Groundwater flow and salinity in the Illinois Basin

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ABSTRACT
Modeling groundwater flow is a vital process to estimate the patterns of flow, salinity, and temperature distributions and the suitable regions for obtaining water for drinking, agriculture, industry, and electrical power generation can be found. In this study ground water flow in Illinois Basin from Christian County to Livingston County is modeled using the Basin2 numerical code developed at the University of Illinois. Input parameters include the profile, time of deposition, and composition of the rock formation column as well as the diffusion coefficients of these formations. In the Illinois Basin, salinity is produced by water interacting with the sandstone and limestone aquifers and therefore contains different minerals. The surface topography significantly affects the groundwater flow in this region. Through these analyses the effects of temperate of the groundwater on the density and thus hydraulic potential of groundwater and also salinity are discussed. The computations show that the salinity of the groundwater decreases towards the Christian County and the acceptable locations for potable water during different seasons of the year are identified according to their salinity and hydraulic pressures.

RÉSUMÉ
Le flux d'eau souterraine de modelage est un processus vital pour estimer les modèles de flux, la salinité, et les distributions de température. Les régions convenables pour obtenir d'eau pour boire, l'agriculture, l'industrie, et la génération de pouvoir électrique peut être trouvé. Dans ce flux d'eau souterraine d'étude dans l'Illinois Bassin du Comté chrétien au Comté de Livingston est modelé utilisant le Basin2 code numérique développé à l'Université d'Illinois. Les paramètres d'entrée incluent le profil, le temps de déposition, et la composition de la colonne de formation de rocher de même que les coefficients de diffusion de ces formations. Dans le Bassin d'Illinois, la salinité est produite par réagit réciproquement d'eau avec les aquifères de grès et calcaire et contenant donc des minéraux différents. La topographie de surface affecte significativement le flux d'eau souterraine dans cette région. Par ceux-ci analyse les effets de modéré de l'eau souterraine sur la densité et de potentiel ainsi hydraulique d'eau souterraine et aussi de salinité sont discuté. Les calculs montrent que la salinité des diminutions d'eau souterraine vers le Comté chrétien et les emplacements acceptables pour l'eau potable pendant les saisons différentes de l'an est identifiée selon leur salinité et selon les pressions hydrauliques.

1 INTRODUCTION

Groundwater is used for human consumption, agriculture, industry, and power generation and in most areas aquifers' potential yield are sufficient to provide water for these purposes. However, most aquifers are neither uniformly distributed, nor homogeneous in their physical and chemical properties from area to area. Therefore geological and hydraulic field investigations, geological mapping, and groundwater modeling are important and necessary to find adequate water. In addition, certain levels of water salinity are required for each various applications of groundwater. Rivers, lakes and wetlands also require certain amounts and qualities of water to maintain the ecosystems.

In the state of Illinois, the rock formations that exist from about Christian county to Livingston county (section B-B' in Fig. 1) are primarily composed of layers of sandstone, siltstone, shale, and dolomite. These layers of rocks are deposited in the form of unconsolidated sediments that later on metamorphosed into hard rocks above one another like pages of a book. Afterwards these rocks were folded, foliated, and faulted due to geologic actions. In this area the beds dip eastward and southward to give spoon like shape and form a depression in the middle that is filled with 14,000 feet Paleozoic sediments. This spoon like shape is known as the Illinois Basin (Bethke et al. 1991). The basin is bounded to the north by the Wisconsin arch, to the east by the Cincinnati arch, to the southeast by the Nashville dome, to the southwest by the Ozark dome and to the northwest by the Mississippi River arch (Neely 2009). Groundwater is developed from three principal aquifer types in Illinois. These are generally categorized as sand and gravel aquifers within the unconsolidated geologic materials overlying the bedrock; shallow bedrock aquifers lying within approximately 100 m of land surface; and deep bedrock aquifers lying at depths greater than 100 m of land surface (Wehrmann et al. 2003). In Illinois Basin unconsolidated sand and gravel of Quaternary age and consolidated sandstone, limestone, and dolomite of Paleozoic age are contributing aquifers. The principal aquifers in Paleozoic rocks primarily are sandstone of Pennsylvanian age, limestone and sandstone of Mississippian age, dolomite and limestone of Devonian and Silurian age, and sandstone and dolomite of Ordovician and Cambrian age. The Illinois

