Evaluation of the Effects of Global Warming on Coastal Groundwater Resources

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論文内容要旨

The motivation of this research was to evaluate the fresh groundwater resources in global coastal regions. The main focus is the effect of global warming on coastal groundwater resources concerning the salinity intrusion in coastal aquifers. Even though there were some researches on the effects of hydrological, geological aspects on coastal groundwater resources, there are no integrated studies can be found in the literature. In this study the integrated effect of global warming (i.e. climate change and sea level rise) and anthropogenic stress such as land use change on coastal groundwater resources has been evaluated. Effect of groundwater recharge on the fresh groundwater systems has been evaluated with respect to the combined effect of land use and climate change. Effect of sea level change on salinity intrusion has been investigated considering two case studies. Finally the long term effect of global warming on the fresh groundwater resources in global coastal regions has been evaluated considering the future climate changes and sea level rise.

The numerical modeling of coastal aquifers has been performed based on sharp interface concept. A numerical model has been developed based on sharp interface approach to evaluate the saltwater intrusion in coastal aquifer systems. In solving the coupled, non linear partial differential, freshwater and saltwater flow equations, the Strongly Implicit Procedure has been successfully utilized to achieve rapid convergence in finite difference numerical scheme. This model helps to study the coastal aquifers for proper understanding of the functioning of the hydro geological behavior of the aquifer systems regionally as well as globally. The sensitivity analysis concludes that hydraulic conductivity is the main hydro-geological factor and groundwater recharge in watershed areas is the main external factor affecting the salinity intrusion in coastal aquifers. The developed model has been verified with observed groundwater salinity data in Southern coastal aquifer in Sri Lanka and Al

In order to introduce sustainable land use concepts, the consequences of land use change on hydrology and coastal groundwater resources have been evaluated. To further investigate the factors affecting groundwater recharge, a water balance technique has been employed in order to establish the groundwater recharge as a function of annual precipitation, mean annual temperature, land use pattern and hydrologic soil condition. The developed methodology will be very useful in areas with limited hydrological data. The aridity index has been introduced to represent the variations in precipitation and temperature scenarios. Results show that when the aridity index is less than 22, groundwater recharge will be zero in all land use patterns. The effect of climate change and land use scenarios show that when the aridity index is less than 60, agricultural lands give higher groundwater recharge than the other land use patterns for all hydrologic soil conditions. It concludes that with respect to groundwater recharge, agricultural lands are the best land use pattern in arid and semi arid areas. The combined effects of deforestation and aridity index on fresh groundwater loss conclude that, deforestation leads to increase the groundwater recharge and to increase existing fresh groundwater resources in areas having less precipitation and high temperature (arid climates). The introduced methodology will be useful in ungauge basins and in areas where limited hydrological data is available.

Analysis of the effect of sea level fluctuations on the movement of freshwater saltwater interface shows that the impact of sea level rise is severe in areas having less groundwater recharge. Comparing two case studies; Western American coast and Bay of Bengal region, the evaluation concludes that, even though the effect of sea level rise is higher in high latitudes than mid latitudes and equatorial areas, the influences of the loss of fresh groundwater resources is more severe in mid latitude and equatorial areas which has arid and semi arid climates and large diversity of seasonal climate. Combined influence of the reduction in groundwater recharge and the sea level rise further shows that there is an increase in the loss of fresh groundwater resources with the reduction of groundwater recharge due to future climate change. These results suggest that sea level rise could be a significant problem and hence it needs to be considered within the policy process in terms of mitigation as well as adaptation.

Prior to global evaluation, the regional evaluation of the effect of climate change on the regional coastal groundwater resources has been carried out considering different climatic regions; central America, Mediterranean, North Africa, South Africa and South Asia. Among the selected five water resources stressed areas the inter annual variation of loss of fresh groundwater resources highlight the complexity of the hydrological consequences, but still indicate a rough increase in loss of fresh groundwater resources except northern Africa and Sahara region which shows an increase in future precipitation. The correlation between the changes in climate variables versus changes in loss of fresh groundwater resources may lead to poor results except the correlation between the changes in precipitation and loss of fresh groundwater resources which indicates the high complexity of the feedback of the climate change on the hydrological cycle at the regional scale. The correlation coefficients are emphasized that the precipitation and temperature individually does not show a good correlation with loss of fresh groundwater resources and the combined effect of precipitation and temperature via aridity index shows a better correlation. The change in loss of fresh groundwater resources has been estimated using groundwater recharges estimated using two different estimation procedures; the method of groundwater recharge estimation using only precipitation and temperature as the climate variables and the detailed estimation of groundwater

recharge using observed climate variables. Comparison of the results concludes that both methods lead to almost similar results of fresh groundwater loss. Therefore, the proposed method, which uses limited hydrological data decided to be used for the global evaluation of coastal fresh groundwater resources.

