

Modelling the Effect of Human Activity on Fresh Water Extraction from the Earth's Reserves

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Abstract. This paper reports on dependencies in changes to fresh water extraction patterns on the various influencing factors. The aim of the study is to develop a mathematical model to predict the influence of human activity on fresh water extraction from the Earth's reserves. The historical background of the process affects the current estimate for fresh water extraction. The current estimate of fresh water extraction is affected by various dynamic factors in human life as well as environmental processes. As a theoretical model for analysing the influence of human activities and their impact on the environment, the authors selected the autoregressive distributed lags model (ADL-model), in which the current values of the series depend both on past values of the series as well as current and past values of other time series. The authors described the methodology of empirical tests of the model. The paper presents the methods used to construct the model and approaches to determining model parameters. Statistical information for the model variables was collected from 1995 to 2016. Empirical testing of the model was carried out by the authors.

1. Introduction

Water is one of the simplest and most amazing substances in nature, existing in solid, liquid and gas states in nature – ice/snow, rivers/oceans and vapour, respectively. Water is present in all metabolic processes in living nature. Water is an inert solvent, i.e., it is not changed under the influence of the substances it dissolves.

About 71% of the Earth's surface is covered with water (oceans, seas, lakes, rivers, ice) and approximately 96.5% of the Earth's water is contained in the oceans. Around 1.7 % of global fresh water reserves is made up of groundwater, 1.7% of it forms glaciers and the ice caps of Antarctica and Greenland. A small part is in rivers, lakes and swamps, and 0.001% makes up the clouds. Thus, most of the Earth's water is salty and unsuitable for agriculture and drinking. Only 2.5% is fresh water, and 98.8% of this is in glaciers and groundwater. Less than 0.3 % of all fresh water is contained in rivers, lakes and the atmosphere, and even less (0.003 %) is in living organisms [1]. Globally, about two thirds of all precipitation returns to the atmosphere.

The most significant renewable water resources belong to the following countries: Brazil (8233 km³); Russia (4508 km³); USA (3069 km³); Canada (2902 km³); China (2840 km³); Colombia (2132 km³); Indonesia (2019 km³); Peru (1913 km³); India (1911 km³); Venezuela (1320 km³) [2]. Looking at water resources, the region of Latin America, which accounts for a third of the global water runoff is the richest, followed by Asia with a quarter of the world runoff. OECD countries possess 20%, while sub-



Saharan countries and the countries of the former Soviet Union have 10%. The most restricted in their water resources are the Middle East and North America (1% each).

Water stress is most intense in Sub-Saharan Africa; however, the overall water supply situation in the world is tense. Experts suggest that the volume of fresh water consumed by humankind will be equal to its reserves between 2035 and 2045. Both a threat of armed conflict caused by the lack of water supplies and the threat of social conflicts in separate countries may occur. Thus, a water shortage, which is turning into a global resource crisis, becomes literally a matter of health and of human life.

The aim of the study is to develop a mathematical model of the effect that human activity has on the fresh water extraction from the planet's reserves. This mathematical model should consist of an equation connecting the resulting (endogenous) variable and the influencing (exogenous) variables. The model will be used to analyse and predict the effect that human activity has on fresh water extraction. The model will detail how the endogenous variable will behave when the exogenous variables change.

The local objectives of the study are as follows:

- to describe the object of study — the extraction of fresh water under the influence of human activities;
- to choose the type of mathematical model;
- to outline the methodology of the empirical validation of the model;
- to validate the model using statistical data between 1990 and 2015.

2. Analysis of factors influencing fresh water extraction

Fresh water extraction is affected by various factors, which have been divided into three groups: human influence factors, environmental factors and the historical background factors of fresh water extraction processes.

The human influence factors: Human activity constantly promotes fresh water extraction, which takes various forms. Manufactures of coal, wood, pulp and paper industry, agriculture and utilities enterprises discharge harmful substances into water. Mercury, lead and their compounds are dangerous for the aquatic environment. Pollution affects not only surface water but also groundwater. In general, the groundwater condition is estimated as critical and has a dangerous tendency to further deteriorate. Underground water suffers from contamination caused by oilfields, mining, filtration fields, sludge ponds and dumps of metallurgical plants, storage of chemical wastes and fertilisers, landfills, livestock farms and inhabited settlements with no sewerage.

With environmental degradation and a growing population, water, once in abundance, virtually free and easy to use, is now becoming scarce and expensive.

