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Uncertainties in the assessment of climate change impacts on groundwater

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(Received March 31, 2014; Revised accepted December 7, 2014)

Uncertainties in modern assessments of the impact of long-term climatic variations on the characteristics of groundwater discharge and groundwater resources are considered. The authors show that when assessing groundwater resources and especially forecasting groundwater resources, the main calculated hydrogeological parameters are insufficiently reliable and estimates of possible changes of main meteorological characteristics should be considered. Therefore, it is currently almost impossible to forecast the impacts of climate change on groundwater resources and regime for the coming decades. A scenario-based approach is the most promising for studying the potential effects of climate change on groundwater.

Introduction

Being a component of the environment, fresh groundwater is formed under the influence of number of natural, climatic and anthropogenic factors. Natural and climatic factors include atmospheric circulation and moisture transfer, which determine the heat balance in the atmosphere, and, above all, precipitation and evaporation at the land surface; river flow; geomorphological conditions and dissected topography; geological, structural and tectonic conditions; permeability of covering and water-bearing deposits, karst development; conditions causing melting of glaciers; expansion of permafrost rocks, and more.

Among anthropogenic factors are, primarily, land drainage, artificial groundwater recharge, hydraulic engineering on rivers (reservoirs, dams, drainage systems), civil engineering, irrigation, canal construction, etc. In most cases, these factors (climatic, natural and anthropogenic) operate in an integrated manner, determining groundwater recharge.

Groundwater recharge originating from precipitation in the long-term average annual profile determines the value of groundwater natural resources, i.e. that part of groundwater continuously being renewed during the water cycle. In practical terms, natural resources characterize the upper limit of the possible use of fresh groundwater from the zone of intensive water exchange without their depletion in the long-term period (when other sources of their formation such as filtration from the rivers during groundwater exploitation or artificial recharge, are absent).

Considerable interest in the problem of the impact of climate

change on groundwater is occasioned, firstly by practical needs - the need to assess the current state and, most importantly, the prospects for the use of fresh groundwater for water supply in order to increase the stability of water availability of the economy.

Today groundwater is the main source of water supply in many European countries (Zektser and Everett, 2006): in Austria, Belgium, Hungary, Germany, Denmark, Romania, Switzerland and former Yugoslavia the contribution of groundwater to drinking water supply is more than 70%. Also, in Bulgaria, Italy, the Netherlands, Portugal, France, the Czech Republic and Slovakia the contribution from groundwater varies from 50 to 70%. In Russia, the part played by groundwater in urban drinking water supply is about 45%.

In addition, groundwater is used (in some cases very substantially) for irrigation in regions with arid climates (Libya (100%), Saudi Arabia (86%); and semi-arid climates (Argentina (70%), Algeria (56%), Australia (46%), the USA and Mexico (38%), India (35%); as well as in the Mediterranean countries (Spain, France, Greece, Italy - over 26%). In arid and semi-arid zones groundwater is the main water resource for extensive livestock farming.

Water supply of many of the world's biggest cities is largely based on the use of fresh groundwater. For example in Munich, Hamburg, and Vienna the role of groundwater in drinking water supply is 90-100%, and in Brussels, Amsterdam, Copenhagen, and Lisbon groundwater use is more than half of the total water use for drinking purposes.

In Russia fresh groundwater is regarded as a strategic water supply resource, especially in emergency situations. For strategic purposes, it is essential that drinking water supply of medium and large cities should be based on at least two independent sources and all suitable resources of fresh groundwater should be used. The Water Code of the Russian Federation provides for the development of reserve sources of water supply on the basis of groundwater, protected from contamination. While a special regime of protection and control over their condition should be specified, unfortunately, in Russia water legislation governing groundwater resources is only enforced to a limited extent.

Groundwater resources, as well as water resources as a whole, are climate-related natural resources. Climate change is inevitable. This is a fact which is confirmed by the whole geological history of the Earth. Investigations of possible changes to water resources as a result of climatic factors are relevant.

Overview of main methods and approaches

A large number of publications devoted to the study of the influence of climate change on groundwater have not demonstrated a

relatively high level of scientific understanding of the issues. According to the findings of the International Panel on Climate Change (IPCC), the present lack of necessary empirical and theoretical data makes it impossible to reliably determine the value and direction of groundwater changes as a result of climate change (IPCC, 2013).