Technical Advisory Committee on Water Resources (ITACWR 1967) report presents maps of the estimated potential yields, expressed as recharge rates in gallons per day per square mile of the principal sand and gravel and shallow bedrock aquifers in Illinois. The water withdrawn from these aquifers tends to be mixed with several minerals and has various levels of salinity. This is because this water interacts with several rock types and dissolves the minerals within these rocks. In this study groundwater flow, salinity, and temperature effects in the Illinois Basin are modeled through solving the governing advection and conduction differential equations. The modeled region comprises about 35500 km^2 and has a population of about 920500. It includes a large area of highly productive agricultural land on which general farming is the principal enterprise (Selkregg and Kempton 1958). In addition, information about the hydrodynamic potentials in aquifers would help petroleum reservoir engineers and geologists to look for the existence of tilted water tables where they can look for oil and gas. Researchers who study the primary accumulation of oil need to know something about the direction and rate of flow of water underground. Others, interested in theories about the source of natural brines, need information about the natural forces available for forcing water through semi-permeable layers, such as shale. Gas storage engineers and designers need to know whether hydrodynamic gradients exist that will add to, or subtract from, the effective closure in proposed reservoirs. Hydrologists are interested in the natural potentials that may cause flow in fresh-water sources or in other aquifers.

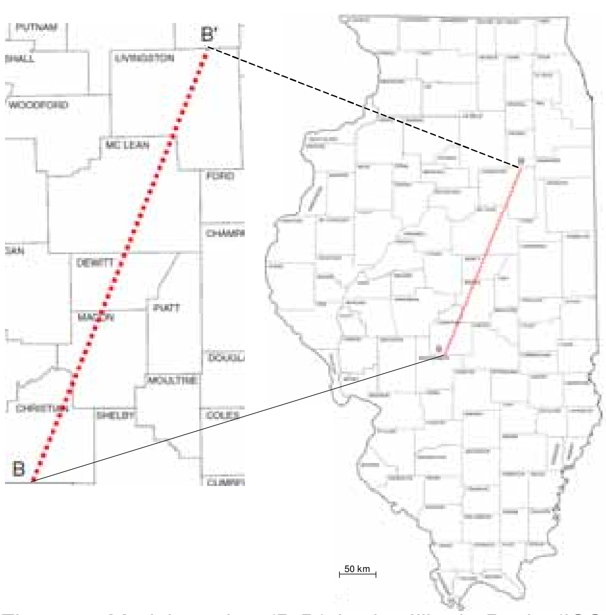


Figure 1. Model section (B-B') in the Illinois Basin (ISGS map series)

2 BASIN MODEL

For this analysis, the Basin2 software (Bethke et al. 2007) developed at the University of Illinois at Urbana-Champaign is used. Basin2 is a numerical model designed to trace the evolution of groundwater flow regimes within sedimentary basins through geologic time. The arrangement of basin strata along a vertical cross section, the timing of sediment deposition (and erosion if any), and the physical and hydrologic properties of sediments and rocks in the basin are the input parameters of Basin2. From these data and equations describing flow and transport, the model reconstructs basin development. The details of the analysis are as below.

2.1 Physical and Hydrological Properties of Soil and Rock Strata

The porosity (ϕ) of the sediments is defined from the vertical stresses and the compressibility of the sediments' pore volume. This is because in an overpressured basin the sediments are likely to be more porous than those buried to the same depth in a normal pressure basin. Such sediments are said to be in the state of disequilibrium (Bethke et al. 2007) and thus the disequilibrium technique is used in this study. Compaction is assumed to be irreversible and is defined in terms of a porosity profile in order to observe how rock responds to burial in nature. The following equation is used to describe how the porosity evolves by compaction:

$$\emptyset = \emptyset_0 \exp(-bZ) + \emptyset_1 \qquad [1]$$

In which, Z is the burial depth, b is the compaction coefficient, and ϕ_0 and ϕ_1 are reducible (at the time of deposition) and irreducible (persists even after deep burial) porosities, respectively. As we go deeper, the porosity decreases and asymptotically approaches the value of 1. Large values of b describe sediments that compact rapidly with burial, whereas small values represent sediments whose porosity is preserved to greater depth.

