

## Structure of ecological indicators and indices for sustainable groundwater development

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**Abstract** A system of indicators and indices of groundwater quality sustainability is described. A system of indicators (Pressure–State–Response) worked out by the European Organization for Economic Co-operation and Development was taken as a basis, but was widened due to addition of a new indicator of *foresight* and also by subdividing all the indicators according to the time of their manifestation (present/future). The response indicator has a more complex structure; it indicates the level of accepted decisions (international, national, regional) and rate of response (planning, operational, proposed). Classification of groundwater sustainability indices has been worked out for anthropogenic conditions. These indices characterizing indicators of Pressure and State are subdivided into the following groups: indices of damage, indices of pollution (chemical indices), static indices (hydrogeochemical indices), dynamic indices and indices of interaction. The use of these indicators and indices when assessing and compiling maps of groundwater sustainability has an advantage over other methods due to its representation of complexity and the fact that it is also a stage in a general structure of assessing sustainable development in the studied regions.

**Key words** groundwater; indicators; indices; sustainable development

### INTRODUCTION

The problem of preserving the natural environment being of the same order as that of national security in many countries, is an important aspect of the global sustainable development problem. The main problems were first formulated at a top level in the Rio de Janeiro Meeting in 1992 (UN, 1992). In many developed countries the basic features of sustainable development are the social and economic factors and the environment, that are characterized by special indicators and indices series. The underground part of the hydrosphere (groundwater), a component of the environment, has undergone, under intensive anthropogenic impact, considerable qualitative transformations that are dangerous for human health and the environment. This is because, due to surface water pollution by industrial, agricultural and domestic waste water in many countries, groundwater use for potable water supply has essentially increased. The qualitative characteristics for groundwater must be more detailed in content, i.e. they should specify processes of groundwater chemical composition change under natural and anthropogenic impacts at both historical and contemporary time scales. As groundwater is in constant contact with other components of the environment (atmosphere, lithosphere, biosphere and the sphere of anthropogenic activity), then its quality directly depends on complex physical–chemical processes. Thus, a complex assessment of groundwater quality is needed, using indicators and

indices of sustainability. An *indicator* is an attributive characteristic of the environmental state (the underground part of the hydrosphere), fixing an impact on it and its response to this impact. An *index* is a quantitative characteristic of the indicator describing a degree of environmental sustainability to negative impacts of natural and anthropogenic factors.

## STRUCTURE OF ENVIRONMENTAL INDICATORS AND INDICES

The author's main aim was to develop a system of environmental indicators and indices that characterized the underground hydrosphere as a component of the environment and to assess the ecological state of the underground hydrosphere using these indicators and indices. A basic structure of environmental indicators and indices, in terms of a 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 indices have qualitative and quantitative characteristics relevant to the ecological state of the underground hydrosphere.

The first indicator characterizing an impact in the PSR system, represents all the continuous impacts of environmental change 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. Thus PSR system should be revised to include the features of different environmental components relative to each other (Belousova, 1998).

The pressure indicator (PI) should be subdivided into two as follows: available pressure indicator (API), representing an impact that has already occurred, and retarded pressure indicator (RtPI), characterizing an impact that has occurred in the neighbouring sphere (atmosphere, biosphere pollution), and 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 ecological and anthropogenic events), a foresight indicator.

The foresight indicator (FI) is so called to avoid a confusion in assessing ecological consequences at present, in the near and in the remote future. This is very important for deciding on a strategy of sustainable development not only for groundwater but also for the environment of separate regions, countries and the planet as a whole.

Indices (I1), characterizing pressure and foresight indicators must quantitatively describe the sources of pressure.

The state indicator (SI) characterizes changes in a given sphere under pressing negative phenomena (pressures). Like pressure indicators, state indicators must be subdivided into two as follows: available state indicators (ASI), and future state indicators (FSI). The latter describe changes that will occur under the impact of a source as a result of retarded (or delayed) pressures.

Indices (I2) 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.

