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Indicators and indexes of groundwater quality sustainability

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Abstract A structure of environmental indicators, based on Pressure, State, Response indicators was developed. The structure of the indexes describing the quantitative maintenance of Pressure and State indicators, reflecting the groundwater sustainability in conditions of anthropogenic loading, is the result. These indexes that characterize indicators of Pressure and State are subdivided by their content into the following groups: indexes of damage; indexes of pollution (chemical indexes); static indexes (hydrogeochemical indexes); dynamic indexes; and indexes of interaction (including protectability and vulnerability indexes). Assessing and compiling maps of groundwater sustainability using indicators and indexes has an advantage over other methods due to the complexity and the fact that it is also a stage in a general structure of assessing sustainable development of the studied regions. The way to estimate risk and damage to groundwater from pollution using indicators and indexes of groundwater quality sustainability is considered.

Key words damage; groundwater quality; indexes; indicators; risk; sustainable development

INTRODUCTION

The problem of preserving the natural environment, being of the same order as national security in many countries, is an important aspect of the global sustainable development problem. The main postulates of the problem were first formulated at a high level at the Rio-de-Janeiro Meeting in 1992. In many developed countries the basic features of sustainable development are social and economic factors and the environment that are characterized by special indicators and index series. At present the underground part of the hydrosphere (groundwater), as an environment component, has undergone intensive anthropogenic impact and considerable qualitative transformations, that are dangerous for human health and the environment. It is caused by the fact that due to the surface water pollution by industrial, agricultural and domestic wastewater in many countries of the world, groundwater use for potable water supply has essentially increased. Qualitative characteristics for groundwater must be more deep and rich in content, i.e. they should specify processes of groundwater chemical composition changes under natural and anthropogenic factors in historical and contemporary time scales. As groundwater, being an environmental component, is in constant contact with the other components (atmosphere, lithosphere, biosphere and a sphere of anthropogenic activities), its quality directly depends on complex physical-chemical processes, being a result of its contact. Thus, a complex assessment of groundwater quality is needed, using indicators and indexes of sustainability (indicators of the environment). An **Indicator** is an attributive characteristic of the environment state (in our case it is the underground part of the hydrosphere), fixing an impact on it and its response to this impact. **Index** is a quantitative characteristic of an indicator describing the degree of the environment’s sustainability to negative impact of natural and anthropogenic factors. The author has preliminarily elaborated a system of indicators and indexes of groundwater quality sustainability.

A STRUCTURE OF ENVIRONMENTAL INDICATORS AND INDEXES

It can be assumed that an indicator is an attributive characteristic of impact (pollution, depletion, etc.), and that an index is a quantitative characteristic of this impact, that can be expressed by a simple value, despite being concerned with complex parameters and multidisciplinary relationships.

Indicators and indexes structures for developing separate environmental components must have both general and specific peculiarities, which are related to the interactions and impacts both on each other, as well as on the environment as a whole. A basic structure of environmental indicators and indexes, in terms of the system of PSR indicators (i.e. Pressure–State–Response), has been adopted as a working base (UNEP, 1996; OECD, 1994, 1996; Friends of the Earth Europe, 1995). The author has considerably supplemented and extended this structure; indicators and indexes have obtained their qualitative and quantitative characteristics as applied to the environmental state of the underground hydrosphere.

The first indicator, characterizing an impact in the PSR system, states all the time peculiarities of the environmental impact and particularly on the underground hydrosphere. To the author’s mind this indicator does not make it possible to estimate completely the whole ecological situation (with groundwater and other environment components) in complex natural–anthropogenic conditions. Therefore, the PSR system should be revised and completed by peculiarities of different environment components relative to each other (Belousova, 1999, 2000, 2002).

Pressure indicator This should be subdivided into two as follows: *available pressure indicator*, representing an impact that has already occurred, and, *retarded pressure indicator*, characterizing an impact that has occurred in the neighbouring sphere (atmosphere, biosphere pollution), that within some lag time, will reach the groundwater. It is reasonable to single out an additional indicator, the impact of which is predicted for a distant future over 50–100 years (to allow for changes of climate and population growth, as well as predicted environmental and anthropogenic events), a foresight indicator.

Foresight indicator This is so called to avoid confusion in assessing environmental consequences in the present, in the near and in the remote future. Its is very important for deciding on a strategy of sustainable development, not only for the groundwater but also for the environment of separate regions, countries and the planet as a whole. ***Indexes*** characterizing pressure and foresight indicators must quantitatively describe the sources of pressure.