About 25% of the water is used by industry processes and only 9% is used in the communal and household sector. According to statistics, most of the water resources are involved in agriculture (about 66% of all fresh water reserves). The main consumer of water is irrigation. To put this in perspective, growing 1 tonne of cotton requires 4-5 m³ of fresh water and growing 1 tonne of rice needs 8 thousand m³.

Household water consumption exceeds 20 cubic km per year globally. The level of development public water supply is defined by two parameters: the population provided with a centralised water supply and the value of specific water consumption. An important task is to reduce the consumption of tap water by industries. In Moscow, for example, industry accounts for 25% of tap water supplied to the capital. However, there is no need to use potable water for technical needs. If the network of industrial water supply expands, the cost of water overall will be reduced.

In total, industry uses about 90 cubic km of water per year. For example, smelting 1 tonne of steel requires 200-250 m³ of water, 1 tonne of pulp needs 1300 m³. Nevertheless, outdated petrochemical refineries consumed from 18 to 22 m³ of water for refining of 1 tonne of oil, while modern plants with circulating water and air-cooling systems use about 0.12 m³/year.

Environmental factors: The Earth is rich in overall fresh water resources; however, these are distributed unevenly. Meanwhile environmental degradation and climate change are also factors in the global fresh water crisis. Environmental degradation is reflected in the following processes:

climatological disasters; changes in CO₂ content; changes in greenhouse gas emissions from industry; changes in greenhouse gas emissions from agriculture; global temperature change; changes in stocks of fresh water and destruction (deforestation) of forest area.

Climatological disasters include: earthquakes; volcanic eruptions; avalanche; weather events; floods; landslides; fires; hurricanes; tsunamis.

The role of carbon dioxide in the biosphere is primarily the maintenance of photosynthesis, performed by plants. As a greenhouse gas, carbon dioxide in the air affects the heat exchange of the planet with the surrounding space, effectively blocking the radiation of heat on a number of frequencies, and thus participating in the formation and maintenance of the planetary climate. In connection with active human use of fossil energy as a fuel, there is a rapid increase in the concentration of this gas in the atmosphere. In addition, up to one third of total anthropogenic CO₂ emissions result from deforestation.

Greenhouse gases are gaseous constituents of the atmosphere, of natural or anthropogenic origin, that absorb and re-emit infrared radiation. Many types of industrial processes are connected with greenhouse gas emissions. The main sources of emissions are from industrial processes of chemical or physical processing of materials (e.g. blast furnaces in the steel industry; ammonia and other chemical products from fossil fuels used as chemical raw materials and cement production are the most important examples of industrial processes associated with the release of significant amounts of CO₂).

These processes produce a variety of greenhouse gases, including carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

The largest source of greenhouse gas emissions in agriculture is enteric fermentation whereby methane is produced by animals during digestion and released into the atmosphere through regurgitation. Emissions from enteric fermentation increased by 11% between 2001 and 2011 [2]. The volume of emissions from the application of synthetic fertilisers accounted for 13% of all emissions in agriculture (the equivalent of 725 million tonnes of carbon dioxide) in 2011. Synthetic fertilisers are the fastest growing source of emissions in agriculture, having increased by 37% since 2001 [2].

One of the most obvious impacts of global temperature change is the shrinkage of forests. The "blame" is both with climate anomalies themselves (prolonged droughts, dry winters), and the outbreaks of pests and pathogens they cause. The shrinkage of forests causes great damage to forest ecosystems and produces conditions conducive to catastrophic wildfires.

Loss of fresh water due to reduced river flows are caused mainly by deforestation, cultivation of grasslands and drainage of floodplain wetlands. This leads, firstly, to increased surface runoff and increased volume of water flowing into the sea, and, secondly, to a decrease in groundwater levels that feed and support rivers. Loss of fresh water in many countries of the world reduces groundwater reserves. The environmental ecosystem is consequently affected, leading to a natural reduction of forest area.

In analysing factors affecting fresh water extraction processes, the history of the process is also relevant, i.e. the extraction of fresh water in the past affects the extraction of future fresh water. The mobility of water in the atmosphere and poor management of water resources can explain the influence of the previous period on fresh water extraction in a future period.

