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Evaluation of Strategies for Human-Induced Land Subsidence Using System Dynamics

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Land subsidence is a relatively overlooked form of environmental degradation caused by urbanization. It poses a significant challenge to the development of urban areas and threatens the long-term sustainability of cities. In recent years, the rate of subsidence has exceeded that of global sea level rise, putting coastal cities at a higher risk of flooding, submergence, and inhabitation. A System Dynamics approach is used to model and simulate the underlying mechanisms of land subsidence and how different factors interact to cause changes in the system over time. The study also evaluates key drivers of subsidence and the potential impacts of different policy options. The study finds that altering the water supply of the system provides the greatest impact on reducing land subsidence. Specifically, adding a source of recycled water to the system is a more sustainable solution, as it reduces the need for extraction from groundwater resources.

1. Introduction

Urban development has been a driving force behind economic growth and improved living standards in many parts of the world. However, this has also brought about environmental degradation caused by the indiscriminate use of natural resources and improper waste disposal. Another major cause of environmental degradation is land subsidence, which has been found to be widely overlooked and is not properly integrated into mitigation and adaptation measures (Hamdani et al., 2021). This is found in many coastal cities around the world, with the most rapid subsidence happening in South, Southeast, and East Asia, as well as developed countries in North America, Europe, and Australia (Wu et al., 2022).

Land subsidence is defined as “a gradual settling or sudden sinking of the Earth’s surface due to removal or displacement of subsurface earth materials”. It is irreversible and poses a formidable challenge to urban development. Unlike more dramatic natural disasters, such as earthquakes or floods, land subsidence can occur over the course of decades or even centuries. The gradual nature of land subsidence makes it challenging to attribute specific instances of damage to subsidence as opposed to other factors such as natural weathering or human activities. Land subsidence is not always visible on the surface, as the sinking or settling of the ground can occur underground as well (Abidin et al., 2015). This is primarily due to changes in and movement of underground materials, as well as the over-exploitation of groundwater resources (Cao et al., 2020).

Research has highlighted that land subsidence is most often associated with human intervention, specifically through the withdrawal of fluids or the extraction of solids from the underground such as groundwater pumping, oil and gas extraction, and soil compaction. Human activities such as urbanization and land-use change also play a significant role in land subsidence by increasing the weight on the ground and altering natural drainage patterns. This has received international attention and was evident in the inclusion of land subsidence as a key topic on the agenda of UNESCO's Hydrological Decade (Poland, 1984). Among the various factors that contribute to land subsidence, excessive groundwater extraction has been identified as a major cause (Galloway and Burbey, 2011). This excessive extraction is often linked to the growing water demand that accompanies rapid urbanization and industrialization in an area.

With this, several policies have been put forward on the issue of land subsidence. The majority of this makes use of Interferometric Synthetic Aperture Radar (InSAR) and GPS tracking to analyze the rate of subsidence according to the systematic review of Hamdani et al. (2021). Others have used a more analytical approach,

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making use of machine learning (Arabameri et al., 2021), spatial regression (Chu et al., 2021), or monte carlo simulations (Aichi, 2020). Game theory for water system analysis and conflict resolution was used by Madani (2010), while an operational water governance model for predicting the future water cycle was developed by Huo et al. (2016) through the use of a simulation method. Despite the efforts of these studies to understand and explain the governance of water and groundwater systems, they were unable to create a system that could demonstrate the evolution of land subsidence across time and various scenarios.

This research aims to fill that gap by utilizing System Dynamics (SD). SD is a methodology that can be used to model complex systems, such as land subsidence, and to understand how different factors interact to cause changes in the system over time. As demonstrated in Vallerotonda et al. (2018), SD provides a holistic view of a system that subsequently aids in policymaking. This approach is particularly relevant for developing strategies to address land subsidence because it allows policymakers to identify key drivers of subsidence and evaluate their potential impacts. Given this, the general objective of the study is to evaluate different adaptation strategies to determine which information and evidence are seen to be relevant for policymaking. The software Vensim PLE was utilized to build a System Dynamics model for analyzing the dynamic groundwater balance and simulating accumulated land subsidence.

