Environmental Protection Research
https://ojs.wiserpub.com/index.php/EPR/

Research Article

The Impact of Climate Change and Urbanization on Groundwater Levels: A System Dynamics Model Analysis

Amin Asadollahi, Asyeh Sohrabifar, Amrit B Ghimire, Bishal Poudel, Sangmin Shin*

School of Civil, Environmental and Infrastructure Engineering, Southern Illinois University, Carbondale, USA
E-mail: sangmin.shin@siu.edu

Received: 2 October 2023; **Revised:** 21 November 2023; **Accepted:** 15 December 2023

Abstract: Climate change and population growth have placed increasing stress on groundwater resources. Effective management of groundwater resources is crucial for promoting sustainable development, especially in areas heavily reliant on groundwater supply. However, sustainable groundwater management is more complex due to various factors affecting key drivers and their feedback interactions. In this regard, this study aims to examine the key driving forces and their interplay concerning fluctuations in groundwater levels within a study area in Illinois, United States, which heavily relies on groundwater for water supply. To achieve this objective, a system dynamics (SD) simulation model was developed, utilizing hydrology, climate, and urbanization data spanning from 2010 to 2020. Through calibration and validation of the SD model with historical data, the model demonstrated reliable simulation capabilities for groundwater levels. Additionally, sensitivity analysis and exploration of water resource scenarios were conducted to evaluate the critical factors influencing groundwater levels. Results revealed that population dynamics, agricultural land, and groundwater recharge were analyzed as key drivers influencing the change in groundwater level for the study area, among the climate and urbanization factors that had different contributions to the groundwater dynamics. A 10% increase in population, agricultural land, and groundwater recharge led to a decrease of approximately 5.5% and increases of 4.5% and 4.27% in groundwater levels, respectively. The results of the four-scenario analysis indicated that both climate change and urbanization exerted significant and adverse impacts on the groundwater level in the study area. These scenarios represented prominent and worst-case situations, highlighting the potential challenges and risks associated with the combination of these factors, which resulted in about a 77 mm decrease in groundwater levels by 2030. Overall, given limited data availability for SD model parameterization, the study emphasizes the need to consider the effects of both urbanization and climate change on groundwater supplies in decision-making for sustainable groundwater management, as well as the need for adequate management measures to maintain the long-term usage of groundwater resources.

Keywords: groundwater, water resources management, SD, climate change, water sustainability, urbanization

1. Introduction

Groundwater plays a vital role in the hydrologic system, but obtaining precise information about its quantity, extent, and quality often remains challenging and uncertain. Multiple factors, including climate, geography, and geological structure, influence the recharge rates and storage capacity of aquifers. These complex interactions

DOI: https://doi.org/10.37256/epr.4120243531

subsequently impact the overall dynamics of groundwater availability and distribution [1, 2]. Furthermore, the quantity and quality of groundwater supplies are significantly influenced by human activities like urbanization, groundwater pumping, and land use and land cover (LULC), which can complicate decision-making on resource management [3, 4]. Groundwater is also a critical water resource for both residential and agricultural use, with agriculture being the world's greatest consumer of freshwater [5].

Since groundwater is an invisible resource and its management system is complex (e.g., broad spatial distribution with contamination entry points and interactions with surface water resources), its depletion and contamination can pose challenges and require substantial time for remediation [6]. A region's water balance is monitored and managed to sustain groundwater supply and related ecosystem services. This approach ensures the availability and quality of groundwater while also preserving the ecosystems that rely on it. In addition to the environmental needs, groundwater availability also affects food security and local economic growth because sectors such as agriculture, manufacturing, and energy consume the groundwater for their food, industrial, and energy production [7].

According to the previous studies [8-11], the components of climate (e.g., increased temperatures and changes in precipitation patterns) and urbanization (increased water demand and changes in land covers) substantially influence groundwater availability, especially in terms of maintaining a supply-demand balance. While both factors have an impact, a previous study found that urbanization can have a more immediate and direct impact on groundwater supplies compared to climate change [8]. Rapid urbanization leads to an increase in water demand, alters the land cover, and creates more impervious surfaces, all of which have significant impacts on groundwater recharge and availability. Changes in hydrological processes caused by urbanization, such as lower infiltration rates and higher surface runoff, can lead to lower groundwater recharge rates and changed groundwater dynamics [9].

However, it is important to consider that the precise effects of climate change on groundwater supplies can vary depending on local climatic factors, including modifications to precipitation patterns, temperature, and evaporation rates [10]. A comprehensive examination is required to understand the implications of climate change and urbanization on groundwater supply and quality, specifically their impact on groundwater depletion and deterioration.

Sustainable groundwater management is critical for ensuring a reliable freshwater supply across various sectors. However, many places are already suffering from reservoir depletion, highlighting the critical need for long-term management strategies [11]. To estimate existing and future groundwater conditions, reliable methodologies and tools for data extraction and analysis are necessary. Indeed, water resources management is a complex system that involves dynamic feedback interactions among various interconnected sectors, such as society, finance, and climate. These interactions play a crucial role in determining the effects of different water management options [12]. Thus, decision-making in water resources management and understanding its effects require a system modeling approach. In this regard, system dynamics (SD) models have been employed in several studies to understand the effects of the sustainable management of groundwater resources within a systems framework. For instance, Barati et al. [13] suggested improving infiltration and reducing extraction rates as key strategies for successful groundwater management, using an SD model. Similarly, Ranjan et al. [14] evaluated how groundwater supplies in coastal aquifers are affected by climate and land use changes using an SD model. The impacts of various economic and climatic change scenarios on groundwater dynamics and depletion were also examined by Balali et al. [15] using an SD model. Huang et al. [16] also used an SD model to analyze management options for reducing land subsidence caused by groundwater depletion. They also conducted simulations to assess the availability and demand for water resources. Even though these studies have made efforts to evaluate and explain groundwater systems, they have not fully exploited the knowledge of how the groundwater table has changed over time in response to climate change and urbanization factors. Additionally, for groundwater resource management (e.g., prioritizing management options), there still needs further investigation to determine whether factors related to climate or those linked to urbanization are more vulnerable to changes in groundwater.

In this regard, this study investigates the dynamic contributions of climate and urbanization (LULC) to groundwater balance in supply and demand using the SD modeling approach for a study area in McHenry County in northern Illinois, United States (U.S.). The contributions of this study include providing an SD-based decision support model for groundwater supply-demand balance analysis to evaluate the critical drivers and water management effects and providing insights for policymakers and decision-makers into climate-resilient groundwater management actions, plans, and policies in the long term.

2. Materials and methods

2.1 *Study area*

McHenry County is in the state of Illinois, U.S., with coordinates ranging from 88.200° W to 88.706° W longitude and 42.155° N to 42.495° N latitude. The county's primary aquifer is the unconsolidated sand and gravel aquifer, which covers an area of 1,580 km^2 [17]. This region has hot and humid summers and cold and snowy winters, and it is highly prone to extreme weather conditions such as strong winds, blizzards, thunderstorms, tornadoes, and floods [18]. In recent years, the average annual precipitation in this area has been 959 mm, with temperatures ranging from 12 °C in January to 29 °C in July [19]. Figure 1 shows the study area's location and the types of LULC. The McHenry County watershed is 731 feet to 1,189 feet above sea level. In 2020, McHenry County's land cover comprised 0.18% forest, 11.53% grassland, 0.61% surface water, 76.67% agricultural land, and 11.01% urbanized area.