In the planet's atmosphere, water takes the form of small droplets, grouped into clouds and fog, as well as steam. In condensation, it is removed from the atmosphere in the form of precipitation (rain, snow, hail, dew). The condensation volume of the previous period affects the precipitation of the future period. Water, which undergoes the most global movement, after air, is constantly moving and travels over very long distances. When exposed to the sun's heat, water evaporates from plant surfaces, soil, rivers, ponds and seas. This forms water vapour, which is collected into clouds and transported by the wind before falling onto different continents in the form of snow or rain.

3. Literature review

The problem of water as an important element of human life causes scientific disputes between economists, lawyers, geographers and anthropologists [3]. The research examines the fresh water crisis

as a new environmental crisis of the 21st century. Scientists emphasise [4,5] the need to consolidate the status of fresh water in international law and to conduct a comprehensive analysis of water law from the perspective of climate impacts [6].

Various authors analyse the use of fresh water for agriculture and problems arising in connection with this. The study [7] considers the introduction of institutional mechanisms, such as the introduction of quantitative water prices at the level of individual groups, replacing the existing pricing with a different approach in regard to the areas in question.

The study also considers how the fresh water scarcity affects the development of agriculture [8]. The paper presents the estimation of the benefits of irrigated agriculture as a result of access to different sources of water (water portfolio). The results of the study show that the use of water resources of different quality for agriculture, on the one hand, negatively affects the value of agricultural land but, on the other hand, reduces the sensitivity of agriculture to factors related to climate.

The research compares the use of fresh groundwater in Russia and in the United States [9]. The authors demonstrate the use of fresh groundwater for public water supply in separate regions and cities. They show that significant reductions in groundwater increase the danger of subsidence. Models of ground and surface water systems are presented in their works [10,11].

One of the main factors influencing the extraction of fresh water is human activity. The dynamic factors of human life are described in terms of economic growth and population growth [12-14]; from the perspective of ecology [15,16]; from the perspective of different influencing factors, including increasing demand for water [17]. Models exist that show the impact of human activities on greenhouse gas emissions [18]. The research [19] studies the impact of hydrological changes on biodiversity. Various anthropogenic activities are threatening the biodiversity of rivers and the water systems associated with them. Fresh water ecosystems are central to the global water cycle, its healthy functioning and the sustainability of other ecosystems. Inefficient use and extraction of fresh water are mainly studied from the position of possible threats to humans [20-22]. These threats, along with the growing demand for water resources can aggravate the problem of sustainable development.

4. Methodology

As a theoretical model for the analysis of the influence and impact of human activities on the environment, the authors selected the autoregressive distributed lags model (ADL-model), in which the current values of the series depend both on past values of the series and on current and past values of other time series.

In general, the ADL model of a multiplicative kind is shown below:

$$y_t^6 = A_0 \prod_{i=1}^m a_i y_{t-i}^6 \prod_{\substack{i=1,m; \\ k=1,n}} b_i x_{t-i}^k \prod_{\substack{s=1,N; \\ i=1,m}} c_i y_{t-i}^s \quad (1)$$

where A_0 is a free equation member; y_t^6 – is the endogenous variable "extraction of surface fresh water" in the year t ; y_{t-i}^6 – is the exogenous variable - a factor in the prehistory of the process of fresh water extraction in the year $t-i$; m – the number of lags of the endogenous variable "extraction of surface fresh water", all the exogenous variables are included into the model with the same number of lags; x_{t-i}^k – k – type exogenous variable – the factor of human life in the period $t-i$; k – the number of exogenous variables; y_{t-i}^s – s - type exogenous variable – environmental factor in the period $t-i$; a_i , b_i , c_i - the parameters of the equation that need to be defined.

The methods of determining equation parameters include the following main stages: inspection of stationarity of the endogenous and exogenous variable time series using the Dickey-Fuller test; checking the multicollinearity of the exogenous variables; selection of the endogenous variable's lags, which have a strong correlation with the variable value in the last period and testing the significance of autocorrelation coefficients using the Ljung-Box Q-test; the choice of exogenous variables that have a

strong correlation with the endogenous variable's value in the last period and testing the significance of correlation coefficients; representation of the ADL model equation in its multiplicative and additive form; finding the equation coefficients using the least squares method; model and determination coefficient accuracy validation using the F-Fisher criterion; validation of the regression equation coefficients using Student's t-criterion; executing the endogenous variable forecast for two years.

5. Date and analysis of the primary data

Working with the input data consisted of two steps: a) data collection for the selected variables; b) the primary processing of endogenous and exogenous variables that correspond to the analysed process and reflect the essence of the problem.