Sediment permeability is the most critical variable in a hydrologic simulation which may vary over many orders of magnitude and therefore could be the principal cause of uncertainty in basin modeling. In this study the permeability of each rock along strata is determined by a correlation to its porosity as below:

$$Log(k_x) = A\emptyset + B \qquad [2]$$

A and B are permeability coefficients and a maximum permeability (k_{max}) is used in order to prevent the correlation from predicting unrealistic values near the basin surface. Permeability anisotropy (k_x/k_z) resulting from the alignment of flat grains within sediments, the interlayering of laminae of varying permeability, and the orientation of fractures and joints is also considered.

Heat transport and the thermal history of the basin are modeled by determining the thermal conductivity of the basin sediments. Since minerals are more conductive than water, thus similar to permeability, thermal conductivity also varies with porosity. Thermal conductivity is assumed to be isotropic in the basin and Equation 3 is used to define the thermal conductivity (k):

$$k = A\emptyset + B \quad [3]$$

Where A = -4.4×10^{-3} and B = 5.35×10^{-3} (Sclater and Christie 1980) are used for all of the rock types in this study.

Diffusion (the molecular process of solute transport) and dispersivity (mechanical transport resulting from the irregular nature of flow through porous media) control the diffusion through basin strata and the effect of hydrodynamic dispersion on solute transport. Diffusion coefficient (D_0), and longitudinal, α_L (along flow direction) and transverse, α_T (across flow direction) dispersivity coefficients are used in the analysis to describe the hydrodynamic diffusion and dispersion. Fluid viscosity varies with fluid temperature and salinity and affects how rapidly groundwater migrates under a given potential gradient through basin strata. Here viscosities of water and salt solutions from Phillips et al. (1980) are used. However, the error in determining viscosity is much smaller than that in estimating permeability, and assigning values to fluid viscosity adds little to the uncertainty in the calculations. In addition, fluid's heat capacity which affects the fluid's ability to redistribute heat within the basin is determined from the rate at which fluid enthalpy (Phillips et al. 1981) changes with temperature. The aforementioned properties are show in Table 1 for each of the rock types.

Furthermore, the salinity of the basin at its top and bottom surfaces are assumed here as 0 and 80000 ppm (1.37 molal), respectively (Midwest Geological Sequestration Consortium 2005). Note that sub-aerial seawater evaporation is the primary source of salinity of the fluids in the Illinois Basin and evaporate dissolution is a minor component of total salinity (Walter et al. 1990; Stuebner et al. 1993; Kesler et al. 1995; Viets et al. 1996).

Table 1. Properties of the rock types present in the Illinois Basin (data from Bushbach and Bond 1974; Ranganathan 1993; Bethke et al. 2007).

Property	Siltstone	Shale	Sandstone	Dolomite
ϕ_0	0.25	0.55	0.4	0.04
ϕ_1	0.02	0.05	0.05	0.01
b (km^{-1})	0.6	0.85	0.5	0.6
A	15	8	15	15
B	-3	-7	-3	-3
k_x/k_z	10	10	2.5	10
k_{max} (darcy)	2	1	1	0.0001
G_S	2.65	2.74	2.65	2.55
D_0 (cm^2/sec)	2.3×10^{-7}	10^{-6}	10^{-6}	9.6×10^{-10}
α_L (cm)	1000	1000	1000	1000
α_T (cm)	100	100	100	100

