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A THREE-DIMENSIONAL (3-D) MODEL OF GROUNDWATER AND SURFACE WATER INTERACTION IN THE CENTRAL PASSAIC RIVER BASIN, NEW JERSEY

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The impacts of groundwater pumping on surface-water features were evaluated by use of a numerical groundwater model of the Central Passaic River Basin (CPRB) in New Jersey. The CPRB is underlain by sedimentary and igneous rocks from the New Jersey and Newark and New Brunswick group. The topography of the basin maps out a series of valleys that are filled with glacial deposits. The bedrock aquifer consists of fractured sedimentary rocks, including claystone, shale, siltstone and sandstone representing the red beds interbedded with basalt units resulting from three major volcanic events that interrupted sedimentation. The CPRB aquifer system consists of surficial and bedrock aquifers that are hydraulically connected.

Groundwater and surface-water interaction was simulated with MODFLOW under natural steady-state (prepumping) and pumping conditions in the last century. Under prepumping conditions, the model correctly predicts 50% recharge, and 50% discharge areas for the basin. Simulations of pumping at water supply wells, at known locations and rates, indicate that pumping has increased groundwater recharge and decreased discharge across the basin over the last century. This response has resulted in continuous reduction of the areal size of groundwater-fed wetlands in the basin. The wetland cover has been reduced from about 50% to 40%, and to 25% in 1898, 1925 and 1995 respectively. Thus, the model shows some concern to the ecological integrity of wetlands that should be considered in the environmental management of the CPRB and other areas of similar environmental characteristics.

INTRODUCTION

It has long been established that most surface water bodies, such as lakes, rivers, springs, and groundwater in aquifers are hydraulically connected and should be managed as one unit. Groundwater pumping from aquifers is of growing concern because of its potential effects on surface-water resources, particularly wetlands and their control on ecosystems. Hydrogeologic literature is replete with groundwater withdrawal limits based on aquifer yields estimated from pumping tests that were conducted without consideration of the groundwater-surface (GW-SW) interactions. More recently, however, the long-term consequences of groundwater development on surface water resources and related ecosystems are now being considered (Eggleston et al. 2012).

Early studies of the effects of groundwater pumping on surface water applied analytical models (Theis 1935, Glover and Balmer 1954, Hantush 1965, Hunt 1999, 2008, Butler et al. 2001). Simplified assumptions inherent in these models do not account for the complex geological and boundary conditions of regional groundwater systems (Rushton 2007). Numerical models are now being explored to overcome the imitations of analytical models (Spalding and Khaleel 1991, Sophocleous et al. 1995, Fox et al. 2002, Eggleston et al. 2012, Kornelsen and Coulibaly 2014, Robinson 2015, Conant Jr et al. 2019, Xu et al. 2021).

Baalousha (2012) modeled GW-SW interaction in the Ruataniwha basin, Hawkes's Bay, New Zealand using MODFLOW 2000 (McDonald and Harbaugh 1988). He concluded that rivers in the basin gained from the groundwater system during pumping, while springs flow has been decreasing. His study covered a time period of 20 years (from 1990 to 2009). Eggleton et al. (2012) simulated GW-SW interaction during groundwater pumping in a complex glacial-sediment aquifer in East Central Massachusetts with MODFLOW-NWT. Their results showed that a seasonal or stream-based groundwater pumping schedule can reduce the effects of pumping during periods of low flow (Eggleston et al. 2012). They assumed only hypothetical pumping conditions in their study. Many studies have characterized direct groundwater discharge to open bodies of surface water under conditions of seasonal and climate variability. For example, Hoaglund et al. (2002) used a MODFLOW model to characterize groundwater inflow and outflow from the Michigan Peninsula. Feinstein et al. (2010) used MODFLOW and SEAWAT models to simulate groundwater changes in the Lake Michigan Basin over the time interval of 1864-2005. Xu et al. (2021) utilized a large-scale fully integrated hydrologic model (HYDROGEOSPHERE) to characterize groundwater discharge into the Lauretian Great Lakes. None of these studies considered the effects of groundwater pumping in their analyses. There is the need to develop a large-scale groundwater model, capable of evaluating GW-SW interactions between groundwater and wetlands, in which real long-term field collected groundwater pumping data are utilized. Such a model will contribute to our understanding of the delicate relationship between the demands for water-supply needs and the existence of natural surface water bodies and their protection.

