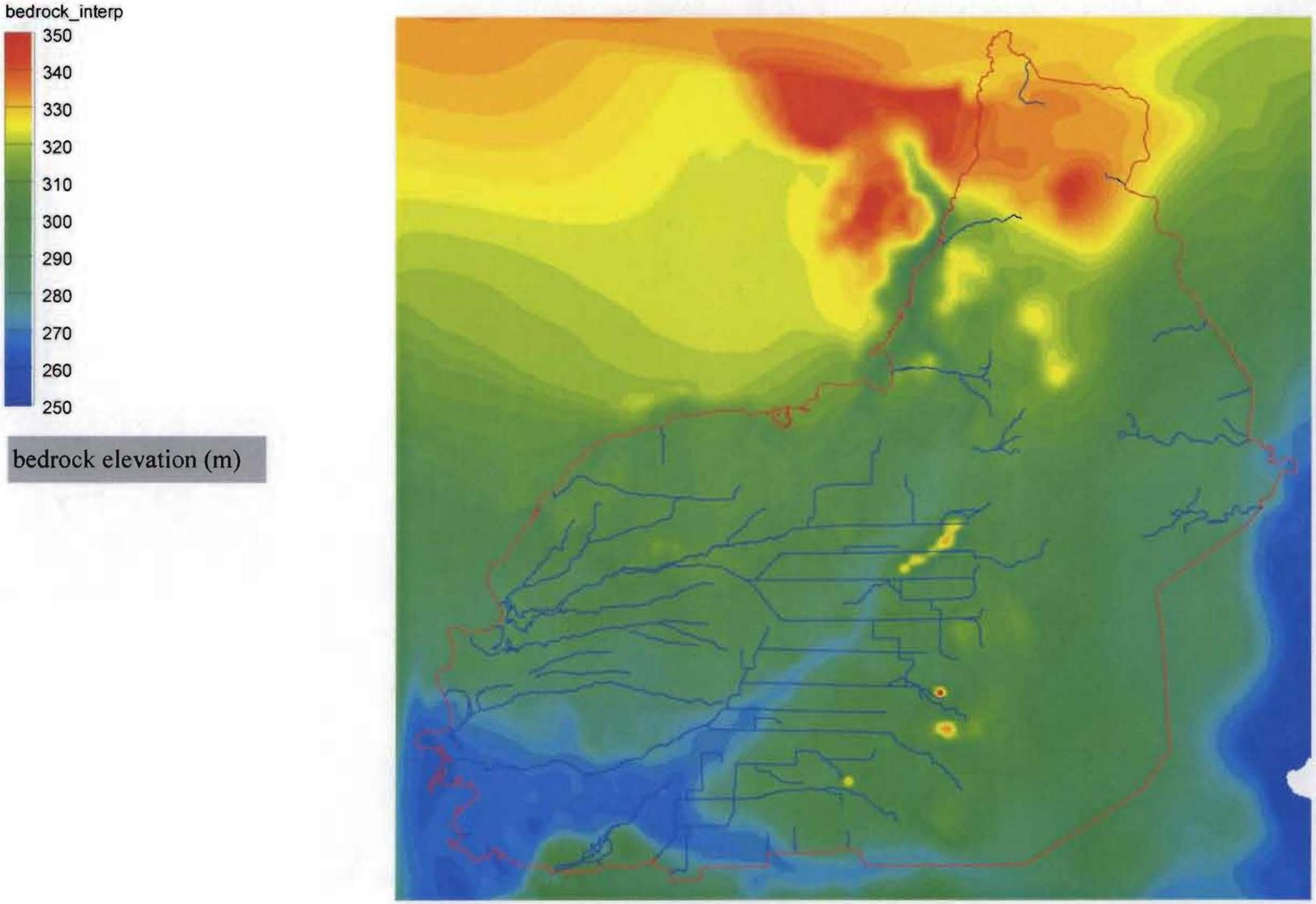


Figure 6 Interpolated bedrock surface

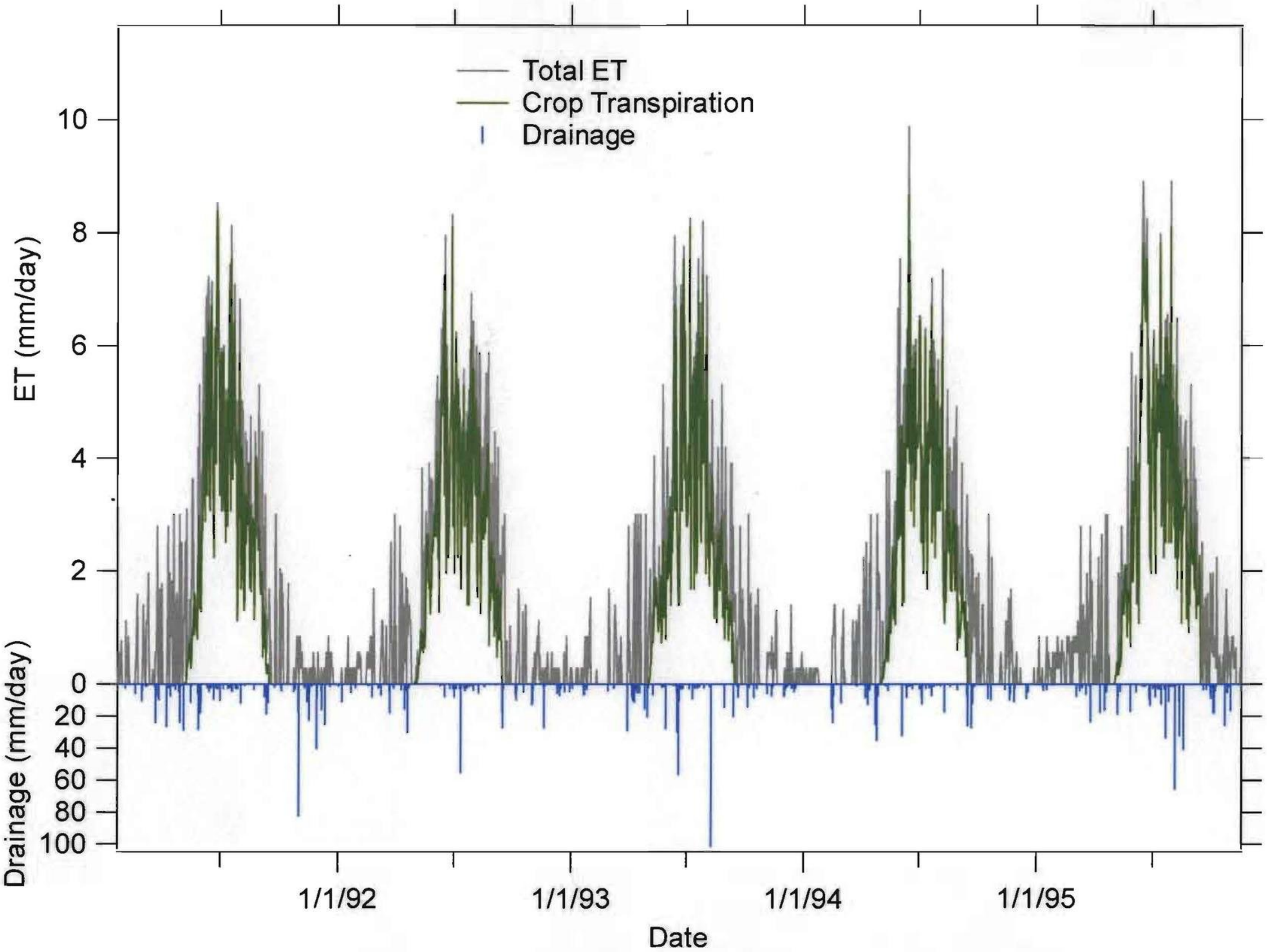