2.2 Arrangement of Strata in the Basin and the Evolution of the Basin through Time

After setting the properties for the rock types and fluid, the stratigraphy of the Illinois Basin is defined by dividing the basin into six time-stratigraphic units of Pleistocene, Pennsylvanian, Mississippian, Devonian, Silurian, Ordovician, and Cambrian layers. Thickness, composition (as fractions of each rock type within the unit), and time of deposition of each stratigraphic unit (assuming a uniform rate of deposition after the completion of the previous unit) are specified. Arithmetic and harmonic averaging techniques are used to average rock type properties of composite strata along horizontal (x-direction) and vertical (z-direction) directions, respectively. This further adds to the formation anisotropy. Figure 2 shows the analyzed profile through Christian county (point B in Fig. 1) to Livingston county (point B' in Fig. 1) and Table 2 presents the geological times and compositions of each unit.

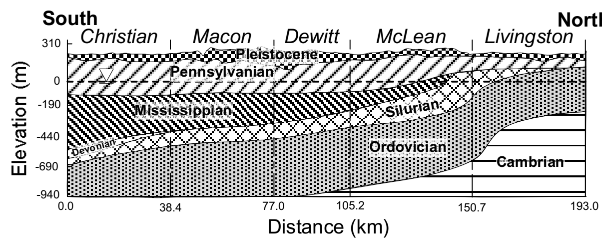


Figure 2. Stratigraphic profile of the Illinois Basin through B to B' (see Fig. 1)

Table 2. Geological times and compositions of the stratigraphic units in Illinois Basin (after Leetaru 2000).

Rock period	Age (10^6 years ago)	Composition
Pleistocene (Quaternary)	0.01 - 1.8	Siltstone (100%)
Pennsylvanian	290 – 323	Shale (100%)
Mississippian	323 – 354	Shale (75%) and Sandstone (25%)
Devonian	354 – 417	Dolomite (100%)
Silurian	417 – 443	Dolomite (100%)
Ordovician	443 – 490	Shale (40%) and Sandstone (60%)
Cambrian	490 – 543	Shale (17%) and Sandstone (83%)

The analysis is performed after setting all input data. It is assumed that the flow regime, temperature distribution, and solute distribution are at a steady state and had sufficient time to adjust to the basin configuration. The top surface of the basin is assumed to be open to groundwater flow and the bottom and sides of the basin are barriers to groundwater flow. Groundwater flow rate is calculated using Darcy's law which accounts for the convective forces resulting from lateral variation in fluid density; and salinity distribution is determined by solving the solute transport equations which account for the effects of molecular dissolution, hydrodynamic dispersion, and groundwater advection.

3 RESULTS AND DISCUSSION

Figure 3 shows the hydraulic potentials and flow directions in the Illinois Basin (at 25^{o}C ground surface temperature) and indicates that surface topography significantly affects groundwater flow. Hydraulic potential increases in hummocks and decreases in surface depression areas causing the hydraulic potential to vary across the basin surface and giving rise to groundwater flow. Note that topographically driven flow is generally accepted as the most plausible mechanism to explain regional flow of basin brines and the temperatures calculated in these deposits (Bethke and Marshak 1990).

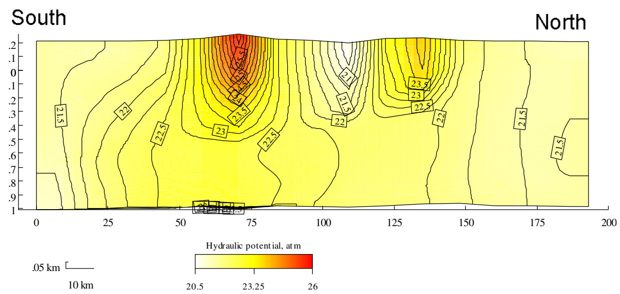


Figure 3. Color map and contours of hydraulic potential in the Illinois Basin at 25^{o}C ground surface temperature.