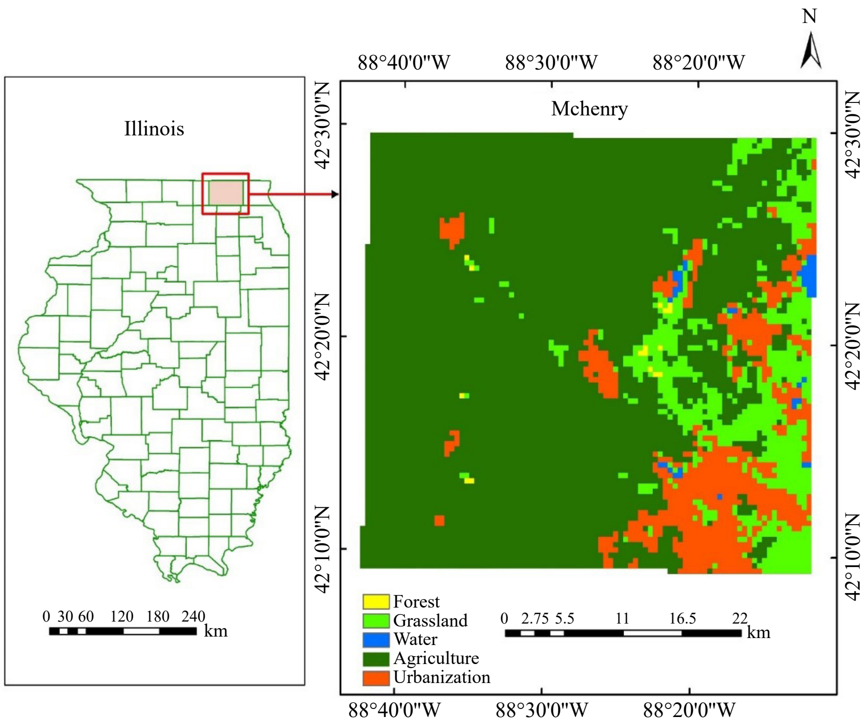

Figure 1. Study area map

2.2 *Data collection*

The hydrological study of the study area requires the collection of various data types, such as topography data, metrological data, and hydrological data. The basic topographic data necessary for hydrologic modeling include the Digital Elevation Model (DEM) and LULC data. To detect changes from 2010 to 2020, all topographic data were obtained from a publicly accessible internet source and pre-processed in ArcGIS 10.8. DEM data was obtained from the websites of the U.S. Department of Agriculture-National Resources Conservation Service (USDA-NRCS) through this link: https://datagateway.nrcs.usda.gov/. The LULC dataset was also obtained from the U.S. Geological Survey (USGS) Earth Explorer at this location: https://earthexplorer.usgs.gov/.

McHenry County, Illinois, has experienced diverse and dynamic groundwater conditions influenced by factors such as precipitation, land use, and geology. With 37 wells ranging from 20 to 345 feet deep, groundwater levels undergo fluctuation over time, including periods of recharge and depletion [20]. The selection of this area for this study was based on its heavy reliance on groundwater as the primary source of drinking water for both individuals and businesses in the region. Therefore, it is vital to comprehend the levels and fluctuations of groundwater to ensure a dependable and sustainable water supply.

Furthermore, McHenry County is expected to experience a substantial population surge by 2030, with projections indicating a 47% increase to reach 486,000 compared to the year 2000. Alongside this rapid population growth, groundwater withdrawal is anticipated to rise significantly to 67.5 million gallons per day, representing a 49% increase compared to 2000 [21]. Consequently, with such alarming trends in population growth and groundwater consumption, conducting a comprehensive study on potential future water shortages becomes imperative [22, 23]. Therefore, continuous research of groundwater will be crucial for ecological preservation, sustainable water management, and societal well-being. This knowledge will also assist policymakers and stakeholders in developing plans that satisfy communities' changing requirements while facilitating successful groundwater management.

2.3 *SD model*

SD modeling provides a robust and analytical approach for comprehending and managing complex systems by understanding inherent feedback interactions and the system's non-linear behaviors [12]. The SD approach depends heavily on quantitative data to generate feedback models. Through the continuous collection and review of these feedback models, concepts are organized and categorized to form dynamic hypotheses—feedback interactions among the system components, which determine the dynamics and non-linearity of system behaviors [24, 25].

In SD modeling, a causal loop diagram is used to evaluate the major components and their feedback loops, which consist of a positive feedback loop (reinforcing) or a negative feedback loop (balancing) a given change in a system variable [24]. A feedback loop is a succession of causes and effects (causal links) such that a change in a given variable travels around the loop and comes back to affect the originating variable. If an initial increase in a variable in a feedback loop eventually results in an increasing effect on the same variable, then the feedback loop is identified as a 'reinforcing or positive' feedback loop. If an initial increase in a variable eventually results in a decreasing effect on the same variable, then the feedback loop is identified as a negative, counteracting, or balancing loop. The positive feedback loops could potentially stimulate unstable exponential growth or collapse patterns in system behavior. For instance, Figure 2 is a causal loop diagram that represents the feedback loops included in a groundwater supply system. It shows how variables such as land use, population, climate change, and groundwater table change are interconnected and influence each other.

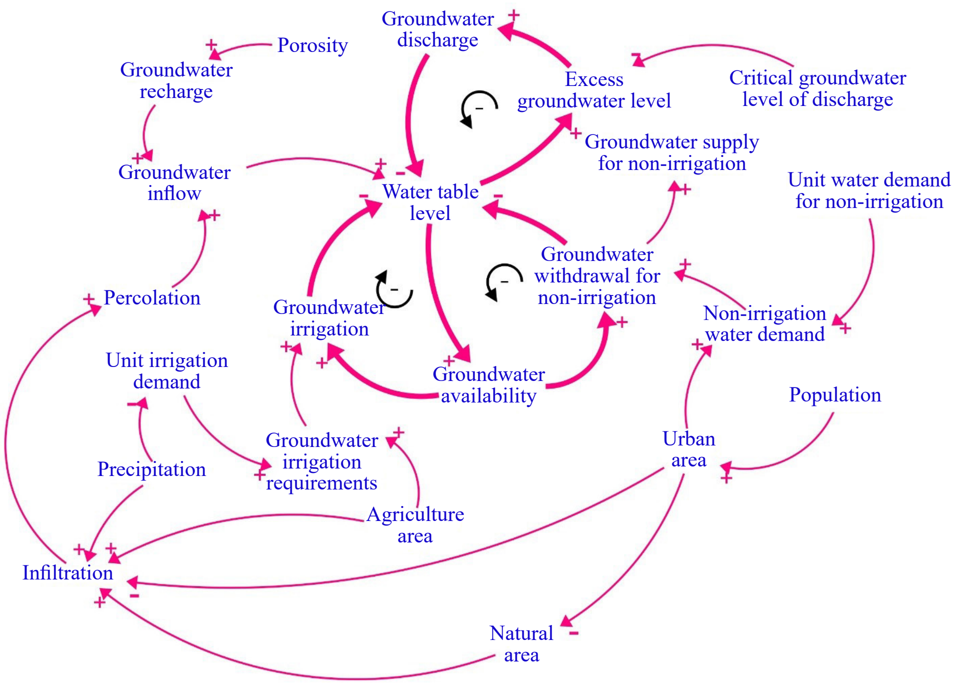

Figure 2. A causal loop diagram for a groundwater supply system

This causal loop diagram forms the foundation of the proposed SD model, which focuses on capturing the dynamic interactions among water supply, water demand, and land subsidence. By modeling these interactions, the SD model can provide insights into the complex feedback mechanisms and help assess the potential impacts of different interventions or policies aimed at mitigating land subsidence.