Figure 7 Five-year excerpt from water budget model output

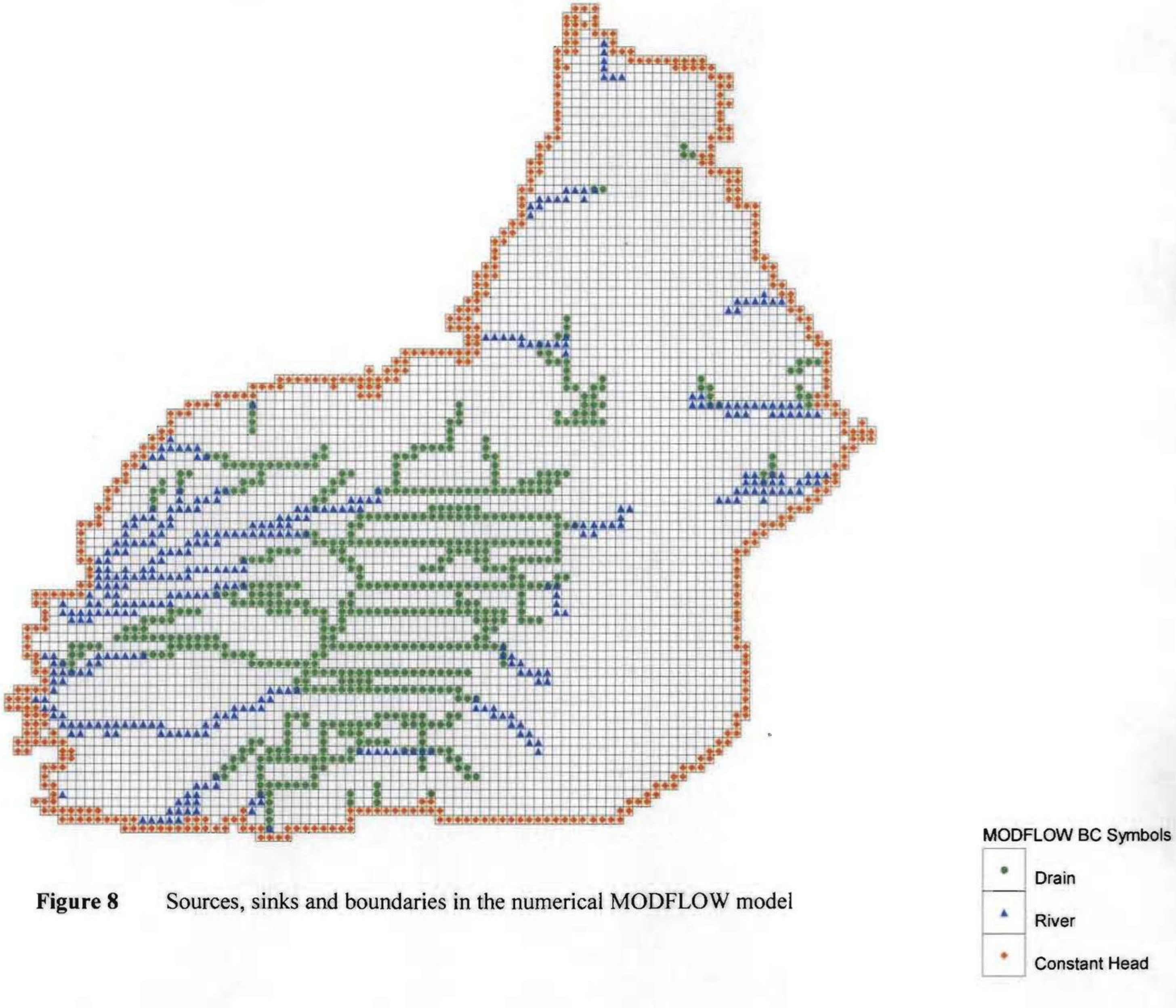


Figure 8 Sources, sinks and boundaries in the