State indicator This characterizes changes in an investigated sphere under pressing negative phenomena. Like pressure indicators, state indicators must be subdivided into two as follows: *available state indicators*, and *future state indicators*. The latter describe changes that will occur under the impact of a source as a result of retarded (or delayed) pressures. ***Indexes*** characterizing indicators of state must quantitatively describe those changes in the studied sphere that have already occurred or will occur under the impact of accomplished or retarded pressure.

Response indicator This characterizes political–social–economic decisions made in response to environmental changes (and groundwater in particular). It provides an elaboration of measures for improving the characteristics for sustainable development. It should represent the level of a political decisions as follows: international, national, regional, and also specify the terms of its realization as follows: operative and perspective (in both the near and remote future). ***Indexes*** characterizing indicators of response must quantitatively characterize political, social and economic measures necessary for improving the environment towards sustainable development.

INDEXES OF GROUNDWATER QUALITY SUSTAINABILITY

Groundwater quality sustainability indexes, characterizing indicators of pressure and state (used for regional and local estimates) can be subdivided according to their meaning into the following groups:

Group I indexes of damage, I_d. Indexes of this group characterize an areal spreading of pollution and are expressed by a ratio between area of spreading (S_s) and total area of a studied object (S_0):

$$I_d = S_s / S_0$$

Index values range from 0 to 1, the more the area is polluted, the closer will the index value of I_d be to 1.

Group II indexes of pollution, I_p (chemical indexes). For estimating the level of groundwater pollution with low-hazard pollutants the following formula can be used:

$$C_1 / MPC_1 + C_2 / MPC_2 + ... + C_n / MPC_n$$

where C_1, C_n are concentration of separate pollutants, and MPC_1, MPC_n represent maximum permissible concentration.

For assessing the level of pollution due to extremely hazardous and highly hazardous pollutants, it is necessary to use both the equation above and additionally:

$$C_1 / BC_1 + C_2 / BC_2 + ... + C_n / BC_n$$

where BC is a background concentration of active ingredients.

If the sum of the concentration ratios is more than 1, then the groundwater is polluted. For all cases, pH must not be outside the limit 6.5–8.5.

For each category of toxic pollutants it is necessary to carry out more detailed research (chemical, radiochemical, etc.) of the pollutant's properties, and the natural chemical elements describing the complexity of processes of interaction in the rock–pollutant–water system. To do this, the pollutants within the limits of one category of toxicity are divided into two classes of rock–pollutant–water interaction: stable and unstable pollutants. Stable pollutants—non changing properties (toxicity) in the geochemical environment (near neutral, acid, alkaline), and unstable pollutants—changing properties (toxicity) in the geochemical environment.

It is necessary to divide pollutants on their stability over time connected to disintegration of pollutants in time (radionuclides, pesticides, etc.). Unstable pollutants can be created and other processes occur in the changing geochemical environment (sedimentation, denitrification, detoxification pesticides, etc.).

Unstable pollutants are connected to change of their toxicity in the geochemical environment; one pollutant can increase the toxicity at change of parameters of the environment, and others can reduce it. Then for pollutants lowering the toxicity (in the given geochemical or time conditions) to enter the lowering factor into the definition of an index of groundwater pollution by it pollutants, and for pollutants raising the toxicity to enter the raising factor into the definition of an index of groundwater pollution by it pollutants. The quantitative estimation of such factors should be established individually for all of the pollutants, depending on geochemical conditions not only in the groundwater, but also in the protective zone through which pollutants get into groundwater. Clearly, such research demands a lot of study, and a generalization of information on the behaviour of various pollutants in the rock–pollutants–groundwater system and the subsequent establishment of factors lowering and raising toxicity.

Group III static indexes (hydrogeochemical indexes)—I_s. Indexes of this group characterize the groundwaters hydrochemical condition. The stability of the hydrocarbonate–calcium system is determined by an index of its state ($I_s^{\mathrm{HCO3–Ca}}$) as follows:

$$I_s^{\mathrm{HCO3–Ca}} = C_e / C$$

where C_e is the experimental coefficient, depending on ion activity, their concentration and calcite solubility product; C is a constant of system equilibrium. If ($I_s^{\mathrm{HCO3–Ca}}$) > 1, then the groundwater is oversaturated with carbonates and can precipitate them. If it is equal to 1, then the carbonate–calcium system is in equilibrium and if it is less than 1, then the system is unsaturated with carbonates and groundwater is characterized with carbonic acid aggressiveness.