2. Dynamics of land subsidence

Land subsidence is defined by the relationship between the supply and demand of water. An increase in population affects both the water demand and Greenhouse Gas (GHG) emissions positively. The latter then affects the quantity and quality of water, which collectively impacts water adequacy. Water adequacy is dependenent on groundwater extraction, which subsequently leads to land subsidence. A stock flow model is used to expound on the aforementioned dynamics of land subsidence. Stocks represent variables that accumulate through time while flows represent the variables that define the accumulations (e.g., the difference between rate of inflows and outflows). This model has the capability of providing quantification for the relationships that had been identified within the system. The model is defined by integral equations, usually facilitated through the use of high level simulation programs. The following represents general forms of these equations:

$$Stock(t) = \int_{t_o}^{t} [Inflows(s) - Outflows(s)]ds + Stock(t_o) \tag{1}$$

where, *Inflows(s)* represents the value for the inflow at any time *s* between the initial time t_o and the current time t. Equivalently, the net rate change of any stock, its derivative, is the inflow less the outflow, defining the differential equation,

$$\frac{d(Stock)}{dt} = Inflow(t) - Outflow(t) \tag{2}$$

Figure 1 shows the water demand subsystem of the stock flow model. Household, Agriculture and Industry represent the general population of the system and are the main source of water demand. These are defined to be stock variables and characterize the state of the system. Stocks create delays by accumulating the difference between the inflow to a process and its outflow. The water needs of each sector are linked to the growth and expansion of that sector as well as their rates of water consumption. The growth rates of these sectors are contingent upon the availability of water, as it is assumed that a shortage in water supply will negatively impact the growth of that population. The combined water demand from each sector constitutes the total water demand.

The water supply sub-system in Figure 2 is derived from both surface water and groundwater sources. Surface water is primarily composed of precipitation, such as rainfall, which is affected by greenhouse gas emissions and climate change. As more greenhouse gases are trapped in the atmosphere, the amount of rainfall decreases (Water Services Association of Australia, 2013). The greenhouse gas emission is derived from the per capita rates and the total number of each sector. As rainfall occurs, it contributes to both groundwater recharge and surface water runoff, which in turn replenish the groundwater and surface water supplies. Additionally, the presence of wells for extracting groundwater also plays a role in the overall groundwater supply. The quantity of groundwater available from wells is measured by the number of wells in operation. It is assumed that more wells will be excavated when current water resources cannot satisfy the demand. By multiplying the average amount of water extracted from each well, which is a constant value, with the number of wells, we can determine the overall volume of water withdrawn from wells. The number of wells in operation is reduced by the number of closed walls due to salinization. This salinization is mainly attributed to the level of land subsidence.

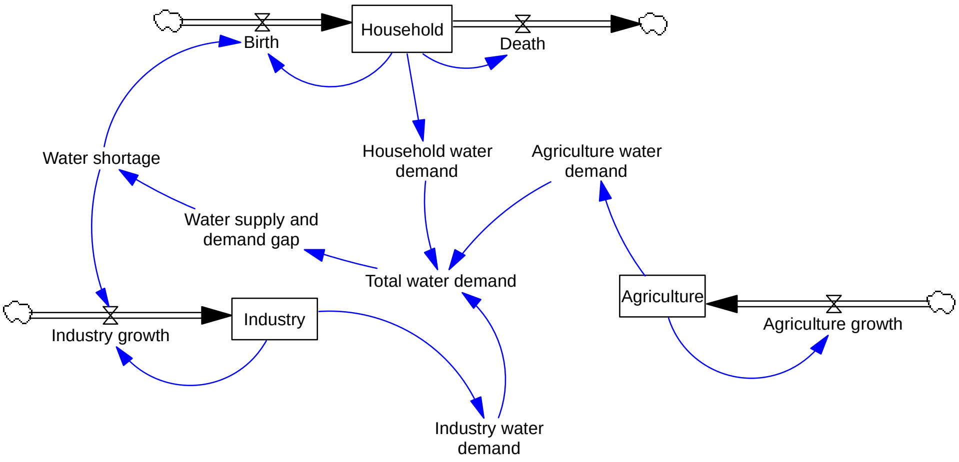

Figure 1: Water demand subsystem

The land subsidence subsystem in Figure 2 is a crucial component in understanding the effects of groundwater overexploitation. By subtracting the demand for groundwater from the recharge, the volume of water being overexploited can be calculated. This value, when multiplied by the volume of water required to cause a 1 cm decrease in land elevation, gives the accumulated land subsidence caused by overexploitation. This land subsidence has a direct impact on the closure of wells, as it can lead to the process of salinization. Salinization occurs when the water table drops and saline water from deeper layers of the aquifer rises to replace the freshwater that has been pumped out. It should be noted. However, that land subsidence is not only dependent only groundwater extraction but includes other factors as well, such as soil load and tectonic plate movements, which are not accounted for in the model.