numerical MODFLOW model

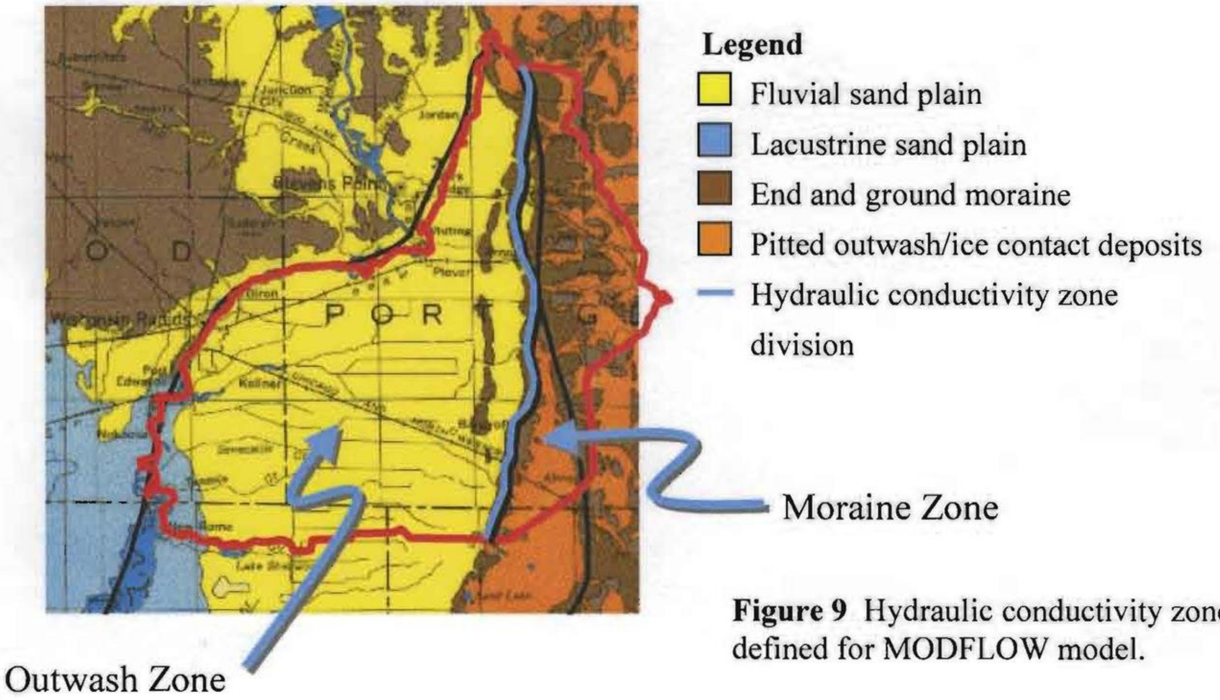


Figure 9 Hydraulic conductivity zones defined for MODFLOW model.