This paper describes the development and calibration of a MODFLOW (McDonald and Harbaugh 1988) groundwater model of the aquifer in the Central Passaic River Basin, New Jersey (CPRB). The paper also describes the use of the model to simulate GW-SW interaction under the past and present conditions of groundwater pumping at the site.

THE STUDY AREA

The study area covers 650 km^2 in the central part of the Hackensack-Passaic River Basin (Seaber et al. 1987) called Central Passaic River Basin (CPRB) in New Jersey (NJ) (Fig. 1). It is bounded by the crest of the Second Watchung Mountain to the north, east and south, and by the Ramapo Fault to the west. It covers parts of five counties and all parts of 48 municipalities. The CPRB is underlain by sedimentary and igneous rocks from the New Jersey and Newark and New Brunswick group. The topography of the area is characterized by a series of valleys that are now filled with glacial deposits.

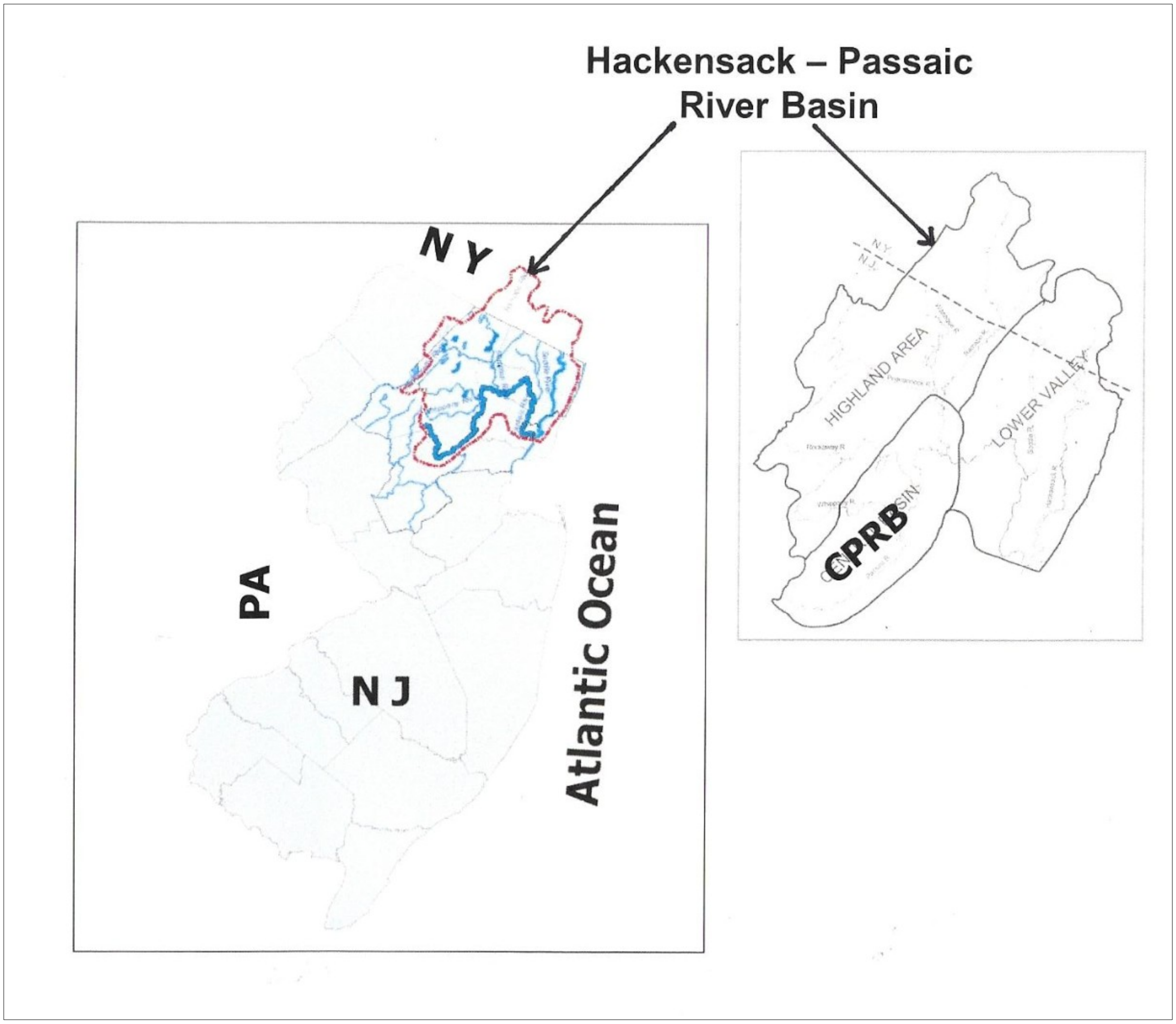

Fig. 1: Location of the study area (CPRB). NY is New York State, PA is Pennsylvania State, NJ is New Jersey State

Illinoian and Wisconsinan glacial sediments, primarily lacustrine and fluvial materials and till occupy low-lying areas north of the Wisconsinan terminal moraine. Glaciolacustrine deposits, including coarse-grained sediments and fine-grained glacial lake bottom deposits, are found throughout the study area (Hoffman et al. 2002). The CPRB aquifer system consists of surficial and bedrock aquifers that are hydraulically connected as described by Geraphty & Miller, Inc (1976). Each aquifer may contain multiple water bearing zones. The surficial aquifer consists of quaternary unconsolidated materials of three types: (1) marsh, swamp and alluvial deposits; (2) glacial deposits from ice and meltwater; and (3) residual deposits of bedrock weathering. Most of the glacial sediments in the CPRB may not be present everywhere. It is believed that at least three glacial episodes have affected the CPRB; pre-Illinoian, Illinoian identified in scattered areas and late-Wisconsinian that represent most of the CPRB deposits (Kümel 1919, Stanford et al. 1990). The bedrock aquifer consists of fractured sedimentary