Data collection: Data was collected from 1995 to 2016. The data contains the values of endogenous and exogenous variables for the corresponding year in the countries of the world. The data was taken from the following sources: Euromonitor Passport Database, <http://www.euromonitor.com/>; World Bank Open Data, <http://data.worldbank.org/>.

6. Empirical testing of the model

The empirical testing of the model consisted of the following steps according to the equation parameter determination methodology.

Inspection of the time series of the endogenous variable and exogenous variables and their stationarity was performed using the Dickey-Fuller test. The Dickey-Fuller test is the solution for each variable of autoregressive equations like the following:

$$y_t = ay_{t-1} + \delta_t, x_t = ax_{t-1} + \delta_t, \quad (2)$$

where y_t, x_t — are time series, and δ_t — is a mistake. If $|a| < 1$, then the series is stationary.

For the endogenous variable "loss of fresh water stock" $a = 0.6645$ with $t_{cal.} = 6,4290 > t_{tabl} = 1,729$. Therefore, the time series of the endogenous variable "loss of fresh water" is stationary.

Checking the exogenous variables – factors of human life.

For x_{1t} $a = 0.9619$ with $t_{cal.} = 18.709 > t_{tabl} = 1,729$. For the exogenous variable x_{2t} $a = 0.9605$ with $t_{cal.} = 54.096 > t_{tabl} = 1.729$. For the exogenous variable x_{3t} $a = 0.9601$ with $t_{cal.} = 65.6115 > t_{tabl} = 1.729$. For the exogenous variable x_{4t} $a = 0.4121$ with $t_{cal.} = 1.8952 > t_{tabl} = 1.729$. For the exogenous variable x_{5t} $a = 0.4095$ with $t_{cal.} = 1.8499 > t_{tabl} = 1.729$. All series of exogenous variables – factors of human life activity – are stationary.

Checking the exogenous variables – environmental factors. For y_{t-i}^1 $a = 0.0507$ with $t_{cal.} = 2,2032 > t_{tabl} = 1,729$. For y_{t-i}^2 $a = 0.9353$ with $t_{cal.} = 47,0291 > t_{tabl} = 1,729$. For y_{t-i}^3 $a = 0.3559$ with $t_{cal.} = 1,8682 > t_{tabl} = 1,729$. For y_{t-i}^4 $a = 0.8185$ with $t_{cal.} = 10.7094 > t_{tabl} = 1,729$. For y_{t-i}^5 $a = 0.2090$ with $t_{cal.} = 2,4627 > t_{tabl} = 1,729$. For y_{t-i}^7 $a = 0.7677$ with $t_{cal.} = 8,5097 > t_{tabl} = 1,729$. All series of exogenous variable - environmental factors are stationary.

Checking whether the exogenous variables are multicollinear: The pair correlation coefficients of indicators “ y_t^2 - CO₂ emissions per production unit”, “ y_t^4 - Greenhouse gas emissions caused by agriculture”, “ y_t^1 - Climate disaster” with other variables more than $|0.7|$, therefore, these factors will not be included in further analysis. Moreover, with the significance level $\alpha=0.05$ and the number of degrees of freedom $n-2=18$, $t_{tabl} = 1,734$ [TB1]. For all the coefficients of pair correlation t – Student criterion $t_{cal} > t_{tabl} = 1,734$, i.e. the coefficients of pair correlation for the selected variables are significant.

The choice of the endogenous variable lags, which have a strong correlation with the variable value in the previous period and testing the significance of autocorrelation coefficients by means of Ljung-Box Q-test.

Analysis of correlation of the endogenous variable with the exogenous variable showed a strong correlation with y_t^1 (correlation coefficient 0.8661), y_t^2 (correlation coefficient 0.7184), y_t^3 (correlation coefficient 0.7619), y_t^4 (correlation coefficient 0.8278), y_t^5 (correlation coefficient 0.8990), y_t^7 (correlation coefficient 0.7190).

Variables $y_t^3, y_t^5, y_t^7, x_{1t}, x_{2t}, x_{3t}, x_{4t}, x_{5t}$ influence the endogenous variable y_t^6 . The other coefficient values for the variables are less than 0.7, therefore they will not be included into further analysis. With the level of significance $\alpha=0.05$, the number of freedom degrees $n-2=16$, $t_{tabl}=1,746$, and on all the cases when $t_{cal} > t_{tabl}$, i.e., the coefficients of pair correlation for the selected variables are significant.