Overall, the capability of SD modeling to elucidate the endogenous structure of systems and the interplay between structure and behavior is vital for comprehending the complexity of real-world systems. By understanding the emergent behavior of these systems and the underlying mechanisms that drive them, decision-makers can develop effective strategies for optimizing system performance and improving decision-making processes.

Stock-flow diagrams for the study area to quantify the causal loop diagram in Figure 2 were developed in adherence to the principles of SD modeling, incorporating a series of causal loops and mathematical equations (Figure 3). These diagrams serve as graphical representations of the dynamic relationships between stocks (accumulations) and flows (rates of change) within the groundwater system in the study area [16]. By employing SD principles, these diagrams enable a comprehensive understanding of the feedback mechanisms and interdependencies that drive the behavior of the McHenry County groundwater system, facilitating the analysis and simulation of various scenarios and policy interventions. The inclusion of causal loops and mathematical equations further enhances the rigor and accuracy of the SD model, allowing for a more robust exploration of the system's dynamics and the potential effects of different factors and policies.

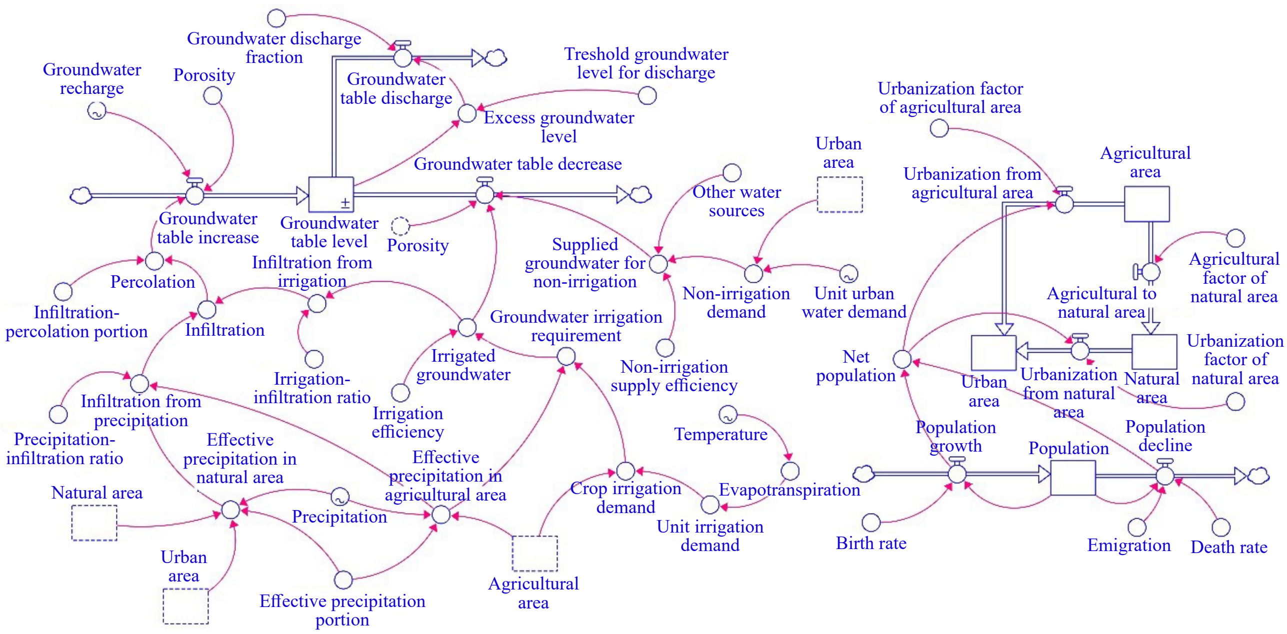

Figure 3. Stock-flow diagram depicting the groundwater system in McHenry County

The SD model in Figure 3 consists of land use, population, and groundwater sectors. The land use sector considers three distinct categories: agricultural, urban, and natural lands. Notably, water demand for groundwater supply is determined by the irrigation water demand depending on the area of agricultural land and the non-irrigation water demand based on the urban area.

The number of populations evaluated in the population sector affects the change in urban, agricultural, and natural lands. The birth rate and death rate contribute to population growth or decline. Analyzing these relationships suggests insights into demographic changes and urban development, which can be useful for urban planning, resource management, and policy-making purposes.

The groundwater sector in the SD model for the McHenry County groundwater system is influenced by parameters such as groundwater discharge, recharge, infiltration, percolation, irrigation, and precipitation. Groundwater discharge involves the outflow of groundwater, which is affected by natural processes and human activities like irrigation. Groundwater recharge, on the other hand, represents replenishment and is influenced by infiltration, irrigation, and precipitation. Adequate precipitation ensures sustainable recharge, while changes in precipitation patterns can impact groundwater levels. Understanding these relationships is crucial for sustainable groundwater management and enables decision-makers to optimize resources and address challenges effectively.

2.4 *SD model formulations*

2.4.1 *Land use section*

The land use section in the SD model focuses on understanding the relationships between land use categories (agricultural, urban, and natural lands) and their impacts on groundwater dynamics. The equations in this section are connected to the groundwater section, as land use influences parameters such as urbanization and infiltration. Equations 1 and 2 in the land use section determine the urbanization of agricultural and natural lands, respectively, based on the net population change and urbanization factors. These equations quantify the conversion of agricultural and natural lands into urban areas, considering the impact of population changes.

$$\text{Urbanization from agricultural land} = \text{urbanization factor of agricultural} \times \text{net population change} \tag{1}$$

$$\text{Urbanization from natural land} = \text{net population change} \times \text{urbanization factor of natural land} \tag{2}$$

2.4.2 *Population section*

The population section in the SD model focuses on understanding the dynamics of population growth and decline, which have implications for land use and groundwater dynamics. The equations in this section are interconnected with the land use and groundwater sections, as population changes influence land use and water demand. Equations 3 and 4 in the population section calculate population decline and growth, respectively. Equation 3 considers the current population, death rate, and emigration, while Equation 4 considers the birth rate and the current population. These equations provide insights into demographic changes affecting urban development, land use patterns, and water demand. The population changes calculated in Equations 3 and 4 are utilized in Equations 1 and 2 in the land use section to determine the urbanization of agricultural and natural lands. This demonstrates the interconnectedness between population dynamics, land use changes, and their effects on groundwater dynamics.

$$\text{Population decline} = \text{population} \times (\text{death rate} + \text{emigration}) \tag{3}$$

$$\text{Population growth} = \text{birth rate} \times \text{population} \tag{4}$$