rocks, including claystone, shale, siltstone and sandstone representing the red beds interbedded with basalt units resulting from three major volcanic events that interrupted sedimentation. The bedrock topography is characterized by interconnected buried depressions also called ‘‘buried valleys’’ that have been carved as a result of glacial erosion that has scoured the sedimentary rocks (Canace and Wayne 1989). Where filled with glacially derived sand and gravel, the buried valleys contain the most productive part of the surficial aquifer.

MODEL DEVELOPMENT

Conceptual model

A 3-D numerical groundwater flow model was developed to describe the regional flow of water in the CPRB bedrock and valley-fill aquifers. It was initially developed by Meisler (1976) and then updated by Hoffman (1989). Meisler's model covered only a small southern portion of the area that is considered in this current study. The MODFLOW modular finite difference code developed by McDonald and Harbaugh (1988) was used to simulate the groundwater flow by Hoffman (1989), and in the current study. However, the current study has included all available hydrogeological data that have been collected since 1989. The model layers consisted of, from top to bottom, a water-table unconsolidated water bearing sand and gravel unit (Layer 1), a semi-confined water bearing sand and gravel unit (Layer 2) mostly found in the central part of the basin, and the bedrock unit of sandstone, siltstone and basalt (Layer 3). The area is bounded vertically by a fault (the Ramapo Fault) on the western side that separates less permeable granites on the west from red beds on the east. As a result, any groundwater flow across the fault is significantly less than other sources of groundwater in the model area. The crest of the second Watchung Mountain corresponding to the northern, southern and eastern boundaries of the area represents a flow divide, and its basaltic nature restricts lateral flow across the model boundary. The top horizontal surface boundary is defined by surface water bodies (lakes, rivers, wetlands) (Fig. 2), some of which are presumed to be groundwater fed. The bottom or no-flow boundary is the bottom of the bedrock layer.