The global scale assessments of coastal groundwater resources are very limited because of the lack of data and available methodologies are laborious, time consuming and costly. To overcome these problems, an approach based on sharp interface concept has been introduced in this study. This approach has been applied to assess global scale evaluation of coastal groundwater resources over the next century considering future global warming scenarios. Even though the results give higher uncertainties, the relative variations of fresh groundwater resources in different hydro-geological, climate and socio-economic regions helps to investigate the future situation of fresh groundwater resources in global coastal regions. The results of the situation of coastal fresh groundwater resources over the next century show that there will be a higher reduction in fresh groundwater resources in the Central American, South American, South African and Australian regions whereas, most of the areas in Asia and Europe show a medium reduction.

Further, future growth of population and increased demand for fresh groundwater will make the situation more complex in most of the regions. The regional basis indications show that, even though the availability of fresh groundwater is relatively higher in Asian region, the per capita fresh water resources availability is less. The African region shows that the most of the coastal areas in Africa give higher loss in fresh groundwater resources than any other regions in the world, but the per capita fresh water resources show relatively higher values in African continent, which has low population density. Future situation of the coastal groundwater in Australia predicts a reduction of fresh groundwater resources in all over the Australian coasts. The loss in fresh groundwater resources may increase in north and west Europe with mixed results for other parts of Europe. Fresh groundwater resources in north American coastal regions show that the central part of the America experiences a higher reduction in groundwater recharge and related reduction in fresh groundwater resources. It further concludes that the impacts of climate change will depend on the baseline condition of the fresh groundwater resources. Hence the ability of water resources managers to respond the system is not only the climate change. The impacts on coastal groundwater resources are extremely complicated and can depend on factors such as population growth, changes in demands, water use patterns, land use activities and economic, social, and legislative conditions

The outcome of this research would assist the planners and decision makers to come up with control measures for ongoing surface and groundwater developments activities in coastal regions, ensuring its long-term sustainability in coastal groundwater systems.

論文審査結果の要旨

気候変動による水資源問題が注目されているが，その中でも人間活動が集中している海岸域での地下淡水資源の減少について本論文は注目した．研究対象を地域から気候区，全球規模へと拡張し，地球数値地図情報と数値計算を用いて将来の海岸地下水資源の評価を行った．本論文は全8章よりなる．

第1章は序論であり，研究の背景と地球温暖化問題について説明している．

第2章では，地下水帯水層への塩水侵入と気候変動に関する既往研究について報告している．

第3章は，本論文で用いられた Sharp Interface Model の構造と数値計算手法について説明し，モデルパラメータの比貯留，空隙率，透水係数に関する敏感度を調べている．その後，塩水侵入の観測をスリランカとオマーン地域において行い，モデルを検証した結果，良好な結果を得ている．半乾燥地域と乾燥域にモデルを適用し，パラメータに詳細な検討を加えたことは新しい知見である．

第4章では，塩水侵入モデルの上流側境界条件を与えるために，水文モデルを加えた．水文モデルは降水データから，土地利用データに応じて蒸発散と流出量を計算し，地下浸透量を計算する．気候を表す乾燥示数と土地利用，地下淡水資源量の関係を求めた．その結果，乾燥が進んだ地域では，森林域よりも耕作域の方が地下水資源を涵養すること，湿潤域では逆に森林域が涵養すること，おおよそ乾燥示数が 80 程度では森林，耕作域，草地それぞれ同程度の涵養をもつことが理解された．また，土壌の性質について，涵養量の差は出るが土地利用の効果の方が大きいことを示した．これらは水資源政策上，重要な成果である．

第5章は，海面上昇と地下水資源の損失について述べられている．特に人間活動の影響をみるため，途上国のバングラデッシュと先進国のアメリカ西岸を対象に議論している．海面上昇によって，両地域とも 3 ～ 5 %の地下淡水資源の減少をもたらす知見を得た．特に地表水の利用が増加すると地下水涵養量は著しく減少するため，先進国の方が渇水に直面しやすいことが示された．この定量評価は重要な知見である．

第6章では，5章までに開発されたモデルと議論を踏まえて，解析対象域を各大陸に拡大した．また，IPCC（気候変動に関する国際委員会）が発表している 2100 年までのシナリオ（SRES）を用いて考察した．その結果，今後 100 年では南アジア，地中海沿岸，南アフリカ，中央アメリカの順で海岸地下水資源の損失の多いことが定量的に理解された．一方，北アフリカでは水資源の上昇が示された．これらはおおよそ線形的に変化している．ここで得られた成果は極めて有益であり，新しい知見である．

第7章では GCM（全球気候モデル）の結果を用いて全球 2.5 × 3.75 度（緯経度）の空間分解能で全球海岸部の地下水資源の損失量を将来 100 年にわたって推測した．ここでは人口増加と土地利用の改変が考慮されている．その結果，地下水資源について，中央アメリカとオーストラリア北部で大きな損失がある一方，インドネシアや極域では増加する結果が認められた．この成果は，温暖化水資源問題の中でもユニークであり，世界に先駆けた成果である．

第8章は結論である．

以上要するに本論文は，気候変動シナリオに応じた海岸地下水資源の変化を数値モデルによって求めることに成功した．本手法によって 2100 年の任意地域の海岸地下水資源推測が可能になった．本手法と成果は水資源計画や環境計画に大いに貢献できるものと評価できる．

よって，本論文は博士（工学）の学位論文として合格と認める．