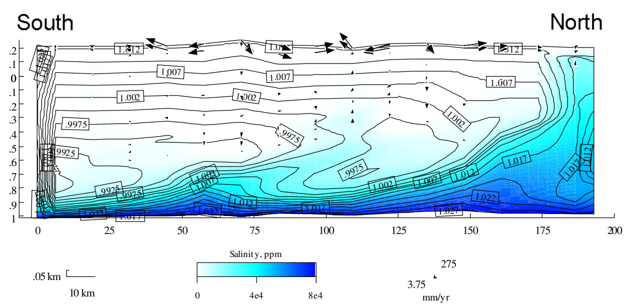


Figure 4. Distribution of groundwater salinity (color map) and density (line contours) at 25^{o}C ground surface temperature.

Figure 4 presents the salinity and density distribution of the groundwater in the basin at 25^{o}C ground surface temperature. According to this figure salinity is larger at the northern parts of the basin (which is consistent with previously published observations) where most of the Cambrian formations are located (Kelly and Wilson 2002) and although the overlying Pennsylvanian rocks that are mostly shale form confining units that impede the downward movement of the freshwater and the flushing of saltwater from the underlying aquifers, the groundwater salinity is below US EPA (2000) standards (maximum salinity of 250 ppm for drinkable water). Contamination of ground water and surface water by salt is a common occurrence in urban areas (Naftz and Spangler 1994; Buttle and Labadia 1999; Mason et al. 1999) and has adversly affected municipal and private water supplies in Illinois as well as other states (Clearly 1978; Moyland 1980; Kelly and Wilson 2002). According to Kelly and Wilson (2002) salinity has increased in shallow waters in north-eastern Illinois since 1980s. Elevated concentration of salt in ground water and surface water within a wetland's watershed and recharge areas can also destroy rare and endangered plant species (Wilcox 1986a, b; Grootjans et al. 1988; Panno et al. 1999).

Moreover, fluid density is affected by salinity and temperature gradient. It is larger than unity, at the lower elevations due to high salinity and at upper elevations of the basin due to its cooler temperatures. Consideration of the effects of variations in water density in aquifers would lead to some important implications about problems related to gas storage, oil accumulation, origin of brines, and underground waste disposal (Bond 1972).

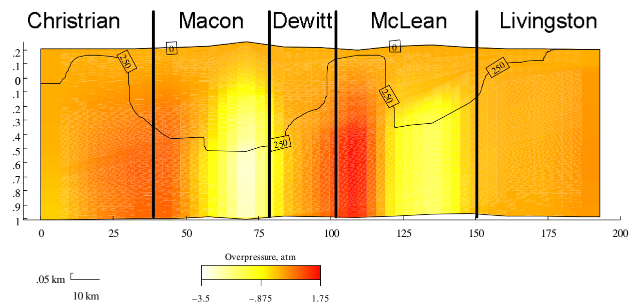


Figure 5. Overpressure color map and maximum potable water salinity contour at 25^{o}C ground surface temperature.

Overpressures (geopressures) are developed by rapid compaction and low permeabilities. These are zones of hydraulic pressures larger than hydrostatic pressure and are beneath depression areas. It is practically difficult and dangerous to drill in these areas and have important roles in faulting, structural formations and localizing petroleum reservoirs. According to Figure 5 which illustrates overpressure color map and the acceptable salinity margin of 250 ppm; water well drilling is best suited in areas of low overpressures and acceptable salinities (<250 ppm). In the overpressure areas of Figure 5, water would tend to move upward towards the shallow depth due to buoyancy and sediments would tend to be looser than those at normal pressures since the pore fluid relieves the sediment framework of much of the weight of the overlying sediments (Bethke et al. 2007).

Figure 6 shows the salinity distributions in winter (0^o C ground surface temperature) for the Illinois Basin indicating that as temperature decreases (e.g. we approach winter) groundwater salinity increases in comparison to that in summer shown in Figure 4 and therefore fluid density also increases (Fig. 7). This further leads to larger hydraulic potentials (Fig. 7), overpressures (Fig. 8), and thermal convections to develop in colder seasons.