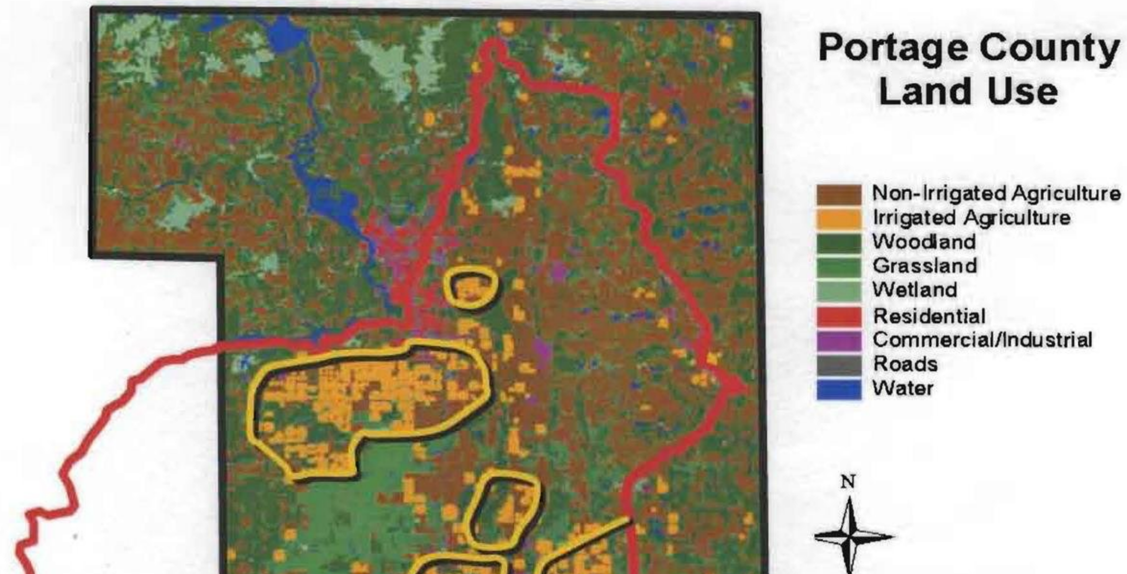


Figure 10 Recharge zones associated with irrigated land use.

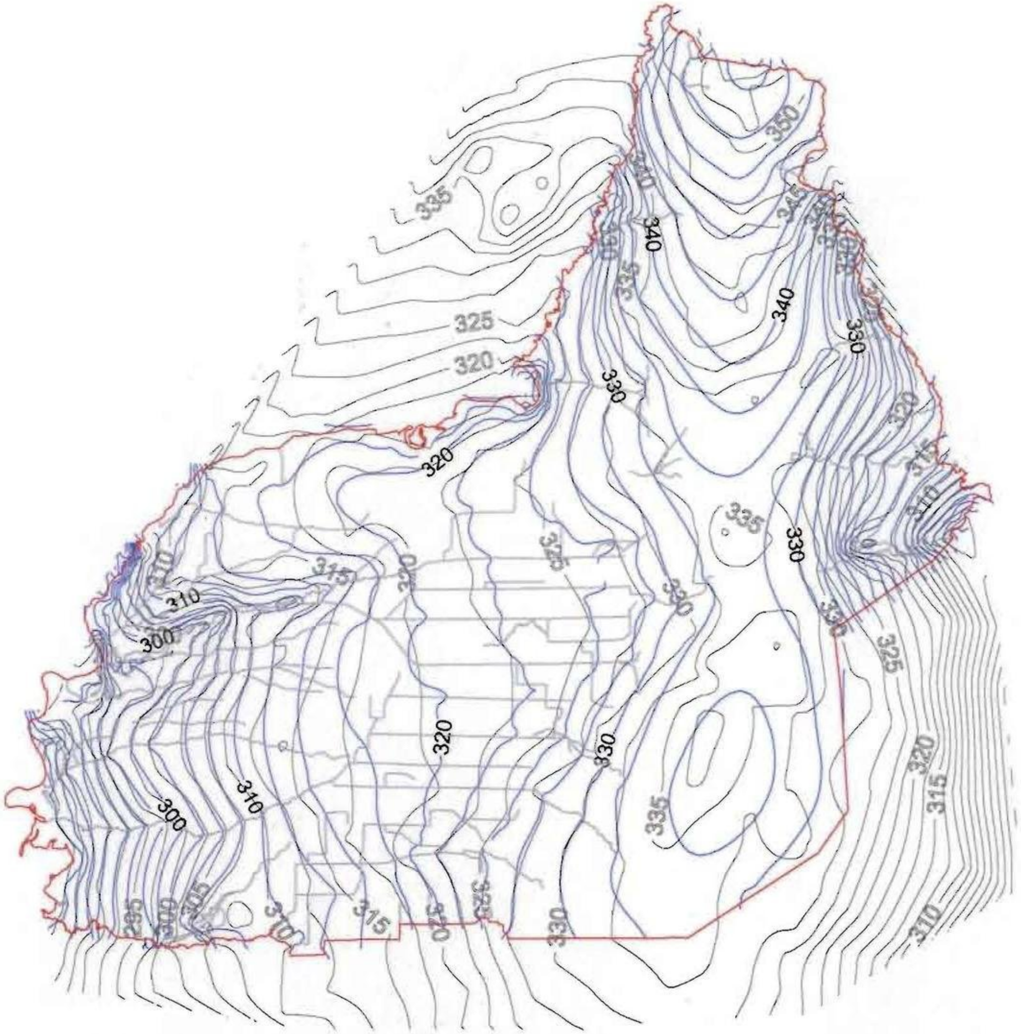


Figure 11 Comparison between modeled heads and calibration targets (simulation using uniform recharge)