To date, physical mechanisms of the interaction of groundwater and the global climate system are largely unknown. There are both objective and subjective uncertainties in assessing the impact of climate change on groundwater recharge (Loáiciga, 2009).

Impersonal uncertainties are insuperable and are related to the pattern of natural structuring and the incomplete ergodicity of the climate system. Mechanisms of direct climatic links and climate feedbacks have complex interactions. The climate system is structured in several types of open nonlinear subsystems with differing levels of organization: dynamically stable, adaptive, and the most complex - the evolving subsystem. Links between them are realized through the chaotic, non-equilibrium state systems of neighboring levels. Disequilibrium is a necessary condition for the appearance of a new order, i.e. climate dynamics. In strongly non-equilibrium state climate subsystems are influenced by factors of outside influences which they would not have responded to if had been in equilibrium. In moderately non-equilibrium conditions the relative independence of the system's elements gives way to corporate behavior of the elements thus: near equilibrium – the element interacts only with its neighbors, and far from equilibrium – the element interacts with the entire system and the consistency of the elements' behavior increases. In states which are far from equilibrium, bifurcation mechanisms come into play. Bifurcation mechanisms mean the presence of short-term bifurcation points of transition to a relatively long-term mode of the system called "the attractor". It is impossible to predict in advance what exact attractor the system will occupy. Partial ergodicity or incomplete transitivity (almost intransitivity) of the climate system appears to be a non-singularity of the climate. Non-singularity of the climate occurs when components of the climate system (e.g., the hydrological cycle, including groundwater from the zone of active water exchange) from nearly identical synoptic conditions with identical external conditions are evolving absolutely differently.

Modern mathematical models of climate and geohydrological models are transitive in principle. Although some of the latest versions of those models give two stable solutions, they do not solve the whole problem, because an infinite number of climate scenarios can be realized with equal probability under these external parameters. Incomplete ergodicity of the climate system appears in different spatial and temporal scales and has essentially important consequences. Firstly, it is practically impossible to predict climate. A second consequence is that there is no need to look for linear trends to explain the severe fluctuations of climatic parameters between neighboring climatic intervals. In different areas dramatic changes of climatic parameters are recorded. Therefore, the description of the dynamics of the climate system by statistical methods is not exhaustive. Partial

ergodicity (almost intransitivity) of the climate was analytically proved by E. Lorenz (Lorenz, 1970) and can be confirmed experimentally.

IPCC (IPCC, 2013) indicates that the mechanisms and extent of feedbacks between the hydrological cycle and modern dynamics of the climate have been insufficiently studied. In the works of (Dzyuba and Zektser 2009, 2011a, 2011b), possible mechanisms of the formation of climate feedbacks between modern climate change and dynamics of permafrost rocks are described. In these studies, the statistical analysis of long-term changes in surface air temperature, atmospheric composition, depth of seasonal thawing, temperature and distribution of permafrost area in the circumpolar regions of the northern hemisphere were carried out. The preliminary estimates of the possible impact of the observed changes of the thermophysical parameters of permafrost rocks on surface albedo, the moisture content of the atmosphere, the concentration of carbon dioxide and methane in the atmosphere were obtained. The density of anthropogenic and natural methane fluxes from the underlying surface up to the atmosphere was assessed. It was shown that the observed dynamics of major parameters of the permafrost zone has been accompanied by an increase of snow storage, and transfer of significant amounts of moisture from the solid to the liquid state on the land surface and in the upper soil layer. The increase in the water surface area on the underlying surface of these northern territories was identified. This causes an increase in evaporation and moisture content of the atmosphere, increasing the greenhouse effect and brings additional increases in the temperature of surface air.¹ In addition, surface albedo reduces the increase of the heat content of the upper layer of soil, surface and groundwater (taliks²) water bodies. Radiation from surface and groundwater water bodies is also increasing therefore an additional increase in surface air temperature occurs. Progressive thawing of permafrost rocks is accompanied with de-slushing of significant amounts of organic matter, which generates additional methane emissions from surface water and groundwater ecosystems. According to the authors' assessments, the flux density of methane released into the atmosphere exceeds the density of anthropogenic and natural fluxes in other latitudinal zones because of thawing permafrost rocks in the circumpolar latitudinal zone. This is probably why the planetary maximum in latitudinal distribution of CH₄ concentration in the atmosphere occurs in the northern circumpolar region. Results of the analysis of the relationship between processes of climate change in the Arctic zone and thawing of the permafrost rocks has been obtained. Calculations of the density of methane emissions into the atmosphere in different latitudinal zones allowed the authors to express and substantiate the following new hypothesis: the planetary maximum of the warming in the Arctic latitudes is largely caused by emissions of methane and carbon dioxide from thawing permafrost rocks generating additional greenhouse effect. This effect is essentially similar to the influence of anthropogenic emissions of greenhouse gases in the middle latitudes. Dzyuba and Zektser (2011) analyzed the conditions of formation and dynamics of groundwater