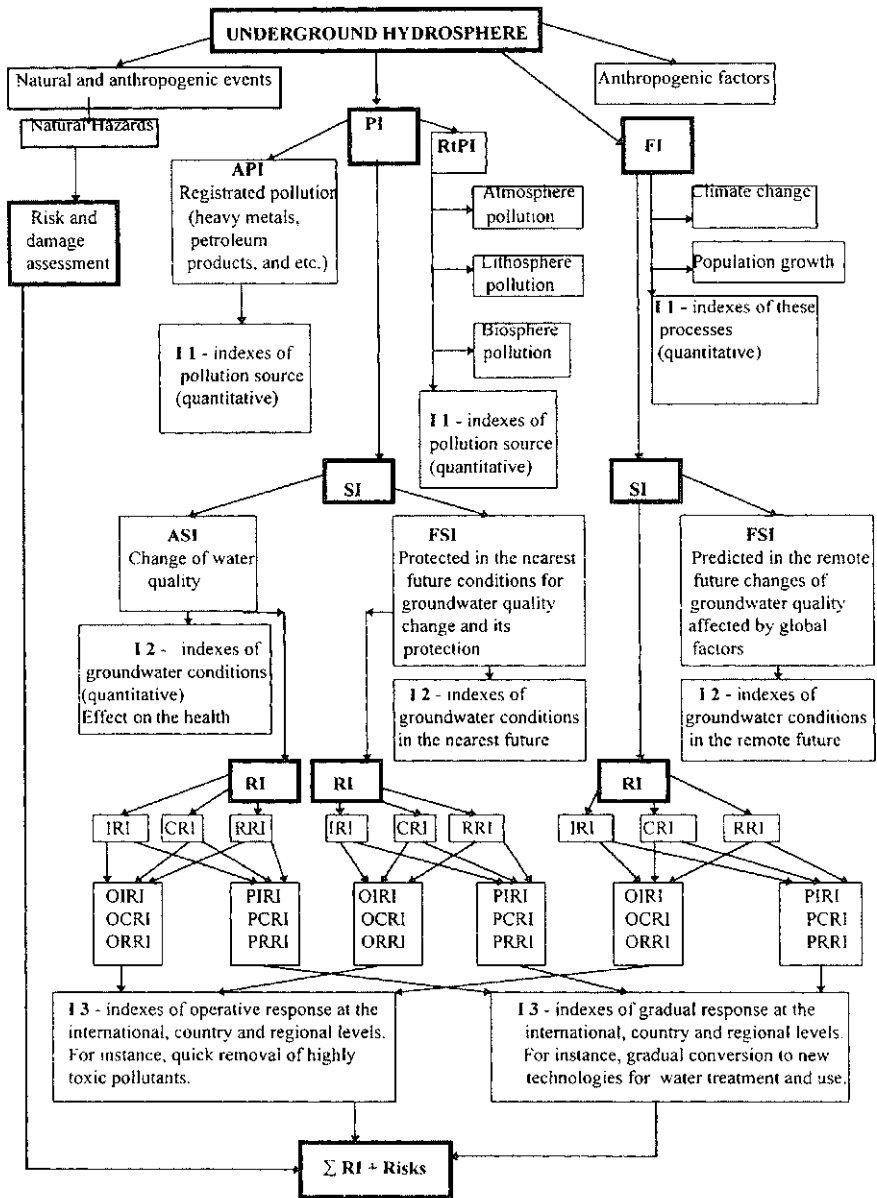


Fig. 1 Structure of ecological indicators and indices of the underground hydrosphere.

The response indicator (RI) represents political/social/economic decisions made in response to environmental changes (in 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 (IRI), national (NRI), regional (RRI), and also specify the terms of its realization as follows: operative (OIRI, OCRI, ORRI), and proposed (in both near and remote future: PIRI, PCRI, PRRJ).

Indices (I3) characterizing indicators of response must quantitatively characterize the political, social and economic measures necessary for improving the environment towards sustainable development.

A potential structure for ecological indicators and indices relevant to the underground hydrosphere is given in Fig. 1.

## INDICES OF GROUNDWATER SUSTAINABLE DEVELOPMENT

Groundwater sustainable development indices, characterizing indicators of pressure and state can be subdivided according to their meaning into the following groups:

**Group I** Indices of damage,  $I_d$ . These characterize areal spreading of pollution and are expressed by a ratio between the area of spreading ( $S_s$ ) and total area of a studied object ( $S_0$ ):

$$I_d = S_s/S_0$$

Indices values range from 0 to 1, the greater the area polluted, the closer the index value of  $I_d$  is to 1.