2.4.3 *Groundwater section*

The groundwater section in the SD model focuses on understanding the dynamics of groundwater within the McHenry County groundwater system. This section utilizes a set of equations to explore the relationships and effects of various variables on groundwater behavior. Groundwater table decrease (Equation 5) calculates the decrease in the elevation of the water table, considering the contributions from groundwater irrigated and supplied for non-irrigation purposes. It takes into account the porosity of the aquifer and the overall groundwater discharge fraction. Groundwater table increase (Equation 6) determines the increase in the elevation of the water table and accounts for percolation and groundwater recharge. It considers the porosity of the aquifer and the inflow from both percolation and recharge. Groundwater table discharge (Equation 7) estimates the discharge of groundwater from the system. It considers the excess groundwater level and the groundwater discharge fraction, which represents the portion of excess groundwater that is discharged. To consider the precipitation contributing to infiltration and groundwater recharge potentially, this study considered the effective precipitation coefficient for different land covers. Effective precipitation in natural land (Equation 8) calculates the effective precipitation that contributes to groundwater recharge in natural areas. It takes into account the precipitation, the extent of natural and urban areas, and the effective precipitation portion. Effective precipitation in agricultural land (Equation 9) determines the precipitation that contributes to groundwater recharge in agricultural areas. It considers the precipitation, the agricultural area, and the effective precipitation portion.

$$\text{Groundwater table decrease} = \frac{\text{irrigated groundwater} + \text{supplied groundwater for non irrigation}}{\text{porosity}} \tag{5}$$

$$\text{Groundwater table increase} = \frac{\text{percolation}}{\text{porosity}} + \frac{\text{groundwater recharge}}{\text{porosity}} \tag{6}$$

$$\text{Groundwater table discharge} = (-\text{ excess groundwater level}) \times \text{groundwater discharge fraction} \tag{7}$$

$$\begin{aligned}\text{Effective precipitation in natural land} = {} & \text{precipitation} \times (\text{natural area} + \text{urban area}) \\ & \times \text{effective precipitation portion}\end{aligned} \tag{8}$$

$$\begin{aligned}\text{Effective precipitation in agricultural land} = {} & \text{precipitation} \times \text{agricultural area} \\ & \times \text{effective precipitation portion}\end{aligned} \tag{9}$$

These equations provide insights into groundwater dynamics, including groundwater extraction, percolation, recharge, discharge, and the impact of effective precipitation in different land areas. They help analyze the relationships between these variables and gain a better understanding of the overall groundwater behavior in the system.

2.4.4 *Groundwater supply section*

Using the SD model, this study investigates the effects of two critical parameters: urbanization and climate change. Urbanization involves the expansion of urban areas, which leads to increased impervious surfaces such as roads and buildings. These impermeable surfaces disrupt the natural infiltration of water into the ground, reducing groundwater recharge. Additionally, urban areas typically exhibit higher water consumption demands due to increased population and economic activities, intensifying the strain on groundwater resources and contributing to depletion. Combining these equations provides an understanding of the different sources and factors contributing to infiltration. Infiltration can occur through irrigation practices, where groundwater is applied to the land, and through precipitation, which affects both natural and agricultural areas. The infiltration coefficient was estimated to range between 0.32 and 0.54, indicating the proportion of water that enters the soil. Furthermore, estimates indicate that water losses from groundwater range between 0.13 and 0.21, representing the fraction of groundwater that is lost or does not contribute to groundwater recharge [26]. Analyzing the relationships between these variables helps us comprehend the overall water movement into the ground and its implications for groundwater availability and recharge.

$$\text{Infiltration} = \text{infiltration from irrigation} + \text{infiltration from precipitation} \tag{10}$$

$$\text{Infiltration from irrigation} = \text{irrigated groundwater} \times \text{irrigated infiltration ratio} \tag{11}$$

$$\begin{aligned}\text{Infiltration from precipitation} = {} & (\text{effective precipitation in natural land} + \text{effective precipitation} \\ & \text{in agricultural land}) \times \text{precipitation infiltration ratio}\end{aligned} \tag{12}$$

Changes in precipitation patterns, including alterations in rainfall intensity, percolation, irrigation, frequency, and distribution, directly impact groundwater recharge rates. Shifts in temperature and evapotranspiration rates also influence the overall water balance, affecting groundwater availability. Equation 18 provides an estimation of the relationship between temperature and evaporation for the study area [26]. These equations are interconnected and provide a comprehensive understanding of the factors influencing water demand, groundwater requirements for irrigation and non-irrigation purposes, and the movement of water through infiltration and percolation processes. Analyzing these relationships helps gain insights into water management, efficiency, and sustainability in various contexts, such as agriculture and urban areas. Non-irrigation efficiency and irrigation efficiency coefficients were used to consider the transmission losses in groundwater irrigation and supply.

$$\text{Percolation} = \text{infiltration} \times \text{infiltration percolation portion} \tag{13}$$

$$\text{Irrigated groundwater} = \frac{\text{groundwater irrigated requirements}}{\text{irrigation efficiency}} \tag{14}$$

$$\text{Groundwater irrigation requirements} = \text{crop irrigation demand} - \text{effective precipitation in agricultural land} \tag{15}$$

$$\text{Crop irrigation demand} = \text{unit irrigation demand} \times \text{agricultural area} \tag{16}$$

$$\text{Unit irrigation demand} = 5{,}000 + \text{evapotranspiration} \tag{17}$$

$$\text{Evapotranspiration} = (0.142 \times \text{temperature} + 1.095) \times (\text{temperature} + 17.8) \times 0.036 \times 25.4 \tag{18}$$

$$\text{Supplied groundwater for non-irrigation} = \frac{\text{non-irrigation demand} - \text{other water sources}}{\text{non-irrigation supply efficiency}} \tag{19}$$

$$\text{Non-irrigation supply efficiency} = \text{unit urbanization water demand} \times \text{urbanization area} \tag{20}$$

Overall, the quantitative understanding of these interconnected components and their relationships using these equations provides valuable insights into population dynamics, urbanization, groundwater behavior, water management, and a deeper understanding of the complex groundwater system. By utilizing this knowledge, system managers can make informed decisions and implement strategies to address the challenges associated with population growth, urbanization, and water resource management.

2.5 *Verifying the developed SD model*

The verification of the developed SD model aims to test the model's ability to achieve a close alignment between the model's outputs and their historical data and reproduce the behavior of key components qualitatively and quantitatively. Comparing the model's outputs with known or observed data helps evaluate the model's accuracy and reliability [27]. In this context, this study evaluated the performance of the SD model by comparing the model outputs with the observed data for the groundwater level in the study area, urban water demand, total population, and urban area in the study area between 2010 and 2020. A coefficient of determination (R^2) was employed to provide a quantitative assessment of the SD model's performance and accuracy [28]. This statistical metric offers a quantified assessment of the model's ability to mirror historical data, thus aiding in the assessment of its accuracy and overall performance.

In this study, the model verification process provided new estimations of groundwater recharge and groundwater discharge. McHenry County is a humid region where groundwater recharge occurs in all inter-stream areas. Recharge rate estimations for McHenry County are limited to those of Walton [29]. As part of a state-wide study, Walton estimated recharge in the Kishwaukee River basin upstream of Belvidere, Illinois. This basin includes much of western McHenry County. Their study estimated recharge in the area for years of below-normal, normal, and above-normal precipitation at 97,000, 194,000, and 401,000 gallons per day per square mile (gpd/mi^2), respectively. They estimated recharge rates of 125,000 and 127,000 gpd/mi^2, respectively [29]. Discharge from the saturated zone primarily takes place in streams, lakes, wetlands, floodplains, and areas where the capillary fringe intersects the land surface. In these locations, water flows out of the groundwater system [30]. Additionally, a specific portion of groundwater, which surpasses a critical discharge level, is annually discharged into freshwater supplies. This discharge contributes to the availability of freshwater resources. A critical discharge level of -4,500 mm was set as a reference point. The SD model in this study was simulated using Stella® Architect 2.0 software.