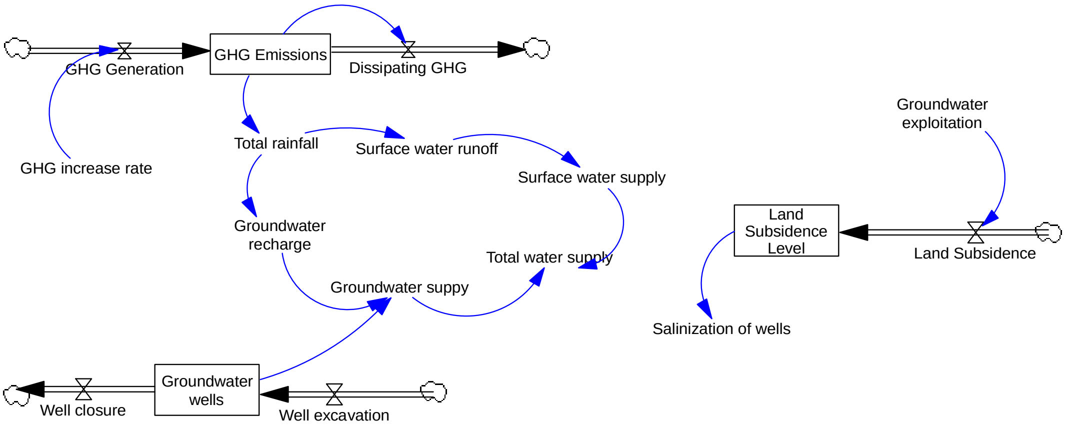

Figure 2: Water supply and Land subsidence subsystem

3. Computational experiments

Computational experiments were performed using the commercial simulation software Vensim PLE. This software is specifically designed for systems dynamics modeling and features a graphical interface for creating stock and flow diagrams, as well as the ability to embed text-based equations. The results of the base scenario are presented in Figure 3a and Figure 3b, which are based on key variables such as accumulated land subsidence and the difference between the total water supply and demand, also referred to as the water deficit. The accumulated land subsidence demonstrates an exponential growth pattern with a decreasing slope. This indicates that under the current rate of groundwater extraction and without any intervention, land subsidence will continue to occur at an increasingly rapid rate. Similarly, the water deficit shows a downward trend for Year 1, followed by exponential growth in the following years. This suggests that the current water supply is able to sustain the demand of the various sectors for 1 y. However, due to the continued increase in population, the water deficit also increases. This deficit subsequently leads to an increase in groundwater excavation. It is clear from the results that the current rate of groundwater extraction is not sustainable, as both the accumulated land subsidence and water deficit increase over time. These results emphasize the need for effective management strategies to address the challenges posed by groundwater overexploitation and land subsidence.