Model discretization

The current model also used the advanced techniques of the MODFLOW codes in the new Groundwater Modeling System (GMS) to refine the finite-difference grid, and to simulate the new groundwater recharge map of the area more precisely. The grid spacing was 1,220 by 610 m, and it was refined in the center area to 610 by 610 m. The thickness of the cells depends on the local geology. The unconfined sand and gravel aquifer has an average thickness of 1.5 m. The thickness of the semi-confined sand and gravel is up to 30 m in the central part, with an average of 4.5 m elsewhere. The permeable part of the bedrock aquifer corresponds to an average thickness of 60 m.

Hydraulic parameters

Values of hydraulic conductivities, storage coefficients and recharge were taken from available field data, and had been adjusted during a prior calibration (Hoffman 1989). The horizontal hydraulic conductivity of layer 1 was set to 1.8×10^{-5} m/s and the ranges of hydraulic conductivities for layers 2 and 3 are 3.5×10^{-5} to 1.1×10^{-3} m/s and 2.1×10^{-6} to 1.4×10^{-5} m/s, respectively. The vertical hydraulic conductivity is assumed to be 10% of the horizontal hydraulic conductivity for all 3 layers. Storage coefficients of 0.3, 0.0002 or 0.25 when dewatered, and 0.0005 or 0.25 where unconfined were assigned respectively to layers 1, 2 and 3. A leakance value is used to simulate the vertical flow between adjacent layers. This value is a function of the thickness, and vertical hydraulic conductivity of

Fig. 2: Prepumping (1898) Wetlands in the CPRB. Colored shaded areas are wetlands

the intervening semi-confining unit. The average values of leakance used between layers 1 and 2, and between layers 2 and 3 were 1.1 x 10^{-6-s} and 0.9 x 10^{-7-s}, respectively.

Groundwater recharge and discharge

Surface water can greatly affect groundwater levels especially in water-table aquifers. The aquifer may be recharged from, or may discharge to, overlying surface water depending on the relative water levels. Groundwater withdrawal had several effects in the study area causing significant water level fluctuations and drop in the surficial aquifer. In order to evaluate the transient effects, drawdowns from 1898 to 1995 were simulated with 30 pumping periods ranging from 1 to 5 years. Historical pumpages are given in Hoffman and Quinlan (1994). These data have been collected over the years from a relatively large number of pumping and observation wells (Figs. 3 and 4). On the other hand, recharge will have an effect on the developed groundwater flow system. The pumping wells will capture water from recharge areas to induce increased recharge and reduce discharge and storage. At the initial stages, recharge rates adjusted from a prior simulation were used as input.

Model Simulation and Calibration

The steady-state model was calibrated to land surface elevation due to the fact that prepumpage available water level records were not complete to determine the water table. It is known that the water