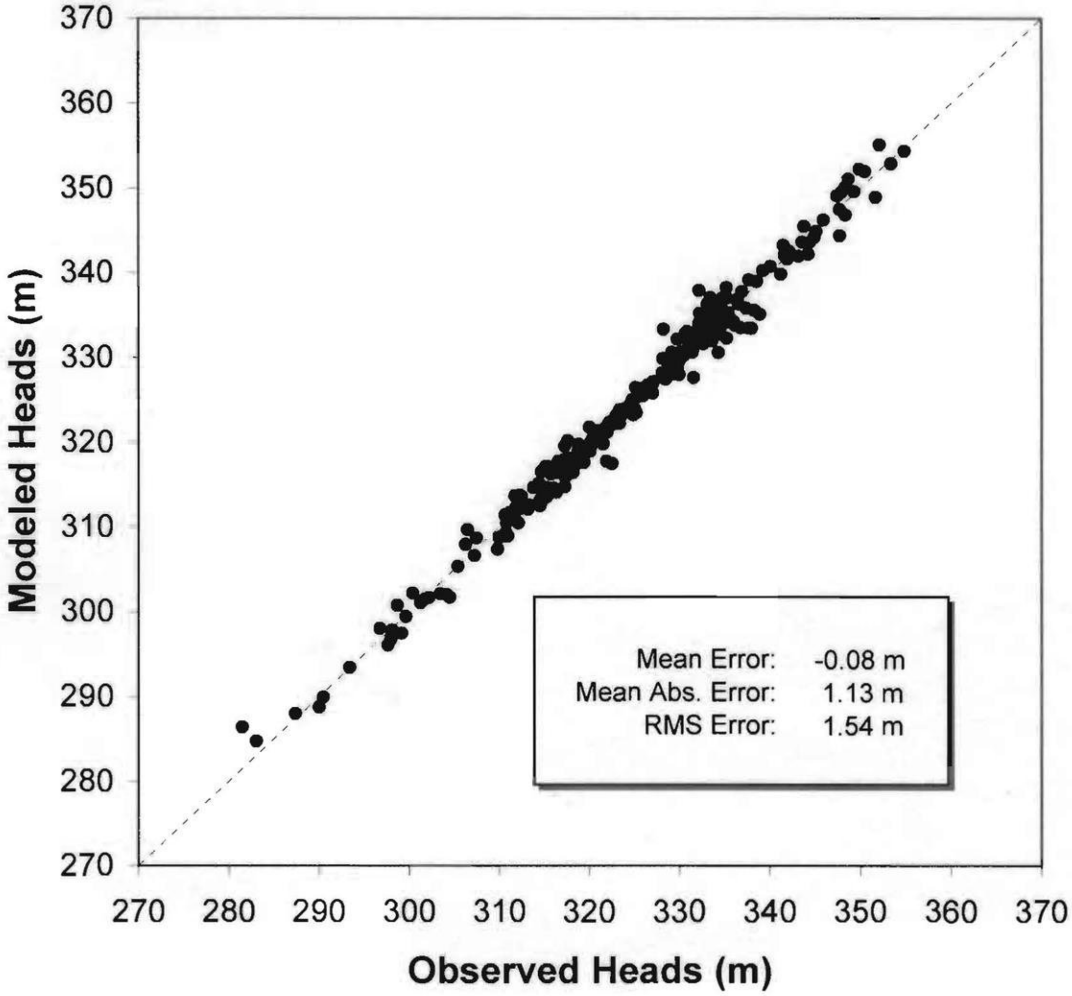


Figure 12a Comparison of modeled heads with cell-averaged observations

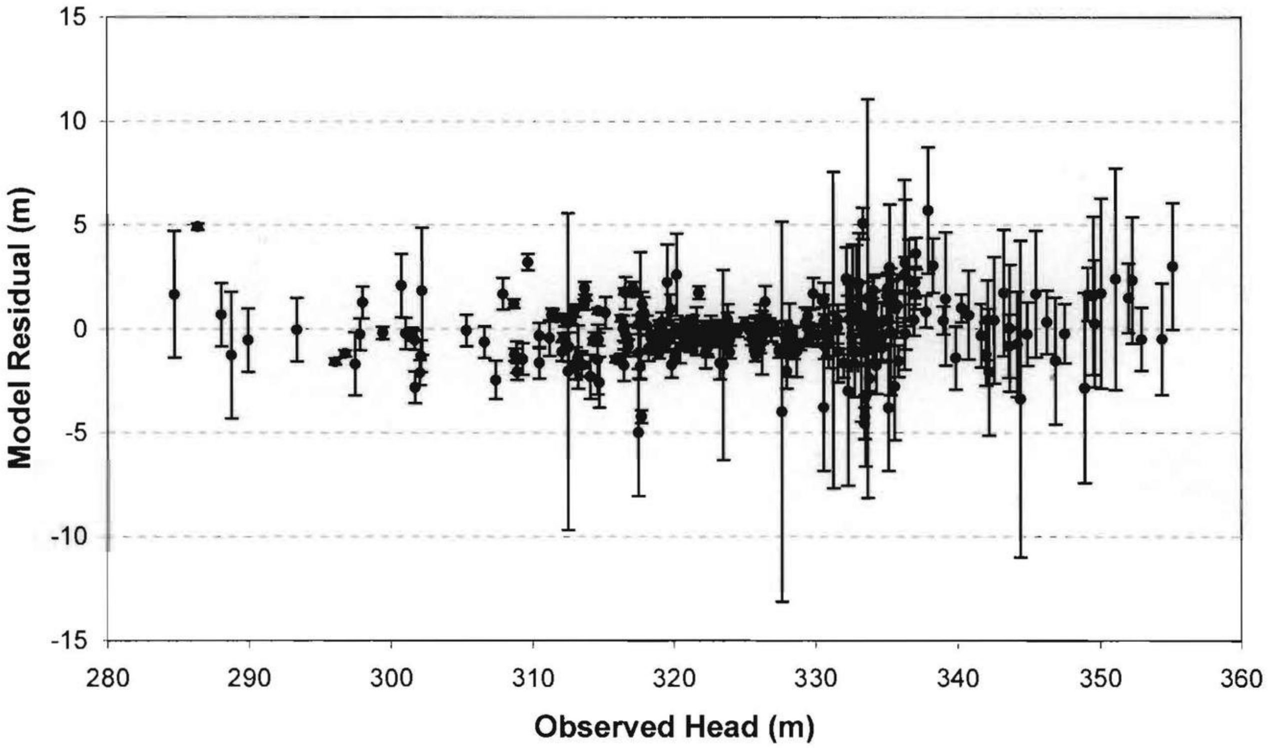


Figure 12b Model residuals (modeled minus observed heads) vs. observed head