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

$$C_1/MPC_1 + C_2/MPC_2 + \dots + C_n/MPC_n$$

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

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

$$C_1/BC_1 + C_2/BC_2 + \dots + C_n/BC_n$$

where  $BC$  is a background concentration of active ingredients.

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

**Group III** Static indices (hydrogeochemical indices)  $I_s$ . Indices of this group characterize groundwater hydrochemical condition. The stability of the hydrocarbonate–calcium system is determined by an index of its state ( $I_s^{\text{HCO}_3\text{-Ca}}$ ) as follows:

$$I_s^{\text{HCO}_3\text{-Ca}} = C_e/C$$

where  $C_e$  is an experimental coefficient depending on ion activity, their concentration and the calcite solubility product;  $C$  is a constant of system equilibrium. If ( $I_s^{\text{HCO}_3\text{-Ca}} > 1$ ), then the groundwater is oversaturated with carbonates and can precipitate them. If it is equal to 1, the carbonate–calcium system is in equilibrium, and if it is less than 1, the system is undersaturated with carbonates and groundwater is characterized by carbonic acid aggressiveness.

The condition of sulphate–calcium systems is determined by ( $I_s^{\text{SO}_4\text{-Ca}}$ ) as follows:

$$I_s^{\text{SO}_4\text{-Ca}} = L_e/L_{\text{CaSO}_4}$$

where  $L_e$  and  $L_{CaSO_4}$  are an experimental and a theoretically derived gypsum solubility product. 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 the ionic exchange index ( $I_i^{Ca \leftrightarrow Na}$ ) is as follows:

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

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

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

To represent 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 the groundwater buffering properties (e.g. ability to neutralize the acid rain impact):

- (pH/8.5) > 1, groundwater is sensitive to alkalization;
- > pH > 6.5;  $HCO_3 = HCO_3b$ , groundwater is not sensitive to acid rain impact ( $HCO_3b$  is background concentrations 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:

- $(HCO_3 + CO_3)/SO_4 \ll 1$ , for humid areas;
- $(HCO_3 + CO_3)/SO_4 \gg 1$ , for semiarid areas;
- $(HCO_3 + CO_3)/SO_4 \geq 1$ ;  $Cl/SO_4 \geq 1$ , for arid areas.

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

**Group IV** Dynamic indices,  $I_d$ . These represent pollutant transport and migration behaviour. The *transport characteristics* of pollutants can be expressed by index  $I_d'$ , equal to the sum of the ratios: surface runoff ( $V_{sr}$ ) to groundwater discharge ( $V_{dg}$ ), vertical ( $V_{dg}^v$ ) to horizontal ( $V_{dg}^h$ ) component of groundwater discharge, atmospheric precipitation ( $P$ ) to evaporation ( $E$ ), and atmospheric precipitation to infiltration recharge ( $W$ ):

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

The *migration characteristics* of pollutants can be expressed by index  $I_d''$  equal to the sum of the ratios: dispersion (diffusion) coefficients for unsorbed ions ( $D_u$ ), to the dispersion coefficient of pollutants ( $D_i$ ), unsorbed ion ( $n_u$ ) to effective porosity of

pollutant ( $n_i^*$ ), and unsorbed ion retardation ( $R_u$ ) to coefficient of pollutant retardation ( $R_i$ ):

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

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

**Group V** Indices of interaction ( $I_i$ ). There are *indices of leakage*,  $I_i^l$  which represent aquifer interaction with the underground part of hydrosphere.

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

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

*Indices of penetration*,  $I_i^{pn}$ , characterize groundwater interactions with other components of the environment that have been polluted:

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

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

The system of indicators and indices suggested here is under development and it will be added to and widened after studying more complex natural and anthropogenic conditions of groundwater quality transformation. Assessment of the sustainability of the surficial hydrosphere and of the lithosphere (soil and rock in the unsaturated zone) can be made analogously.

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