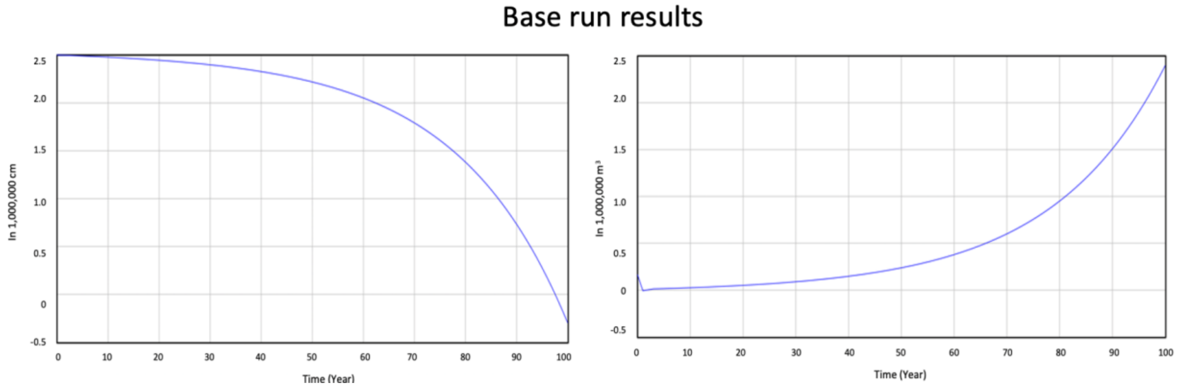

Figure 3: (a) Base run results for accumulated land subsidence level and (b) Base run results for water deficit

3.1 Increasing well closure in relation to land subsidence

Groundwater extraction is a vital component in meeting the water needs of a population. However, a possible solution to land subsidence can be in the form of increasing well closures. This is an external intervention that aims to provide stricter measures by the government to curb the effects of groundwater extraction by sealing unused or abandoned wells.

There is an abundance of abandoned wells that exist for various reasons, such as the construction of new wells, wells that no longer have water, or wells that are contaminated. These abandoned wells can lead to further contamination of other wells that draw from the same groundwater. Furthermore, these wells can exacerbate the problem of land subsidence. Proper decommissioning of wells should be performed where wells are adequately filled and sealed. The results from this intervention are presented in Figure 4a and Figure 4b.

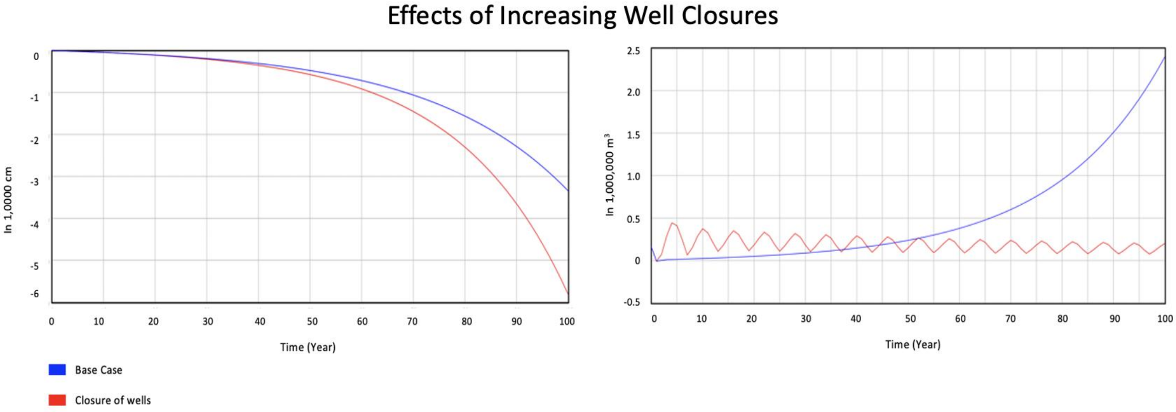

Figure 4: (a) Accumulated land subsidence level under increasing well closures policy and (b) Water deficit under increasing well closures policy

Increasing the number of wells closed is shown to create a less steep slope in terms of land subsidence. With more wells closed and properly sealed, the chances of the water table collapsing, causing the ground level to drop, decreases. Additionally, with a smaller amount of land subsidence, the likelihood of these wells becoming salinized also decreases, meaning that excavating more wells is not necessary to meet the water demand. The water deficit shows a fluctuating pattern, where the initial closure of wells would cause an increase in the water deficit, but as more wells are excavated, the deficit decreases.

3.2 Water conservation efforts

The next strategy is to reduce water consumption by promoting water conservation efforts. As stated by Wang et al. (2020), water saving projects account for one of the key drivers in sustainable water management. The goal of this effort is to reduce water demand per capita in households, industries, and the agriculture sector by half. To achieve this goal, various measures can be implemented such as educating the public on the importance of water conservation, implementing water-efficient technologies, and promoting water-saving habits. In the model, the variables for water use of households, industries, and agriculture were reduced to 50 %. Additionally, water recycling was introduced as a means of augmenting the overall water supply. This can be done by treating and reusing water that has been used in households, industries, and agriculture for non-potable purposes. The feedback loop for this new policy is provided below. By implementing these measures, water consumption can be reduced, and the overall water supply can be managed more sustainably.