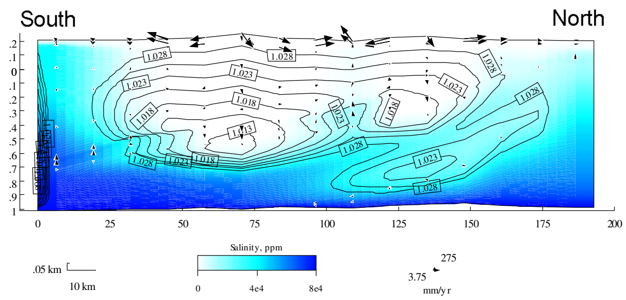
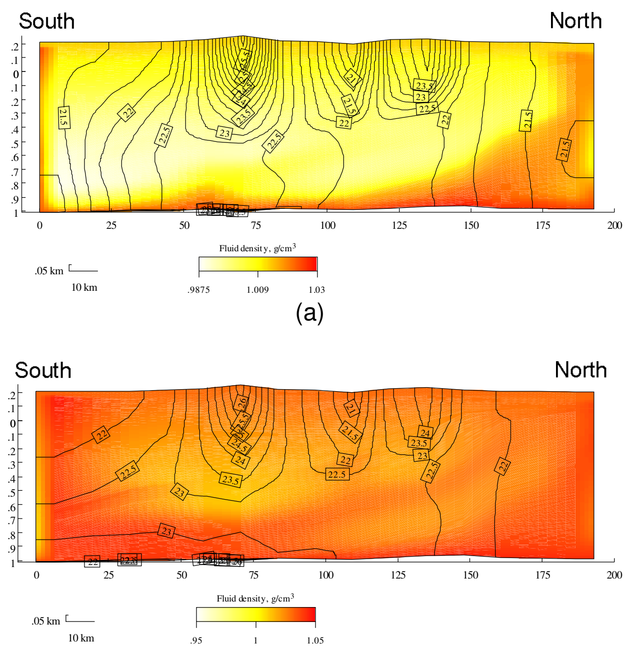


Figure 6. Salinity distribution in Illinois Basin at ground surface temperature of 0°C (in winter)



(a)

(b)

Figure 7. Fluid density distribution color maps and hydraulic potential line contours in Illinois Basin (a) in summer (ground surface temperature of 25°C) and (b) in winter (ground surface temperature of 0°C)

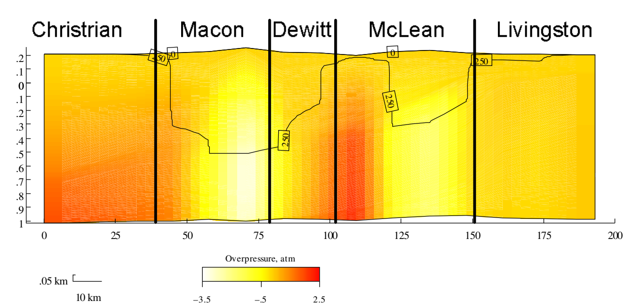


Figure 8. Overpressure color maps and maximum potable water salinity contours in Illinois Basin in winter (ground surface temperature of 0°C)

Comparing salinity distributions in Figures 4 and 6 further indicates that in Christian county fresh water is accessible at shallow depths (<100 m) in summer but in winter drinkable water (salinity < 250 ppm) is not obtainable in this county. Similarly in Livingston County, the maximum depths of potable water decrease in winter. Such findings are particularly important since proper water is essential to an expanding economy and the location of new industries, the growth of communities, and any forms of land improvement are controlled by the water resources of an area.

4 CONCLUSIONS

Groundwater flow, salinity distribution, and effects of surface temperature on the groundwater flow and salinity in the Illinois Basin are modeled. The model results indicate that ground surface topography significantly affects groundwater flow whereas hydraulic potential increases in hummocks and decreases in surface depression areas. Fluid density is affected by salinity and temperature, which then affects hydraulic potential in the basin. And areas of low overpressures and acceptable salinities (<250ppm) can be defined to locate potable water wells. The acceptable depths and location of such wells become more limited as the temperature decreases.

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