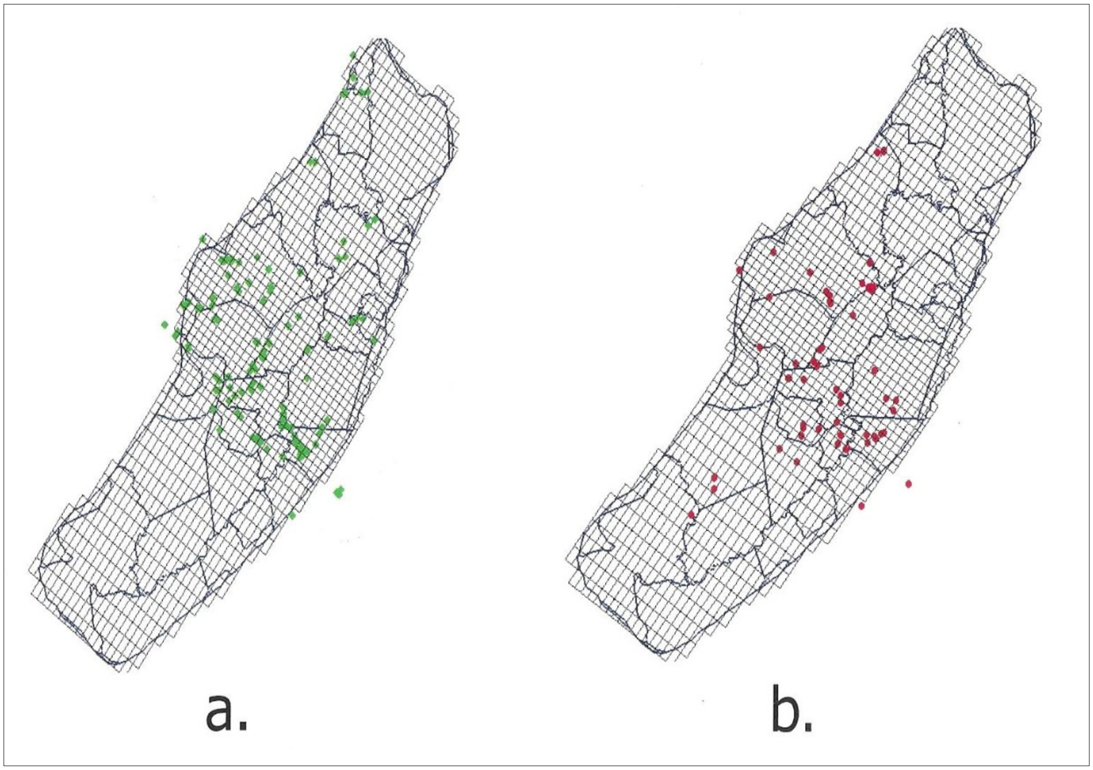

Fig. 3: Groundwater wells used in the sand and gravel unit (layer 2) of the model. a. pumping wells, b. observation wells

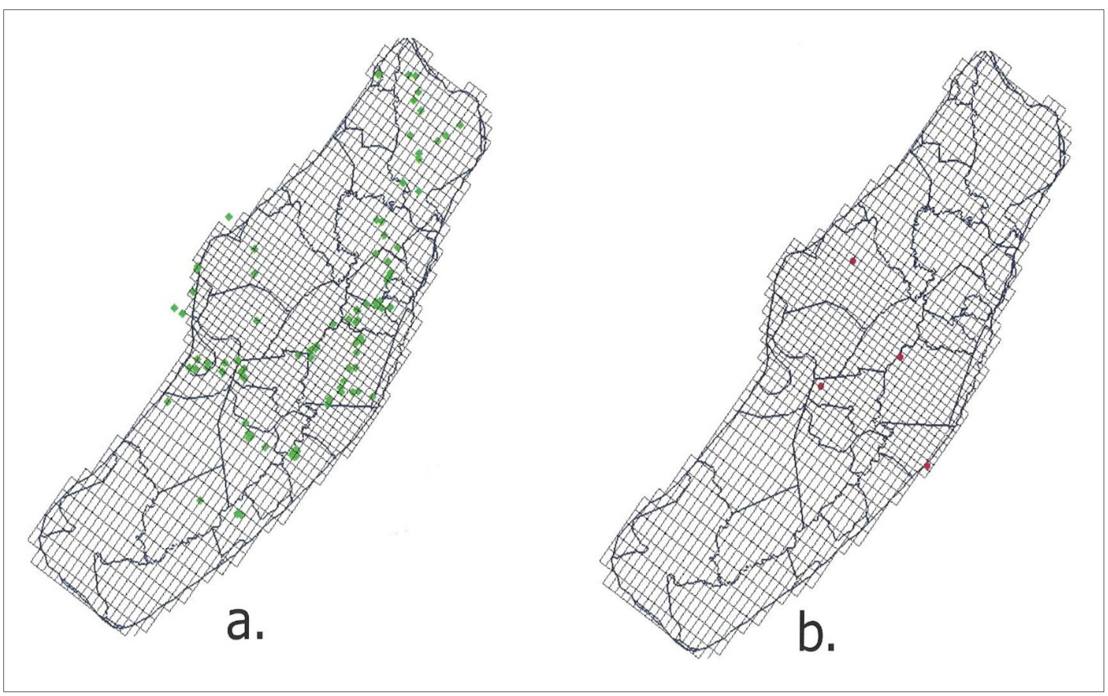

Fig. 4: Groundwater wells used in the bedrock unit (layer 3) of the model. a. pumping wells, b. observation wells