The conditions of a sulphate–calcium system are determined by ($I_s^{\mathrm{SO4–Ca}}$) as follows:

$$I_s^{\mathrm{SO4–Ca}} = L_e / L_{\mathrm{CaSO4}}$$

where L_e and L_{CaSO4} are the experimental and theoretically derived gypsum solubility product, respectively. If the index of the sulphate–calcium system is more than 1, then the system is oversaturated and can precipitate gypsum, if it is less than 1, then groundwater is aggressive to gypsum.

Assessment of ionic exchange equilibrium conditions with an ionic exchange index ($I_i^{\mathrm{Ca} \leftrightarrow \mathrm{Na}}$) is as follows:

$$I_i^{\mathrm{Ca} \leftrightarrow \mathrm{Na}} = Y_e / Y$$

where Y_e and Y are experimental and theoretical constants of ionic exchange.

Besides the indexes given above, it is necessary to consider an index of decay under radioactive contamination as well as indexes of complex pollution formation for nitrates, heavy metals, and biodegradation of oil pollution, and in addition other indexes characterizing a variety of physical–chemical processes in the rock–water system.

For characterizing the impact of global pollution factors such as acid rain, it is necessary to introduce an index of sensitivity (I_{sn}). Here sensitivity results mainly from pH values, although in some situations it is necessary to consider a ratio of ion concentrations which determine groundwater buffer properties (e.g. the ability to neutralize the impact of acid rain).

(pH / 8.5) > 1, groundwater is sensitive to alkalization;
> pH > 6.5; HCO_3 = HCO_3b, groundwater is not sensitive to acid rains impact (HCO_3b is background concentration of hydrocarbonate);
> pH > 6.5; HCO_3 > HCO_3b, groundwater has low sensitivity to alkalization;
> pH > 6.5; HCO_3 < HCO_3b, groundwater has low sensitivity to acidification;
(pH / 6.5) < 1, groundwater is sensitive to acidification.

The level of sensitivity is determined by ion ratios as follows:
HCO_3 / HCO_3b; HCO_3 / HCO_3p (p is atmospheric precipitation);
(Ca + Mg) / (HCO_3 + CO_3); (HCO_3 + CO_3) / SO_4;

The last ratio can be used as a zonality index:
(HCO_3 + CO_3) / SO_4 << 1, for humid areas;
(HCO_3 + CO_3) / SO_4 >> 1, for semiarid areas;
(HCO_3 + CO_3) / SO_4 ≥ 1; Cl / SO_4 ≥ 1, for arid areas.

All the ratios are appropriate when there are no other sources of macro-component pollution.

Group IV dynamic indexes, I_d. Indexes of this group characterize pollutant transport and migration behaviour. The *transport peculiarities* of pollutants can be expressed by index I_d^t, equal to a sum of surface runoff (V_{sr}) and groundwater discharge (V_{dg}) ratios, ratios of vertical (V_{dg}^v) and horizontal (V_{dg}^h) components of groundwater discharge, and ratios of atmospheric precipitation (P) and evaporation (E), atmospheric precipitation and infiltration recharge (W):

$$I_d^t = V_{sr} / V_{dg} + V_{dg}^v / V_{dg}^h + P / E + P / W$$

Migration peculiarities of pollutants can be expressed by index I_d^m equal to a sum of ratios of dispersion (diffusion) coefficients for unsorbed ion (D_u), to dispersion coefficient of pollutants (D_i), ratios of unsorbed ion (n_u^*) to effective porosity of pollutant (n_i^*), ratios of unsorbed ion retardation (R_u) to coefficient of pollutants retardation (R_i):

$$I_d^m = D_i / D_u + n_i^* / n_u^* + R_i / R_u$$

For dynamic indexes it is necessary to formulate their values gradations from 0 to 1 for different conditions of their transport and for pollutants of different toxicity classes.

Group V indexes of interaction (I_i). There are *indexes of leakage*, I_i^l, which in this group characterize aquifer interaction within the underground part of the hydrosphere.

$$I_i^l = H_1 / H_2 + H_2 / H_3$$

where H_1, H_2, H_3 are the heads of the first, second, and third aquifers from the surface.

Indexes of protectability, I_i^{pr}, which characterize groundwater interaction with other components of the environment that has been polluted:

$I_i^{pr} = t_p / t_{ch}$

where t_p is travel time of pollutant into the groundwater, t_{ch} is the characteristic calculated time.