¹ A climate feedback involves changes in any of the properties of clouds as a response to a change in the local or global mean surface temperature. Understanding cloud feedbacks and determining their magnitude and sign require an understanding of how a change in climate may affect the spectrum of cloud types, the cloud fraction and height, the radiative properties of clouds, and finally the Earth's radiation budget. At present, cloud feedbacks remain the largest source of uncertainties in climate sensitivity estimates. In this paper cloud feedbacks are not considered

² Talik: within a permafrost zone, the layer of unfrozen ground that lies between the permafrost and the seasonally thawed active layer. Talik most often occurs below rivers and lakes, or where strong springs emerge; open taliks develop under large rivers such as the Yenisey or Lena. Taliks play an important part in fluvial activity in periglacial environments since they further thermo-erosion (Oxford Dictionary of Geography).

of upper hydrodynamic zone of the northern coast of European Russia, discharging directly into the Barents and White Seas. The values of water, ionic and heat long-term annual average submarine groundwater discharge into the Arctic Ocean as well as submarine groundwater discharge, which might appear in the coming decades into the Arctic Ocean were quantitatively assessed. The competence of methane hydrates from the Arctic sea in the conditions of observed and expected climate change was carried out. The concept of climate-driven increase of submarine groundwater discharge as a possible reason for the growth of the intensity of the destruction of Arctic methane hydrates was physically substantiated and confirmed by empirical evidence. Relatively small perturbation in the form of the increase of submarine groundwater discharge into the area of the Arctic shelf is capable of causing a positive climatic feedback of a global scale. Ferguson and Maxwell (2010) analyzed feedbacks between the systems “Groundwater - Land - Atmosphere”. The results obtained in that study indicated that the value of feedback in the system “groundwater - the earth’s surface” can be quantified as the difference of the latent heat flux between regions from the near-surface groundwater (assumed depth is less than 1 m) and areas of deep groundwater (depth is provisionally more than 10 m). In hot and dry summer and fall months, this feedback value exceeds 75 W/m^2 . During these periods, groundwater is close to the surface, which provides higher humidity, while the regions with deep groundwater are more arid. All these cause substantial spatial inhomogeneity of the balance of heat and moisture on the earth’s surface.

Modern stage of climate evolution is characterized by the increase of concentration of greenhouse gases in the troposphere. Considerable contribution to the increase of the surface air temperature is determined by the increase in concentrations of CO_2 and other long-lived and thermodynamically active gases. Also concentration change of carbon dioxide in the troposphere can directly influence evapotranspiration, which is one of the main climate forming processes. Evapotranspiration substantially determines groundwater recharge. In addition, CO_2 can doubly influence vegetation dynamics by being the substrate (starting material) during the photosynthesis as well as the regulator of vegetation processes. Moreover, the influence effect of CO_2 is opposite in sight for plants with C_3 and C_4 photosynthesis types and for plants with CAM-photosynthesis. A direct relation between plants’ growth and CO_2 concentration in the air is typical for C_3 plants; for C_4 plants and CAM plants inverse relation is more common. C_3 plants include majority of plants growing in the temperate and high latitudes. C_4 plants are the plants with different third stage of photosynthesis. At this stage CO_2 is associated with three-carbon compound – phosphoenolpyruvic acid instead of ribulose diphosphate (as for C_3 plants). It leads to the formation of four-carbon (C_4) compound – butanone diacid. This type includes plants such as corn and some other gramineous plants, growing mostly in tropical and subtropical latitudes (sugar cane, sorghum, etc.). Most of the plants performing CAM-photosynthesis are succulents, i.e. plants which have special tissues for water storage. These plants are common in the arid desert areas. These wonderful features of terrestrial flora acquired during evolution provide natural damping mechanism of humidity and temperature effects from climate change, which occurs due to concentration change of carbon dioxide in the troposphere. Preliminary calculations show that in the middle and high latitudes the growth of C_3 plants with increasing of CO_2 concentration in the troposphere can sufficiently change transpiration, so that precipitation increase can be partially or in some regions even fully compensated.