table is commonly a subdued replica of the surface topography (Ophori and Tóth 1990; Haitjema and Mitchell-Brucker 2005). Transient water level records for 70 observation wells that cover entirely or partially the simulated period were used in the calibration of the transient model. Parameters were adjusted to fit the model simulated head values with the observed heads. The recharge values were adjusted during the calibration process because the initial results showed that the simulated heads were too high compared to the observed ones. Initial recharge values were refined using recharge values from a recharge map of NJ, that better characterized the spatial variability of recharge. The calibration resulted in recharge rates that were reduced to 1/10th of the initial values. The recharge in some areas covering the central, western and eastern part of the basin were further adjusted manually because those areas are higher in elevation and assumed to get more recharge. The development of the recharge distribution map is described in greater details in the Geological Survey Report 32 (Charles et al. 1993), and basically takes into account several factors that better characterize the recharge in the area. The aquifer is assumed to be recharged from the water table and the recharge rates remained the same during the entire simulation period. It was also assumed that the seasonal fluctuation of recharge rates was not significant enough to cause seasonal variations in the regional flow during the simulated period. For the transient model, the minimization of the mean absolute difference of computed minus measured heads is used as part of the calibration process. In the model calibration process, simulated water levels in about 70% of the wells were very close to the measured water levels, and in about 30% of the wells, water levels were acceptably close (Fig. 5). The measured versus simulated water levels were plotted on a graph to show how well the values matched. The year 1990 was arbitrarily selected to represent a period when most of the pumping wells were already in place, and have been pumping for a reasonable period of time. Deviations in head were noted and corrected as much as possible through the calibration process. The values on the 45-degree calibration line indicate a very good correlation.

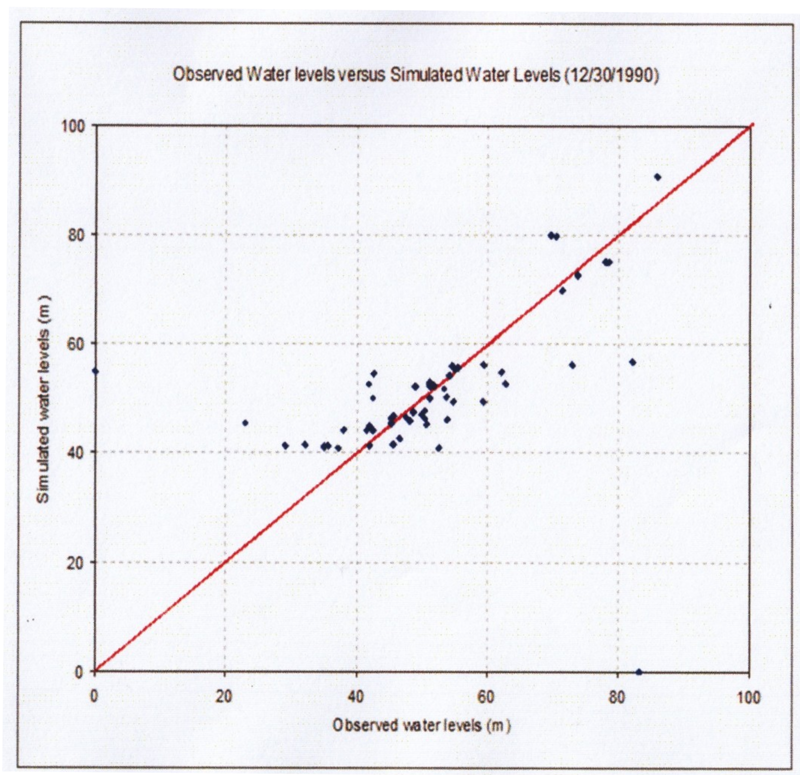

Fig. 5: Plot of simulated versus observed heads for transient model calibration

GROUNDWATER SURFACE WATER INTERACTION

Recharge and discharge areas

Recharge areas are zones where groundwater moves downward from the surface (water table) into the model. Discharge areas, on the other hand, are zones where groundwater movement is upward from the model to the surface (Tóth 1962, 1963). In this study, simulated hydraulic heads, h_1 and h_2, were used to outline the recharge and discharge areas, where h_1 is the head in model layer 1 and h_2 is the head in layer 2. For recharge areas, $h_1 > h_2$, and $h_1 < h_2$ in discharge areas. Figure 6 shows the simulated recharge and discharge areas. The prepumpage conditions in 1898 (Fig. 6a) indicates that discharge areas cover about 50% of the basin as expected from the papers by Tóth (1962, 1963). Groundwater pumping over the century has reduced and weakened the strength of groundwater discharge in the basin (Fig. 6b).