2.6 *Identifying critical components*

A comprehensive sensitivity analysis was performed, incorporating the hydrologic budget and other pertinent factors, to determine the critical components that significantly impact groundwater levels within the study area. The primary objective of sensitivity analysis is to assess how the input variables of a model influence its output or response. Thus, the sensitivity analysis can evaluate the relative significance of different variables and their effects on the overall outcomes [31, 32]. Sensitivity analysis facilitates a deeper comprehension of the system's behavior, aids in identifying critical components or parameters, and enables the optimization of decision-making processes. Its ultimate purpose is to enhance the understanding of complex systems and improve the effectiveness of decision-making [33]. The results obtained can potentially help guide the analysis of simulation scenarios. In this sensitivity analysis, the focus was on seven key model variables: precipitation (Pr), temperature (T), groundwater recharge (GR), population (P), agricultural land (AL), urban land (UL), and urban water demand (UWD). The target variable of interest was the water table level in the region. To conduct the sensitivity analysis, a one-at-a-time (OAT) strategy was employed [33]. Each input variable was varied individually while keeping the remaining variables fixed at their nominal values. The aim was to observe the impact of each variable on the model outputs. To assess the sensitivity of each state variable, the selected variables were altered by approximately ±10% over the study period from 2010 to 2020. The model was then executed for each variable's variation, and the corresponding outputs were collected. By employing this OAT strategy and systematically varying the variables, the sensitivity of the model to changes in each variable could be evaluated. The ±10% adjustment allowed for an assessment of the degree of sensitivity for each state variable and provided insights into the influence of the selected variables on the water table level.

2.7 *Analysis of climate and urbanization impacts on groundwater*

Using the developed SD model, what-if tests with various climate and urbanization scenarios were conducted to study how historic or projected changes in climate, population, and land use in combination impacted the groundwater level in the area. Sun et al. [34] examined six scenarios to study the impacts of climate change, population, land use change, and their combinations on groundwater water stress in the southern U.S. The intention of this analysis is to develop an experimental simulation platform that can serve as a valuable tool for water resource planners to address water shortage problems in the long-term strategic management of water resources in the study region. This paper presents four scenarios that compare the variations of the groundwater level response to multiple stressors (Table 1). The base scenario as a reference performance (i.e., water table) of the groundwater system in the study area was considered to compare the performance under water stress conditions with changes in climate, population, and land cover. The base scenario represented the observed values (without change) of average historical climate, population distribution, and land cover conditions in the study area from 2010 to 2020.

Table 1. Different scenarios and descriptions

Scenario	Description
Base run	• Variables used were the average of the observation data from 2010 to 2020
Scenario 1: Climate changes	• Changing climate change variables with constant population and land cover variables
Scenario 2: Demographical change	• Impact of urban water demand increasing under constant climate conditions
Scenario 3: Combined scenarios 1 and 2	• Impact of climate changes and demographical changes
Scenario 4: LULC changes and increase in water demand	• Impacts of LULC changes with an increase in urban water demand

Scenario 1 tests the impacts of climate change on groundwater levels by 2030 without any changes in population or land use. It was assumed that the amount of precipitation had reduced to the minimum level recorded in 2012, which was approximately 650 mm. The average surface temperature in the study area was assumed to increase by about 2 °C, reaching 11 °C in 2030 [34]. Additionally, groundwater recharge is expected to decrease by about 10% from 2020 to 2030 [29].

Scenario 2 investigates the impacts of demographic change—the increase in annual domestic water consumption, specifically driven by population growth—on groundwater levels with constant climate conditions. It was assumed that domestic water demand would rise by approximately 20% by 2030. This increased demand, primarily stemming from population growth and urban expansion in the study area, has significant implications for groundwater resources and supply. As a result, this scenario anticipates a decrease in the overall groundwater level due to the substantial increase in non-irrigation water demand. Managing water resources effectively and considering sustainable water management practices will be important in mitigating the potential impacts on groundwater availability in scenarios of demographic change.

Scenario 3 addresses the combination of Scenarios 1 and 2 to investigate the combined impacts of climate and demographical changes, i.e., changes in temperature and precipitation and an increase in non-irrigation water demand due to urbanization. Thus, this scenario considered that the temperature would increase to 11 °C and precipitation would decrease to the minimum amount of approximately 650 mm. The amount of urban water demand also increases by about 20% at the same time, as described in Table 1.

Scenario 4 examines the impacts of LULC change (deforestation) with a 20% increase in urban water demand on groundwater levels. It was assumed that the agricultural area would increase by approximately 10% due to the need to produce more food. This expansion of agricultural land is expected to come at the expense of natural land, which will decrease in the study area. This scenario considers the trade-off between agricultural needs and the availability of natural land for agricultural expansion.

3. Results and discussion

3.1 *SD model verification*

The validation results of the observed and simulated trends of the groundwater level, urban water demand, population, and urban area were found to be acceptable for the SD model introduced in the previous section. Figure 4 illustrates a commendable agreement between the simulation results and the historical data, signifying a robust correspondence. This suggests that the developed SD model can reproduce the behaviors of different components within the groundwater system and be used to investigate the impacts of groundwater management options on groundwater storage and supply in this study.

3.2 *Critical components of the groundwater system*

The critical components related to climate, population, water demand, and land use in the study area's groundwater system were analyzed through sensitivity analysis. In Figure 5, the individual contributions of various components to the variation of groundwater level are depicted. These components include precipitation, temperature, groundwater recharge, population, urban water demand, urban land, and agricultural land. The analysis reveals that a 10% increase in population leads to an approximate 5.5% decrease in groundwater level. Conversely, a 10% decrease in population results in a 6.1% increase in the water table level. Furthermore, these changes extend to other factors, such as groundwater recharge. Specifically, a 10% increase in groundwater recharge results in a 4.27% increase in groundwater level. Overall, it is noted that population, groundwater recharge (groundwater management option), and agricultural land in the study area are the critical components to the variation of groundwater levels, rather than the climate components (temperature and precipitation). In addition, a 10% increase or decrease in the urban area suggested relatively low impacts on groundwater levels in the study area. These results indicate that human activities such as land use change (e.g., agricultural land), increasing water consumption from population growth, and groundwater management actions can substantially contribute to the groundwater balance in the study area, which can be managed in the water supply and demand domains.