The structural form of the ADL model of the multiplicative kind is:

$$y_t^6 = \alpha_0 \cdot y_{t-1}^{6^{\alpha_1}} \cdot y_t^{3^{\alpha_2}} \cdot y_t^{5^{\alpha_3}} \cdot y_t^{7^{\alpha_4}} \cdot x_{1t}^{\alpha_5} \cdot x_{2t}^{\alpha_6} \cdot x_{3t}^{\alpha_7} \cdot x_{4t}^{\alpha_8} \cdot x_{5t}^{\alpha_9} \quad (3)$$

Having made the left and right part of the equation logarithmic and introducing new variables, the structural form of the ADL model is written in the additive form:

$$A_1 = a_0 + a_1 A_{1t-1} + a_2 A_{3t} + a_3 A_{5t} + a_4 A_{7t} + a_5 B_{1t} + a_6 B_{2t} + a_7 B_{3t} + a_8 B_{4t} + a_9 B_{5t} \quad (4)$$

The model coefficients are found using the least squares method.

The significance of the regression equation and coefficients of the regression equation were verified by Fisher's F-criterion and Student's t-criterion. With $\alpha=0.05$, $F_{tabl}=30.144$, $F_{cal}=52,8449215$ one can see that $F_{cal} > F_{tabl}$. Besides, the determination coefficient $R^2 = 0.932 > 0.7$, therefore, the regression equation is significant.

The equation with the obtained regression coefficients in its additive form:

$$A_1 = -3,09 + 0,24A_{1t-1} - 0,38A_{3t} - 0,185A_{5t} + 0,085A_{7t} + 1,997B_{1t} - 2,867B_{2t} + 1,163B_{3t} + 0,427B_{4t} - 0,321B_{5t} \quad [TB2] \quad (5)$$

The equation in its multiplicative form:

$$y_{6t} = e^{-3,09} \cdot y_{6t-1}^{0,24} \cdot y_{3t}^{-0,38} \cdot y_{5t}^{-0,18} \cdot y_{7t}^{0,085} \cdot x_{1t}^{1,997} \cdot x_{2t}^{-2,867} \cdot x_{3t}^{1,163} \cdot x_{4t}^{0,427} \cdot x_{5t}^{-0,321} \quad (6)$$

7. Results and Discussion

We shall conduct analysis on the obtained parameters of the equation based on the following properties of the production function: the elasticity coefficient factor shows the percentage that the function will increase by if the factor increases by 1%. A positive elasticity coefficient means that the rise (fall) of a factor causes a corresponding increase (decrease) of the function.

Increase (decline) of the rate y_{t-1}^6 (loss of fresh water storage) by 1% in the previous period leads to an increase (decrease) of fresh water reserves by 0.24% in the current period. This process was termed a "background process". Similarly, the following factors influence the analysed endogenous indicator: y_t^7 growth (reduction of the forest area) by 1% leads to decreasing the fresh water supplies by about 0.085%; the growth of y_t^3 indicators (CO₂ emissions from industry), y_t^5 (the increase of global temperature), x_{2t} (increase in employment), x_{5t} (increase in imports) by 1% leads to decrease of fresh water by 0.38;0.18;2,86;0.32 percent, respectively.

The fresh water extraction is most of all influenced by factors of production activities: total world gross product (x_{1t}), the increase in the economically active population (x_{3t}). The growth of x_{1t} factor by 1% causes an increase of the function at 1.997%. The growth of x_{1t} factor by 1% causes an increase of the function by 1.163%.

The value of the constructed function, "the impact of human activities on the extraction of fresh water" lies in the fact that we can find out the maximum value of the function, which can be deduced in a given year with definite sizes and with a definite number of exogenous factors. The structure of the function "the impact of human activities on the fresh water extraction" remains constant over time. It can be adjusted to work both for very short periods of time, and for longer ones. The principle of adjustment is used in order to upgrade the function in regard to increasing accuracy.

8. Conclusions

A mathematical model for analysing the impact of the background of water reduction on the planet, the effects of human activities and the impact of external environment on the fresh water extraction on the planet is developed and presented. The endogenous variable of the model is associated with the exogenous variables, which evaluate the influencing processes. This paper presents the methods of constructing the model and shows how to find model parameters. Empirical testing of the model was carried out with statistical data from the period of 1995 – 2016. Further research is needed to improve the quality of modelling the impact of human activities on fresh water extraction.

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