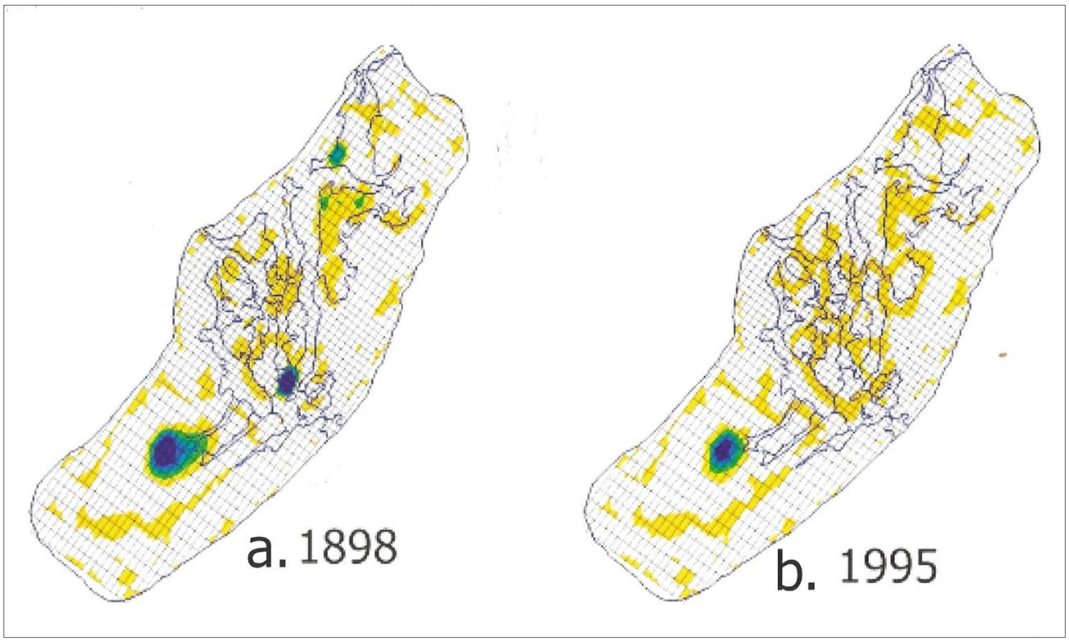

Fig. 6: Simulated groundwater discharge areas (colored) in the CPRB. Blue, green, orange – high, moderate, low discharge rates

Groundwater-fed wetlands

Wetlands provide many social benefits, including food and habitat for fish and wild life, improvement of water quality, flood storage, shoreline erosion control, and economically beneficial natural products for human use. Inspite of their importance, New Jersey has lost 1,755 acres of wetlands per year (Thornton et al. 2001) in the last few decades. The major causes of wetland loss include agriculture, urban and suburban development, mosquito control, and other draining and filling activities. Wetland mitigation is only possible if the causes of their loss are well understood. This modeling study investigates possible wetland loss in the CPRB due to groundwater pumping in the last century (1898 to 1995). This is the time period for which detailed field data are available with which simulated data could easily be compared.

The groundwater-fed wetlands were delineated by outlining areas in the model where the groundwater-surface water system in hydraulically connected (Brunner et al. 2010). In these areas, h_1 is above the elevation of the ground surface, z_a ($h_1 > z_a$), and groundwater is continuously discharging to the ground surface. The impact of groundwater pumping on groundwater-fed wetlands is shown in Figure 7. The size and discharge strength of groundwater-fed wetlands have reduced continuously over the last century (1898 to 1995). At the prepumpage stage in 1898, the wetlands cover about 50% of the CPRB under steady-state conditions (see Figs. 2 and 7a). By 1925 and 1995, groundwater pumping has reduced the wetlands to about 40% and 25% of the CPRB (Figs. 7b and 7c), respectively.