values. Error bars indicate uncertainties assigned to each head observation.

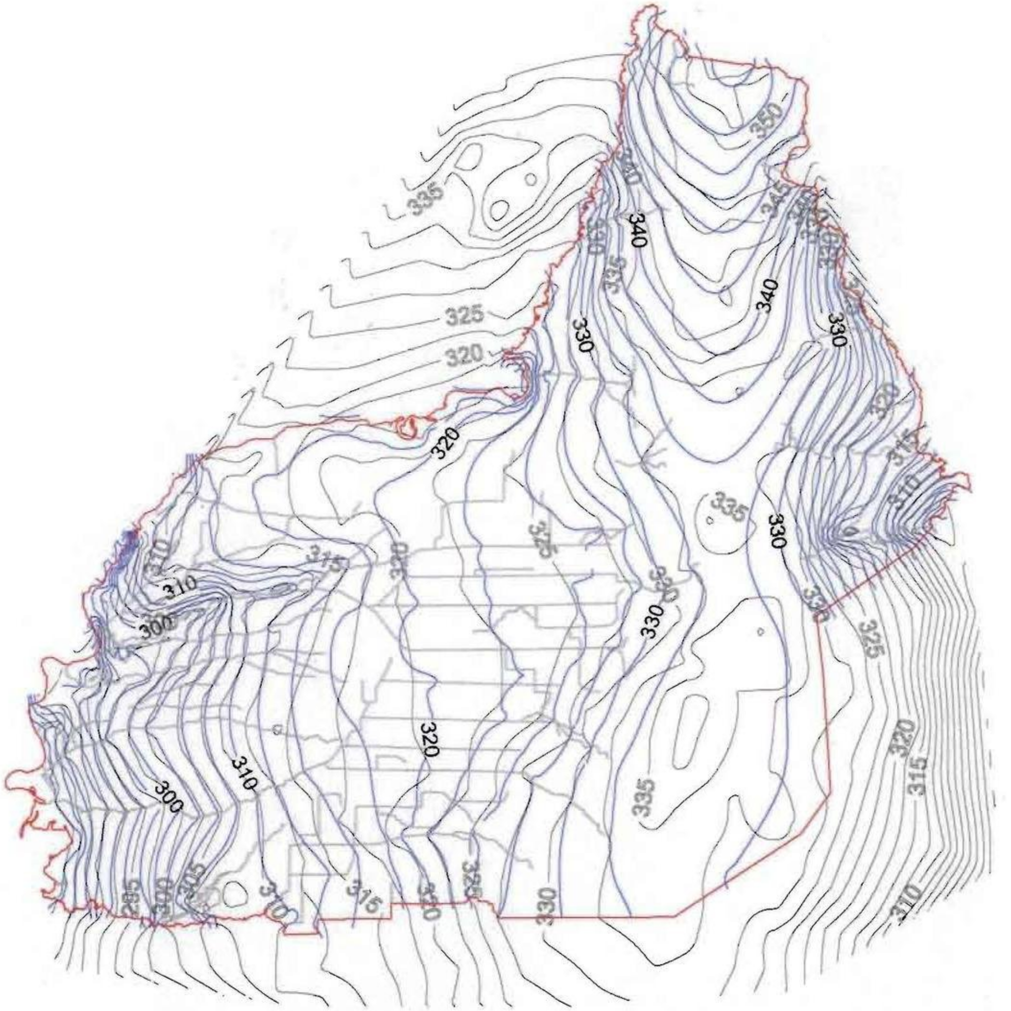


Figure 13 Comparison between modeled heads and calibration targets (simulation using irrigated recharge zones)