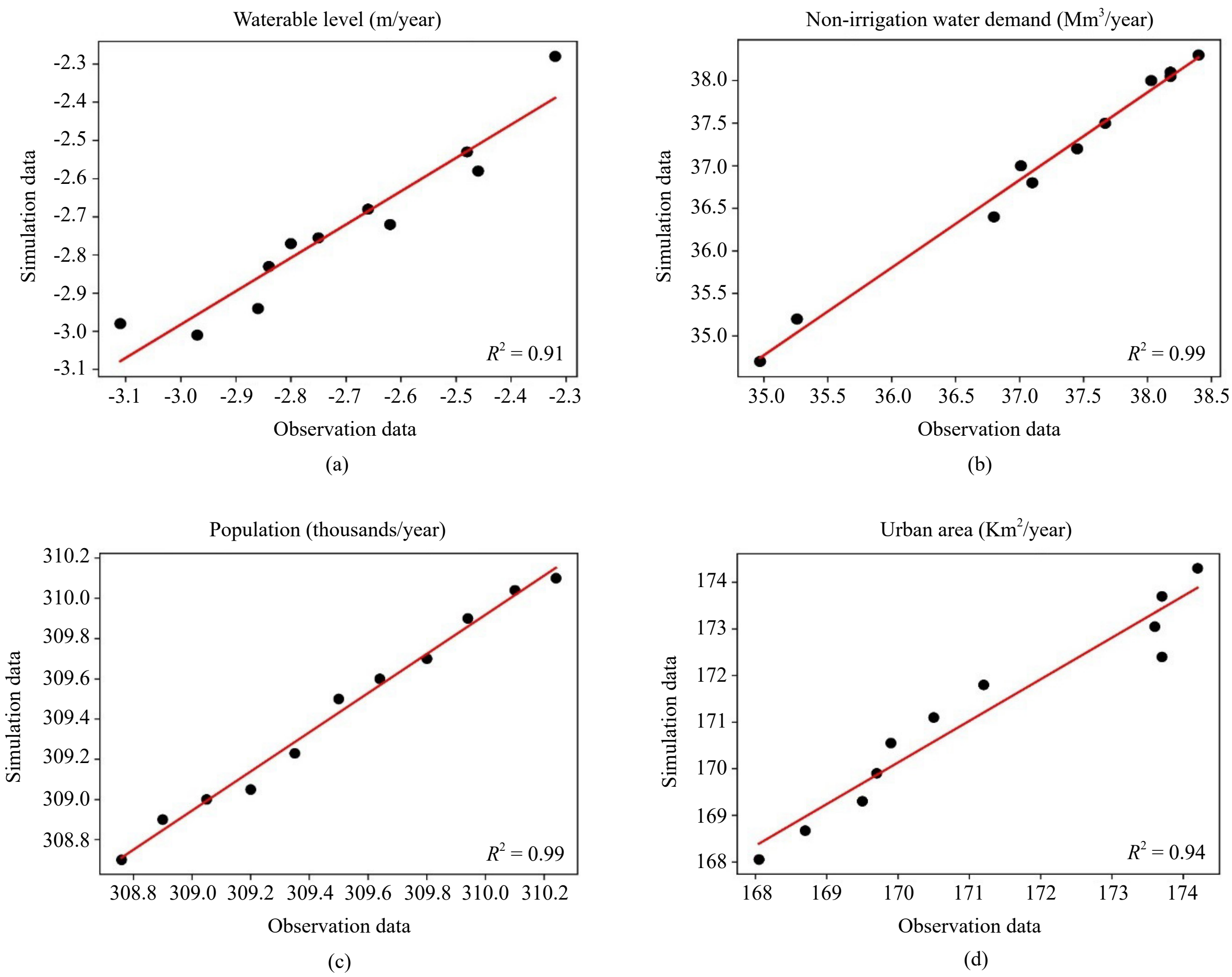

Figure 4. The comparison of observed and simulation data of (a) watertable level, (b) urban water demand, (c) population, and (d) urban area

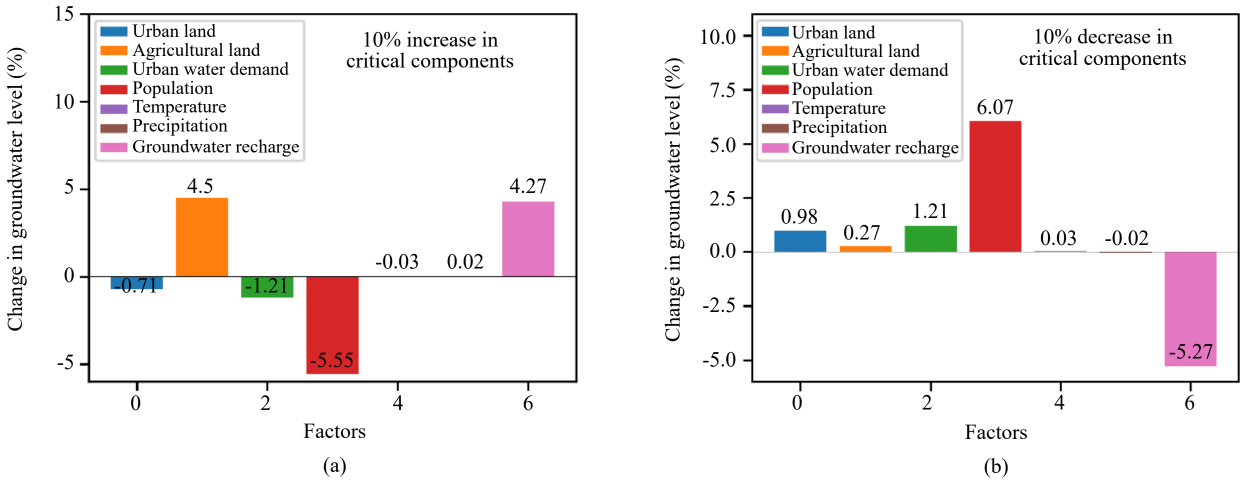

Figure 5. Sensitivity analysis of the model, which included (a) a change in groundwater level (%) after a 10% increase in critical components and (b) a change in groundwater level (%) after a 10% decrease in critical components

3.3 *Groundwater system under climate change and LULC changes*

The groundwater system in the study area was evaluated to understand how the groundwater storage (groundwater level) changes under the impacts of climate, demographical, and LULC changes. Figure 6 shows the variation of the water table under the five scenarios (including the base scenario). Overall, it is observed that the worst-case scenario for the study region is the combination of an increase in domestic water demand and the impacts of climate change, i.e., Scenario 3. The behavior of the groundwater level in response to the scenarios indicates that:

1. It is suggested that domestic water usage can have a significant impact on groundwater levels in the study area (Scenario 2), potentially leading to a decrease in the groundwater level to 2,810 mm below the land surface by 2030. This indicates that the intensive extraction of groundwater for domestic purposes due to the increasing water demand with urbanization will contribute significantly to the depletion of groundwater resources in the study area. Thus, carefully managing and monitoring water demand and implementing water conservation measures are recommended to effectively mitigate the substantial decline in groundwater levels for the sustainability of water resources. Exploring more diverse and alternative water resources can also help mitigate the impacts on groundwater availability. Additionally, Figure 6 indicates that both Scenarios 2 and 4 have nearly the same impact on the groundwater table. In Scenario 4, the increase in agricultural lands led to groundwater recharge, while the decrease in natural land reduced the amount of recharge, which is aligned with the study of Ranjan et al. [14] presenting the impacts of land use changes on groundwater recharge. This suggests that the changes in LULC have the potential to offset or cancel out their respective effects on the groundwater system.
2. The investigation of Scenario 1 suggested that the combination of increasing temperatures and changing precipitation patterns led to a decrease in groundwater recharge, ultimately resulting in a decline in the average levels of the water table in the study area. Scenario 1 notes that climate change has an effect on the decrease of the water table in the area; however, its impact is approximately half that of urbanization. Taylor et al. [10] indicated that the intermittent droughts and decrease in precipitation caused by climate change are projected to have a significant impact on groundwater recharge and groundwater levels, particularly in areas with high population densities, during the first half of the 21st century. Their model predicted a decrease of more than 10% in groundwater recharge and groundwater levels until the 2050s for these regions. According to the scenario, the groundwater level is projected to decrease to approximately 2,780 mm below the surface by 2030. This emphasizes the importance of understanding and managing the impacts of climate change on water resources, as well as implementing sustainable water management practices to mitigate the potential consequences of declining groundwater levels.
3. The combination of climate and demographical changes (Scenario 3) produced a worst-case scenario for groundwater levels. Scenario 3 evaluated the decrease in the groundwater level to approximately 2,830 mm below the surface by 2030. This highlights the potential compounding effects of multiple climate change and urbanization factors on the availability and sustainability of groundwater resources. Ranjan et al. [14] conducted a forecast for coastal aquifers, considering combined climate change and land use scenarios. The study estimated groundwater recharge using the aridity index, which is calculated by dividing the mean annual precipitation (mm) by the mean annual temperature (°C). The findings indicated that, in regions characterized by arid conditions with low precipitation and high temperatures, agricultural lands can play a more significant role in contributing to higher groundwater recharge. However, this study considered the effects of urban lands, demographic changes resulting from urbanization, and agricultural land, revealing the substantial impacts of urbanization on groundwater levels. These impacts are primarily attributed to increased urban water demand and reduced groundwater recharge. Thus, groundwater management strategies to simultaneously implement the options for water demand management and climate mitigation and adaptation are needed to effectively manage the depletion of groundwater and ensure the long-term availability of groundwater in the study area. In addition, the decision-making on climate resilience or sustainability options for water resources management, which mainly focuses on climate change impacts, also needs to consider the integrated impacts or interactions of both climate and socioeconomic components.

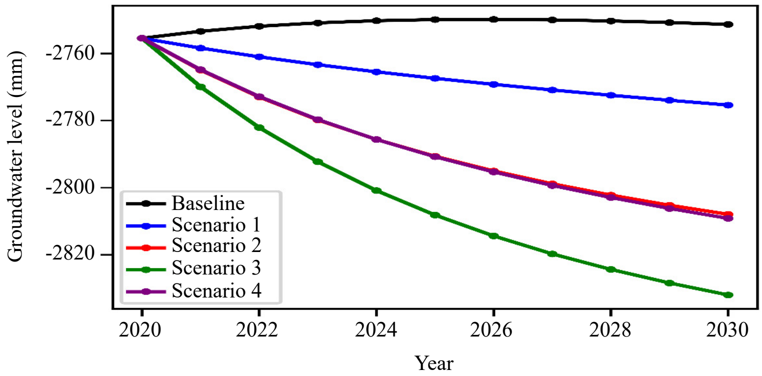

Figure 6. Variation of groundwater level under five scenarios in the period of 2020 to 2030

A challenge in SD modeling in this study is the accurate estimation of evapotranspiration under limited data availability, which can be affected by multiple factors such as humidity, groundwater surface, and surface water interactions. This will exert a significant influence on the water balance evaluated in the SD models. Additionally, incorporating recharge from various sources, such as domestic, industrial, and surface water, would provide a more comprehensive understanding of the groundwater system. Thus, incorporating the various sources of groundwater recharge with the accurate estimation of evapotranspiration into the SD models of this study will provide a more reliable assessment of groundwater levels and the effects of groundwater restoration options.

6. Conclusion

Various drivers of climate, socioeconomic components, and LULC have affected groundwater availability and supply. Decision-making on sustainable groundwater management in short- and long-term periods needs to evaluate and understand the individual or combined impacts of these drivers on groundwater availability, especially for the water service areas highly reliant on groundwater resources. In this regard, this study investigated the relative contributions of climate, demographical, and LULC components to groundwater levels and the potential individual and combined effects of their changes on groundwater levels.

An SD model was developed to analyze the groundwater balance (between water supply and demand) of the McHenry County basin, covering the period from 2010 to 2020. The developed causal loop diagram and stock-flow diagram for the study area's SD modeling were useful for qualitatively understanding feedback interactions across the components of groundwater, demographics, climate, and LULC, determining the behaviors of the groundwater system in the study area.

The results revealed that the critical factors were observed in the components related to population dynamics, groundwater recharge, and agricultural area. Thus, understanding the dynamic relationships between these critical components and groundwater availability will suggest effective strategies to monitor and manage groundwater supply systems under climate and socioeconomic changes. The SD-based groundwater balance model was also useful to analyze the performance (groundwater levels) of the groundwater system in the study area quantitatively.

This study also evaluated the dynamic impacts of climate, demographic, and LULC changes on groundwater storage using the SD model. The scenario analysis results indicated that urbanization factors, such as population growth, domestic water demand, and LULC, have significant and adverse impacts on the groundwater level. In particular, the scenario combining climate and demographical changes produced a worst-case scenario for the groundwater system in the study area. These findings suggested a need to consider the combined impacts of critically affecting drivers in a decision-making process for sustainable groundwater management. Thus, managing and mitigating the effects of climate change, applying land use practices that promote favorable conditions for groundwater recharge, and implementing water demand management are crucial to ensuring the long-term sustainability and availability of groundwater resources in the study area.

Meanwhile, it is important to note that future changes in precipitation patterns and temperature still carry uncertainties, making accurate predictions of future groundwater stress challenging. Therefore, the SD models developed in this study can be further improved by incorporating both the uncertainties in water supply and demand due to climate and socioeconomic changes.

Conflict of interest

There is no conflict of interest for this study.

Acknowledgment

The author expresses his or her thanks to the people helping with this work and acknowledges the valuable suggestions from the peer reviewers.

References

[1] Mukherjee P, Singh CK, Mukherjee S. Delineation of groundwater potential zones in arid region of india—a remote sensing and gis approach. *Water Resources Management*. 2012; 26: 2643-2672. https://doi.org/10.1007/s11269-012-0038-9

[2] Pavelic P, Giordano M, Keraita BN, Ramesh V, Rao T. (eds.) *Groundwater availability and use in Sub-saharan Africa: A review of 15 countries*. Colombo, Sri Lanka: International Water Management Institute; 2012. https://doi.org/10.5337/2012.213

[3] Scheihing KW, Fraser CM, Vargas CR, Kukurić N, Lictevout E. A review of current capacity development practice for fostering groundwater sustainability. *Groundwater for Sustainable Development*. 2022; 19: 100823. https://doi.org/10.1016/j.gsd.2022.100823

[4] Jia X, O'Connor D, Hou D, Jin Y, Li G, Zheng C, et al. Groundwater depletion and contamination: Spatial distribution of groundwater resources sustainability in China. *Science of The Total Environment*. 2019; 672: 551-562. https://doi.org/10.1016/j.scitotenv.2019.03.457

[5] Shahid S, Wang X, Rahman MM, Hasan R, Harun S, Shamsudin S. Spatial assessment of groundwater over-exploitation in northwestern districts of Bangladesh. *Journal of the Geological Society of India*. 2015; 85: 463-470. https://doi.org/10.1007/s12594-015-0238-z