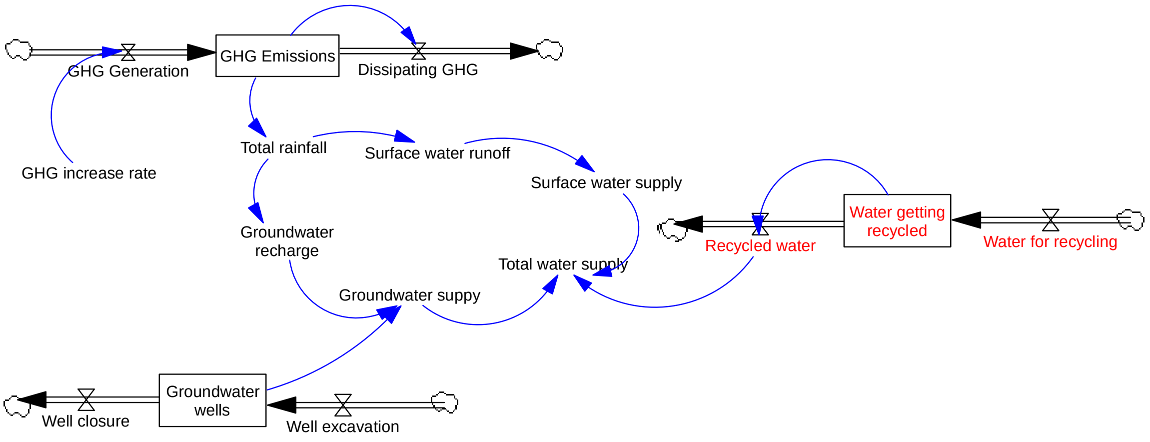

Figure 5: Stock flow diagram under the policy of water conservation efforts

Simulation results in Figure 6a and Figure 6b have demonstrated that the implementation of water conservation strategies, specifically those aimed at reducing demand and promoting water recycling, can result in a significant reduction in the rate of land subsidence. The data presented in the graph illustrates that the slope of subsidence is less steep in the case of conservation efforts, providing clear evidence of the effectiveness of these strategies. Additionally, the simulation results indicate that the new policy also lessens the magnitude of the water deficit. This suggests that the addition of recycled water to the total water supply is a key factor responsible for these positive outcomes. In essence, recycling water not only saves resources and money but also reduces the pressure on freshwater resources and contributes to a more sustainable future.

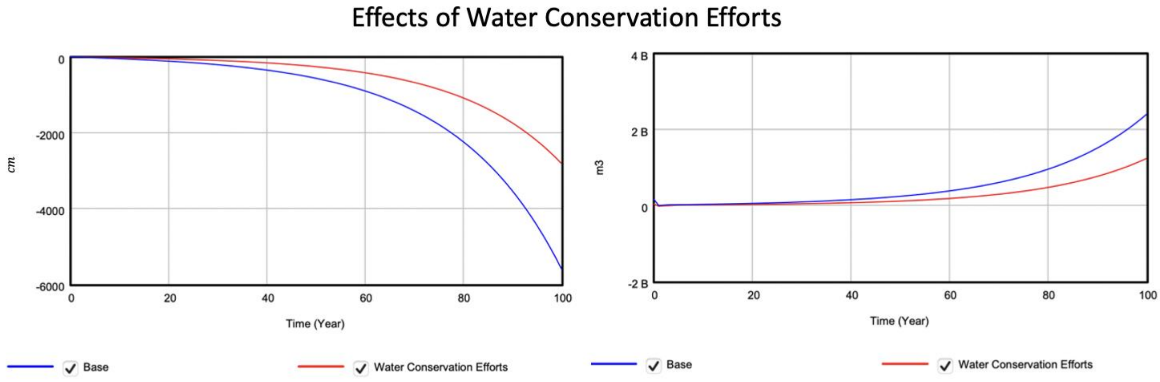

Figure 6: (a) Accumulated land subsidence level under water conservation efforts policy and (b) Water deficit under water conservation efforts policy

4. Conclusions and recommendations

The occurrence of land subsidence poses a significant challenge to the development of urban areas and threatens the long-term sustainability of cities. The current study uses system dynamics as a methodology to evaluate various adaptation strategies and determine the information and evidence that is relevant for policymaking. The study found that altering the supply of the system has the greatest impact on the dynamic problem of land subsidence. The computational experiments showed that eradicating groundwater extraction is not a plausible strategy since the population relies greatly on this. Instead, stricter measures in terms of good abandonment may be implemented. However, the model showed that without other sources of water supply, increasing the number of wells being closed due to land subsidence would reduce the supply for a short time before supplies are replenished by new well extraction, which causes a fluctuation of the population and demand.