Shallow groundwater protectability from any polluting substances depends on the travel time of the front of polluted infiltrating water to the aquifer (t_t). Time of passage of dissolved polluting substances through the soil and aeration zone rocks is determined by the thickness of M, with their filling sorption capacity and the subsequent achieved shallow groundwater level, so:

$$t_t = \frac{M\vartheta}{\nu} + \frac{M\vartheta\,\delta K_d}{W} \qquad (1)$$

where K_d, kg^{-1}, distribution coefficient; δ, kg dm^3, volumetric weight of a rock skeleton; W, m year^{-1}, recharging infiltration of the shallow ground water; θ, (dimensionless size), natural moisture of rocks; M, (m), thickness of a protective zone–depth shallow groundwater; υ, m year^{-1}, rate of precipitation percolation in protected zone.

The first component in (1) characterizes movement of moisture in an unsaturated zone (or movement of neutral polluting substances), the second—physical and chemical interaction (sorption) in the rock–water system (or delay of polluting substances by rock). In a case when the distribution coefficient considerably exceeds unit (as typically for radionuclides) composed in (1) can be neglected the first as well the second when the distribution coefficient is much less than unit.

Time of achievement in groundwater of concentration of equal maximum permissible concentration (t_{mpcc}) for small dangerous polluting substances can be designed by polluting substance (PS) under the following formula:

$$(C - C_s) / (C_p - C_s) = ex\,p(-\lambda\ t_{mcp}) \qquad (2)$$

where C is required concentration PS in shallow groundwater (g L^{-1}) or maximum permissible concentration; C_p, concentration PS in pore solution in an aeration zone (g L^{-1}, in natural conditions); C_s, concentration PS on a surface of the earth (g L^{-1}); e, the basis of the natural logarithm, t_{mpc} is time (day);

$$\lambda = D / n_a\, m\, H \qquad (3)$$

where D, coefficient of dispersion (m^2 day^{-1}), n_a, active porosity, m, aquifer thickness (m); H, thickness of a protective zone (m).

Indexes for sustainable development of the underground part of a hydrosphere must be calculated separately for each class of pollutant toxicity. If dynamic migrational indexes of these materials change less than an order, then index summation is allowed in every group and for every indicator. If pollutants dynamic migration indexes change more than an order, then assessment must be made for every pollutant separately. Summing up the values of indexes is not admitted. For instance: ^{90}Sr and ^{137}Cs belong to an extremely hazardous class, but their migration parameters and MPC differ by two and more orders and assessing groundwater protection and vulnerability to pollution is made separately, as must be done when assessing groundwater quality indexes under radioactive pollution.

USE OF INDEXES OF GROUNDWATER QUALITY SUSTAINABILITY FOR GROUNDWATER POLLUTION RISK ASSESSMENT

Let us consider an application of the determined method for estimation of risks. The estimation forecasts the risks describing the indexes of groundwater sustainability, for a case when the source of pollution is on the surface of the ground and moving through the protective zone separating groundwater from superficial pollution (ground and soils of a zone of aeration), pollution will penetrate through into groundwater (that estimated time) can be expressed as a first approximation as follows:

$$R \;=\; \sum_{i=1}^{n} (I_{i\;\,i}^{vl} \;\times\; D_i) \tag{4}$$

where: R, risk of pollution of groundwater; i,, a polluting substance; n, quantity pollutants; D_i, specific damage ($), I_i^{vl}, is index of groundwater vulnerability to pollution by a certain pollutant, is determined by a ratio technogenic loadings on certain pollutant to protectability from it (protectability of groundwater ability of a protective zone to interfere with penetration pollutant into groundwater):

$$I_i^{vl} = I_p \,/\, - I_i^{pr} = k \times \mathrm{MPC} \;\times\; t_p \,/\, (t_t + t_{mpc}); \tag{5}$$

where k is frequency rate of excess of maximum permissible concentration of the pollutant;

$$D_s = I_d \times D \tag{6}$$

$$I_d = F\,m \tag{7}$$

F is the area of pollution of the Earth surface by the pollutant (m^2); m, thickness of a polluted rocks in the protective zone (m); D, damage to groundwater from pollutant is determined by calculation of the specific cost of clearing of 1 m^3 polluted infiltration water or 1 m^3 of the polluted soil and rocks from pollution on 1MPC ($).

CONCLUSION

The approach considered to estimation of risks and damages to groundwater from pollution is complex. It is based on estimations of groundwater protectability and vulnerability to pollution and on parameters—the indexes describing sustainability of groundwater quality. In aggregate, these methods allow assessment of the existing and forecasting of the future environmental characteristics of the hydrogeochemical condition of groundwater in various territories in various time scales, calculation of the risks and damages to the groundwater from pollution and estimates of the degree of groundwater quality sustainability.

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