[6] Jakeman AJ, Barreteau O, Hunt RJ, Rinaudo JD, Ross A. *Integrated groundwater management: Concepts, approaches and challenges*. Switzerland: Springer Cham; 2016. https://doi.org/10.1007/978-3-319-23576-9

[7] Sharma KD. Groundwater management for food security. *Current Science*. 2009; 96(11): 1444-1447. https://www.jstor.org/stable/24104769

[8] Srinivasan V, Seto KC, Emerson R, Gorelick SM. The impact of urbanization on water vulnerability: A coupled human-environment system approach for Chennai, India. *Global Environmental Change.* 2013; 23(1): 229-239. http://doi.org/10.1016/j.gloenvcha.2012.10.002

[9] Valentin C, Agus F, Alamban R, Boosaner A, Bricquet JP, Chaplot V, et al. Runoff and sediment losses from 27 upland catchments in Southeast Asia: Impact of rapid land use changes and conservation practices. *Agriculture, Ecosystems & Environment*. 2008; 128(4): 225-238. https://doi.org/10.1016/j.agee.2008.06.004

[10] Taylor RG, Scanion B, Döll P, Rodell M, Beek Rv, Wada Y, et al. Ground water and climate change. *Nature Climate Change*. 2013; 3: 322-329. https://doi.org/10.1038/nclimate1744

[11] Bierkens MFP, Wada Y. Non-renewable groundwater use and groundwater depletion: A review. *Environmental Research Letters*. 2019; 14(6): 063002. https://doi.org/10.1088/1748-9326/ab1a5f

[12] Shin S, Aziz D, Jabeen U, Bano R, Burian SJ. A trade-off balance among urban water infrastructure improvements and financial management to achieve water sustainability. *Urban Water Journal.* 2022; 19(2): 195-207. http://doi.org/10.1080/1573062X.2021.1992452

[13] Barati AA, Azadi H, Scheffran J. A system dynamics model of smart groundwater governance. *Agricultural Water Management.* 2019; 221: 502-518. https://doi.org/10.1016/j.agwat.2019.03.047

[14] Ranjan SP, Kazama S, Sawamoto M. Effects of climate and land use changes on groundwater resources in coastal aquifers. *Journal of Environmental Management.* 2006; 80(1): 25-35. http://doi.org/10.1016/j.jenvman.2005.08.008
[15] Balali H, Viaggi D. Applying a system dynamics approach for modeling groundwater dynamics to depletion under different economical and climate change scenarios. *Water.* 2015; 7(10): 5258-5271. http://doi.org/10.3390/w7105258
[16] Huang YH, Lai YJ, Wu JH. A system dynamics approach to modeling groundwater dynamics: Case study of the Choshui River basin. *Sustainability*. 2022; 14(3): 1371. http://doi.org/10.3390/su14031371
[17] Nicholas JR, Krohelski JT. *Water in sand and gravel deposits in McHenry County, Illinois*. United States Geological Survey. Report number: 83-4048, 1984. https://doi.org/10.3133/wri834048
[18] McHenry County Hazard Mitigation Planning Committee. *McHenry County natural hazards mitigation plan*. McHenry County. 2010. https://mchenrycountyil_redesign.prod.govaccess.org/home/showpublisheddocument/109666/638052303004270000
[19] Weather Spark. *Climate and Average Weather Year Round in McHenry Illinois, United States.* https://weatherspark.com/y/13470/Average-Weather-in-McHenry-Illinois-United-States-Year-Round [Accessed 10th May 2023].
[20] United States Geological Survey. *Groundwater Levels in McHenry County, Illinois*. https://rconnect.usgs.gov/McHenry-groundwater/Index.html [Accessed 12th April 2023].
[21] Gahala AM, Gruhn LR, Murphy JC, Matson LA. *Water quality of sand and gravel aquifers in McHenry County, Illinois, 2020 and comparisons to conditions in 2010*. United States Geological Survey. Report number: 2022-5110, 2022. https://doi.org/10.3133/sir20225110
[22] Dorman A. McHenry County's regional drought might be over, but groundwater concerns linger. *Northwest Herald*. July 30 2022. https://www.shawlocal.com/northwest-herald/news/2022/07/30/mchenry-countys-regional-drought-might-be-over-but-groundwater-concerns-linger/?utm_campaign=snd-autopilot&?utm_medium=social&utm_source=twitter_NWHerald [Accessed 22nd June 2023].
[23] O'Shea J. Collar counties fast depleting their groundwater, turning eyes toward the lake. *Crain's Chicago Business.* September 26 2019. https://www.chicagobusiness.com/crains-forum-water/chicagos-collar-counties-are-fast-depleting-their-groundwater-aquifers-turning [Accessed 22nd June 2023].
[24] Sterman JD. *Business dynamics. System thinking and modelling for a complex world*. New York, United States: MacGraw Hill; 2000.
[25] Stave KA. A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada. *Journal of Environmental Management*. 2003; 67(4): 303-313. https://doi.org/10.1016/S0301-4797(02)00205-0
[26] Bowman JA, Collins MA. *Impacts of irrigation and drought on Illinois ground-water resources*. Illinois State Water Survey. Report number: ISWS/RI-109/87, 1987. https://www.isws.illinois.edu/pubdoc/RI/ISWSRI-109.pdf
[27] Mirchi A, Madani K, Watkins Jr. D, Ahmad S. Synthesis of system dynamics tools for holistic conceptualization of water resources problems. *Water Resources Management.* 2012; 26: 2421-2442. http://doi.org/10.1007/s11269-012-0024-2
[28] Chhipi-Shrestha G, Hewage K, Sadiq R. Water-energy-carbon nexus modeling for urban water systems: System dynamics approach. *Journal of Water Resources Planning and Management*. 2017; 143(6): 04017016. http://doi.org/10.1061/(ASCE)WR.1943-5452.0000765
[29] Walton WC. *Ground-water recharge and runoff in Illinois*. Illinois State Water Survey. Report number: 48, 1965. https://www.isws.illinois.edu/pubdoc/ri/iswsri-48.pdf
[30] Meyer SC. *Ground-water studies for environmental planning, McHenry County, Illinois*. Illinois State Water Survey. Report number: CR 630, 1998. https://www.isws.illinois.edu/pubdoc/CR/ISWSCR-630.pdf
[31] Hoffman FO, Hammonds JS. *An introductory guide to uncertainty analysis in environmental and health risk assessment*. U.S. Department of Energy. 1994. https://inis.iaea.org/collection/NCLCollectionStore/_Public/24/045/24045072.pdf
[32] Chhipi-Shrestha G, Hewage K, Sadiq R. Economic and energy efficiency of net-zero water communities: System dynamics analysis. *Journal of Sustainable Water in the Built Environment.* 2018; 4(3): 04018006. http://doi.org/10.1061/JSWBAY.0000854
[33] Razavi S, Jakeman A, Saltelli A, Prieur C, Iooss B, Borgonovo E, et al. The future of sensitivity analysis: An essential discipline for systems modeling and policy support. *Environmental Modelling & Software.* 2021; 137: 104954. https://doi.org/10.1016/j.envsoft.2020.104954
[34] Sun G, McNulty SG, Lu J, Amatya DM, Liang Y, Kolka RK. Regional annual water yield from forest lands and its response to potential deforestation across the southeastern United States. *Journal of Hydrology*. 2005; 308(1-4): 258-268. https://doi.org/10.1016/j.jhydrol.2004.11.021