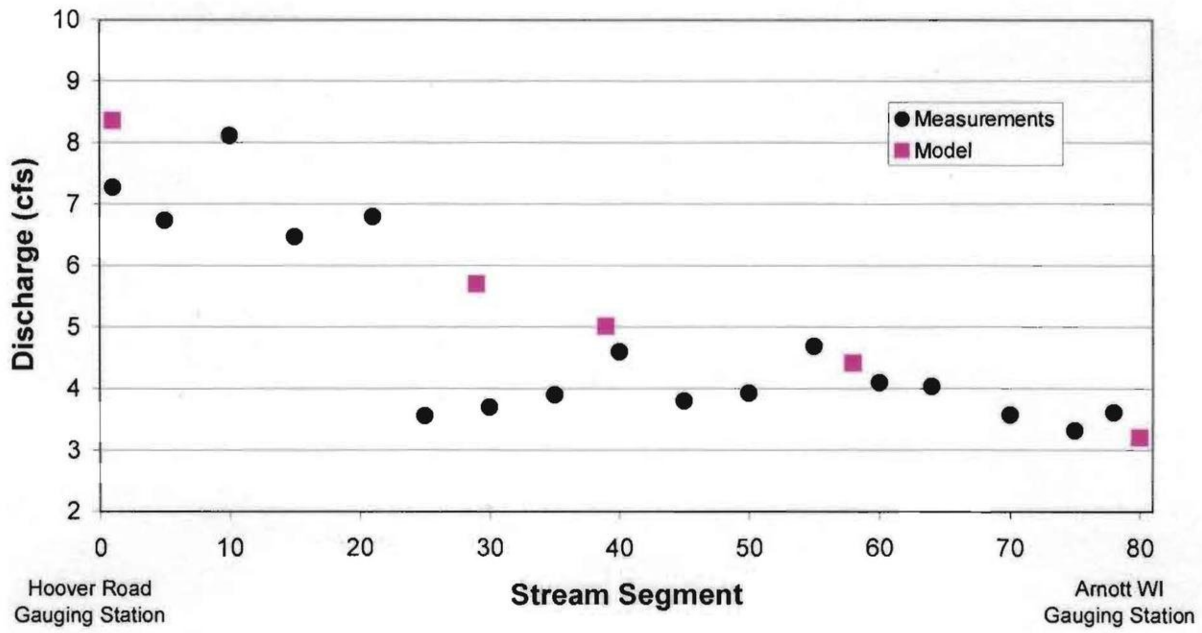


Figure 14 Comparison of modeled cumulative baseflow in the Little Plover River with streamflow measurements made at 300 ft intervals between the Hoover Road and Arnott USGS gauging stations (Browne, et al., 2000).

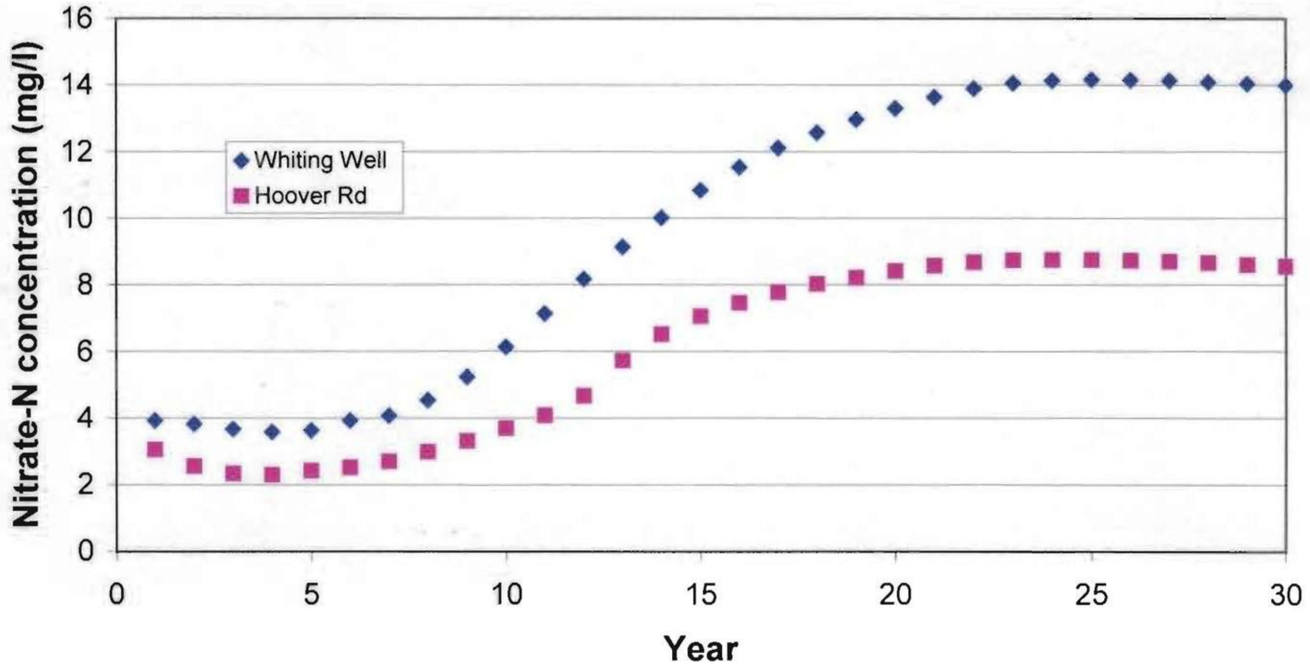


Figure 15 Modeled time-evolution in nitrate concentration near the well in the Town of Whiting and in the Little Plover River, near the Hoover Road gauging station.