In contrast, increase of carbon dioxide in the air performs inhibitory effects on the plants with C_4 and CAM-photosynthesis in arid and desert regions of tropics and subtropics. These can keep on the same level or even increase groundwater recharge in areas where precipitation will slightly decrease.

Subjective uncertainties are mainly related with two factors. Firstly, modern climate change occurs at rates comparable to the rates of increase of anthropogenic impact on the environment. Differentiation of these impacts on groundwater is extremely difficult. The second reason is historically formed non-congruence of climatic and hydrogeological arrays of empirical data. Disparity in duration and representativeness of climatic and hydrogeological series causes lack of comparability of standard errors when analyzing the long-term changes of spatially averaged climatic and hydrogeological specifications. Reliable very long-term forecasts of impacts of climate change on groundwater are currently unrealistic because of our inability to assess accurately the main climate parameters for the coming decades. The absence of reliable very long-term forecasts of the main characteristics of global and regional climate makes the fundamental prerequisite of the dynamic conditions of all components of the environment, including surface water and groundwater uncertain. Interaction between major climatic processes (temperature, humidity and the dynamic regimes of the troposphere) and the regime characteristics of groundwater is studied and modeled to a much smaller degree than the processes of interaction between the atmosphere and surface waters. Until now, researches on, and models of the impact of climate change on hydrological systems have tended to focus mainly on surface water systems. In most cases, when studying the impacts of climate change on water resources, groundwater is either not considered or is extremely simplified. In that case, there is no realistic assessment of the contribution of groundwater to stream-flow. That approach is based on finding that climate change tends to have a more rapid effect on surface water than on groundwater. Thus, it appears that the impact of climate change on groundwater is less intensive. Most of the groundwater models are developed as stand-alone systems using the thermodynamic “stationarity” of the basic climatic characteristics. Thus, changes in shallow groundwater recharge, flow and discharge are usually modeled without considering changing climatic conditions and conditions in the zone of shallow groundwater. Models developed in recent years such as GSFLOW are based on the interrelation of groundwater and surface water.

Integrating the interaction between the surface discharge, processes in the vadose zone, total evaporation and groundwater in these models fill the gaps of previous models only to a certain degree because those climatic models are based on models of general circulation of the atmosphere and ocean. They work in a much larger spatial scales than the value of spatial resolution of the groundwater models.

Discussion

Large numbers of parameters describing the thermodynamic state of the atmosphere, hydrosphere, and the active layer of the soil are calculated in climate models of general circulation of the ocean and atmosphere at each integration step. Users of these calculations often have the illusion that most of meteorological and hydrological parameters can be interpreted by the data coming out of climatic simulation experiments. The fact, it is far from this. The quality of output data from models vary greatly. The reasons of this important