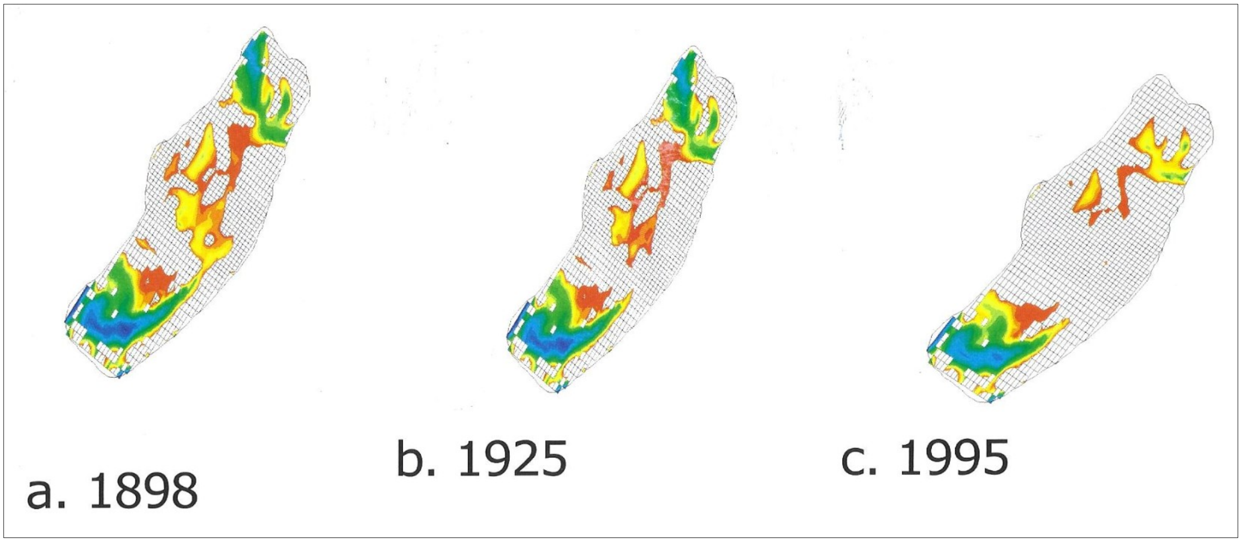

Fig. 7: Simulated groundwater-fed wetlands (colored areas) in the CPRB

CONCLUSION

This modeling study of groundwater flow and GW-SW interactions in the CPRB aquifer system, from which groundwater has been continuously pumped for one century, has produced valuable findings that can be applied in regions with similar hydrogeological conditions. The CPRB is underlain by complex sedimentary and igneous rocks, mainly glaciolacustrine coarse-grained sediments and fine-grained lake-bottom sediments. These complex rocks constitute an aquifer system that consists of surficial and bedrock aquifers that are hydraulically connected in multiple water bearing zones. It has been possible to classify these rocks into three layers: a top unconsolidated water bearing sand and gravel unit, a semi-confined water bearing sand and gravel unit, and a bedrock unit of sandstone, siltstone and basalt. These units formed the basic framework on which a 3-D MODFLOW groundwater flow model was constructed, and a steady-state simulation performed. Historical groundwater pumpage data for the past century were used to simulate the transient response of the system to pumping, and to analyze the effects of pumping on the GW-SW interaction of the system. Simulated water levels compared well with observed water levels, indicating that the groundwater flow was reasonably calibrated for the CPRB.

The study indicates that groundwater discharge areas occupy half of the basin under prepumpage groundwater flow conditions. Groundwater pumping in the last century has reduced the discharge areas, and weakened the strength of groundwater discharge. Additionally, groundwater development has induced increased recharge into the CPRB. The model also indicates that groundwater pumping has contributed to the loss of groundwater-fed wetlands in the basin. This study shows that groundwater pumping should be considered along with other factors in any successful plan to mitigate wetland loss in the CPRB.

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