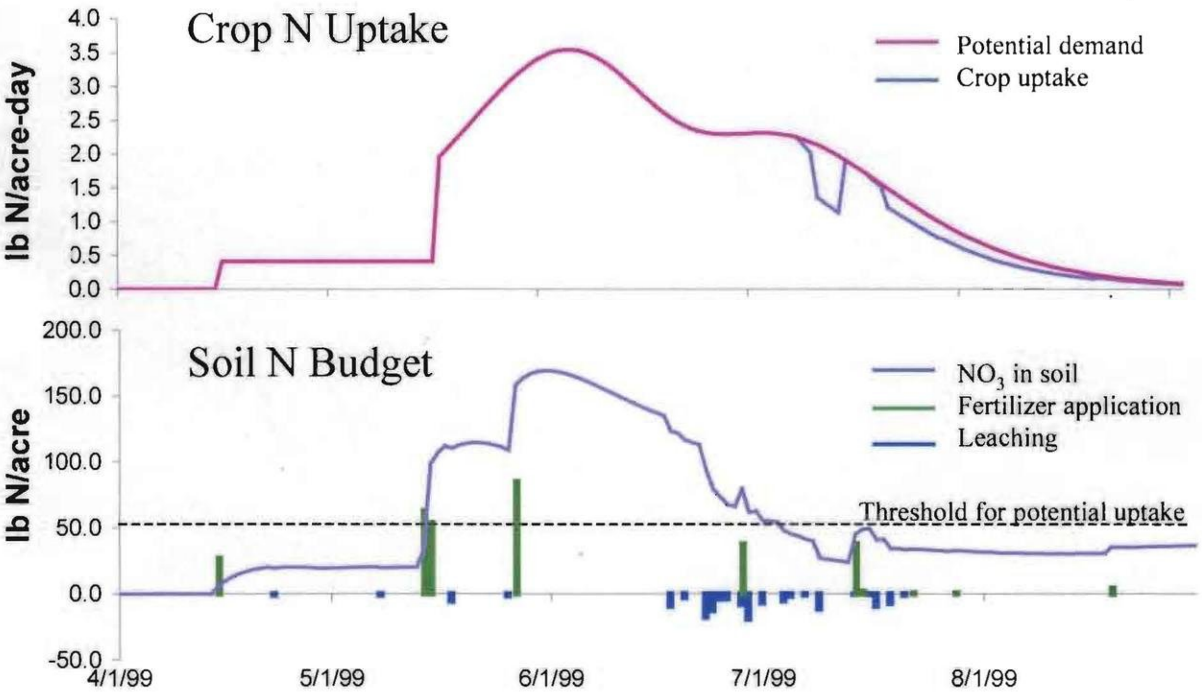


Figure 16 Example output from agronomic submodel

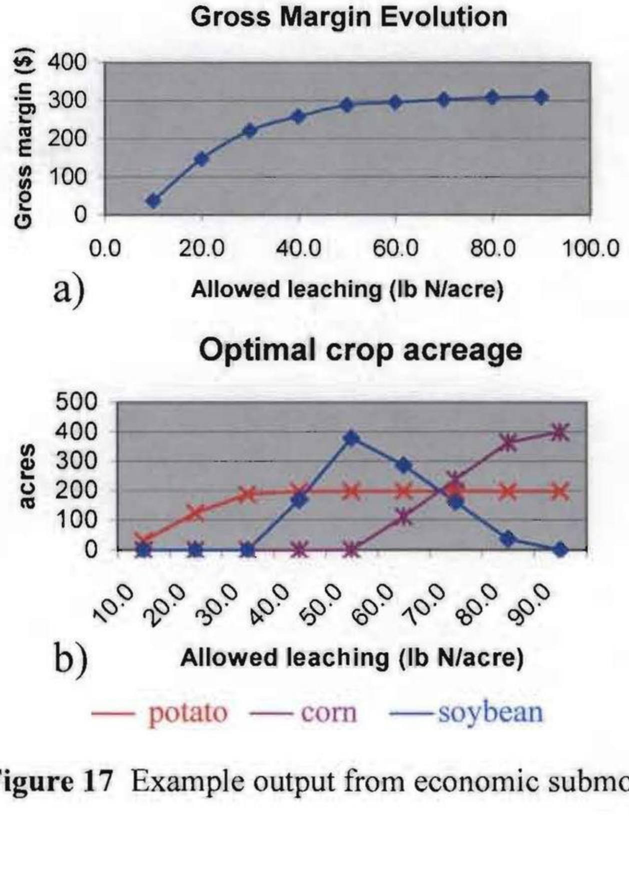


Figure 17 Example output from economic submodel