feature of modern numerical climatic models are the following. The basic reason is determined by the fact that the thermohydrodynamic equations on which modern climate models are based are adapted to generating of large-scale fields. Therefore, their solutions obviously reproduce the fields of air temperature and atmospheric pressure much better than the fields of precipitation, moisture and turbulent fluxes of heat and moisture. Therefore the list of suitable outputs useful for forecasting the latter features are fewer. For example, different climatic models reproduce the fields of clouds in its own way. Therefore, despite the realistic parameterization in all models, it is impossible to compare results from prediction of the features which are determined by radiative flux. These features include in particular the rate of evaporation and evapotranspiration, largely determining the infiltration recharge of groundwater. Another important parameter that must be solved is the level of soil moisture. This feature is also calculated in the models. However, it is extremely difficult to verify the accuracy of these calculations because of limitations of available empirical data. Average or total indicators for the certain period (average for the season, or the sum of positive temperatures within the season, the amount of precipitation, etc.) are important for assessing possible changes in infiltration recharge of groundwater, but indicators characterizing the intensity and duration of the processes are also needed. These indicators are the following: the intensity and frequency of heavy rainfall, the frequency and duration of extreme values of air and soil temperature determining the origin of atmospheric and soil drought, etc. The reliability of predicted model assessments of these parameters is currently insufficient for confident conclusions. It should also be noted that the quality of the model assessments depends on the properties of the underlying surface. Model data are less reliable for mountainous areas, for the sea coasts and in other places where the properties of the underlying surface are very variable. This is because of the fact that the data in models is specified and calculated in a quantized way for certain meshes. Horizontal mesh size in modern models is of at least 100-200 km leading to inadequate model calculations of thermal and moisture features for specified areas. Auditing of groundwater models (comparison of the forecast made with the help of the model and the actual result) shows that even many well-calibrated models do not provide accurate prognostic assessments of future groundwater recharge (Anderson and Woessner, 1992) even in the absence of rapid climate change. Poor verification of existing very-long-term assessments of groundwater recharge is because of the use of an inappropriate conceptual model and the lack of a properly calibrated set of empirical data. The choice of conceptual models which are inappropriate for the simulated system may be caused for two main reasons. First, when developing a conceptual model, large amounts of existing observational data can be interpreted ambiguously and be suitable for more than one conceptual model, despite the fact that the models can be dramatically different. The resulting forecasts of future hydrogeological conditions can be very different. Secondly, if the available data are insufficient, it is impossible to develop an effective model.

Groundwater recharge cannot be measured directly. Groundwater recharge is almost the main and often the only water-budget input for large areas. In practice, the total recharge is mainly determined by water-budget output such as "groundwater discharge into the rivers." However, not all water infiltrating into groundwater is discharged into the rivers. Groundwater is partly discharged through total evaporation and transpiration within the lower areas of the territory

(e.g., floodplains); and partly overflows into deeper aquifers and discharges outside the territory of their recharge. Therefore, the recharge value estimated by the groundwater discharge, as a rule, is less than the value of actual total recharge. There is limited reliable long-term data reflecting natural groundwater recharge which is not influenced by anthropogenic impacts. Therefore, even if there are reliable scenic prognostic assessments of climate change, most of hydrogeological models cannot be efficiently verified when predicting groundwater regime with a lead time of several decades.

Conclusion

Despite continuing objective and subjective uncertainties, the study of the relationship between climate change and fresh groundwater resources is necessary for the development of regional strategies to respond to ongoing global environmental changes. It is currently impossible to reliably forecast the values of climatic parameters over the coming decades at the global and regional levels. Therefore it is necessary to develop strategies for determining scenarios for responses to climate-driven changes of groundwater recharge in different regions.

Most assessments of the impacts of climate change on groundwater resources and regime are obtained from accounting for changes in precipitation and surface air temperature. At the same time, changes of other climatic parameters, such as direct solar radiation and cloud amount, long-wave radiation fluxes, wind at the land surface and absolute air humidity can greatly affect the intensity of evapotranspiration and, hence, groundwater recharge and resources.

When assessing the impact of climate change on groundwater, caused by rising levels of greenhouse gases in the troposphere, temperature and precipitation are considered the most common inductors of changes in the values of evapotranspiration. At the same time the increase of CO₂ concentration in the troposphere can directly affect the transpiration value. For example, the changes in the CO₂ concentration in the atmosphere can cause a number of changes in plants including the increase in leaf area index (area of illuminated leaves on every square centimeter of the soil surface). They can cause changes in the stomatal density (pores through which plants carry out gas exchange with the atmosphere) and changes in the opening and closing of stomata (Bazzaz, Sombroek, 1996). In some regions the increase of CO₂ concentration in the atmosphere can sufficiently change transpiration. As the result, the decrease in precipitation can be at least partially compensated, or the recharge, in areas where precipitation will decrease, can be significantly increased.

The foregoing discussion demonstrates the necessity to continue complex interdisciplinary research of the current stage of co-evolution of climate and groundwater.

To conclude, it is necessary to mention that, independently from the present authors and practically in conjunction with them, closely similar results were published in Taylor et al. (2013).

Acknowledgements

The presented results are obtained in the frame of the researches of Working Group on Drinking Water of IUGS-GEM. The authors are grateful to Dr. Brian Marker and Dr. Jonas Satkunas from IUGS-GEM and Anna Chetverikova from Russian Academy of Sciences. We also thank Russian Scientific Foundation for financial support of the investigations by the project # 14-17-00791.

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