The current model shows a base model of how water supply and demand, as well as GHG emissions' effect on rainfall, affect land subsidence. Land subsidence occurs for other reasons not presented in the model, such as the natural movement of land, external pollution, and soil load from buildings, which can be included in the model for future studies. The model also showed that GHG emissions have minimal effect on the total water supply since the decrease in rainfall caused by GHG emissions occurs gradually over a long period of time. To further analyze the impact of GHG emissions on water supply, the relationship between water quality and GHG emission quantity can be analyzed.

References

Abidin H.Z., Andreas H., Gumilar I., Brinkman J.J., 2015, Study on the risk and impacts of land subsidence in Jakarta. Proceedings of the International Association of Hydrological Sciences, 372, 115–120.

Aichi M., 2020, Land subsidence modelling for decision making on groundwater abstraction under emergency situation. Proceedings of the International Association of Hydrological Sciences, 382, 403–408.

Arabameri A., Yariyan P., Santosh M., 2021, Land Subsidence Spatial Modeling and Assessment of the Contribution of Geo-Environmental Factors to Land Subsidence: Comparison of Different Novel Ensemble Modeling Approaches. Research Square (preprint), DOI: 10.21203/rs.3.rs-194202/v1.

Cao Y., Wei Y.-ni, Fan W., Peng M., Bao L., 2020, Experimental study of land subsidence in response to groundwater withdrawal and recharge in Changping District of Beijing. PLOS One, 15(5). DOI:10.1371/journal.pone.0232828.

Chu H.-J., Ali M.Z., Tatas, Burbey T.J., 2021, Development of spatially varying groundwater-drawdown functions for land subsidence estimation. Journal of Hydrology: Regional Studies, 35, 100808, DOI:10.1016/j.ejrh.2021.100808.

Galloway D.L., Burbey T.J., 2011, Review: Regional land subsidence accompanying groundwater extraction. Hydrogeology Journal, 19(8), 1459–1486.

Hamdani R.S., Hadi S.P., Rudiarto I., 2021, Progress or Regress? A Systematic Review on Two Decades of Monitoring and Addressing Land Subsidence Hazards in Semarang City. Sustainability, 13(24), 13755, DOI: 10.3390/su132413755.

Huo A., Dang J., Song J., Chen X., Mao H., 2016, Simulation modeling for water governance in basins based on surface water and groundwater. Agricultural Water Management, 174, 22-29.

Madani K., 2010, Game theory and water resources. Journal of Hydrology, 381, (3-4), 225-238.

Poland J.F., 1984, Guidebook to studies of land subsidence due to ground-water withdrawal. UNESCO Guidebook to Studies on Land Subsidence, <www.rcamnl.wr.usgs.gov/rgws/Unesco/>, accessed 13.01.2023.

Vallerotonda R., Leva A., Ansaldi Silvia M., 2018, Modeling and training: How system dynamics is usable in OSH and MAH frameworks. Chemical Engineering Transactions, 67, 325-330.

Wang F., Wang F., Li Z., Tan R.R., Ren J., Jia X., 2020, An integrated graphical approach for industrial water conservation project selection. Chemical Engineering Transactions, 81, 985-990.

Wu P.-C., Wei M.M., D’Hondt S., 2022, Subsidence in coastal cities throughout the world observed by InSAR. Geophysical Research Letters, 49, e2022GL098477, DOI:10.1029/2022GL098477.

Water Services Association of Australia, 2013, Dams. <www.wsaa.asn.au/sites/default/files/publication/download/WSAA%20Dams%20Fact%20Sheet%20Information%20Pack.pdf>, accessed 20.02. 2023.