Ecological indicators and indices of sustainable development

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Abstract A system of ecological Pressure-State-Response (PSR) indicators has been developed. The first indicator, characterizing an impact in the PSR system must take into account all time peculiarities of the impact on the underground hydrosphere. However, this will not help to fully assess the whole ecological situation in terms of groundwater in complex natural-anthropogenic conditions. Pressure indicators must be subdivided into Present (current) and Retarded (or delayed) Pressure Indicators. An additional indicator, the Foresight Indicator makes it possible to avoid confusion in assessing ecological consequences at present, with those in the near and remote future. State Indicators characterize changes in the hydrosphere under the impact of negative events (Present and Future State Indicators). Response Indicators characterize political, social and economic decisions. Index groups can characterize each of these indicators.

INTRODUCTION

The development and use of indicators and indexes, characterizing the ecological state of different territories is closely connected with strategies for sustainable development. A suggested concept for forming a structure of ecological indicators and specifying them in terms of indices is a preliminary attempt to create an interrelated structure, based on cause-and-effect connections and time-and-space processes. These affect both pre-existing anthropogenic types of ecosystems and those whose further evolution may be pollution-impacted. It is reasonable to elaborate a system of environmental indicators and indices by their main components (atmosphere, biosphere, lithosphere, and hydrosphere), and considered in terms of the organic (biotic) and inorganic (abiotic) components as developed within an anthropogenic sphere.

A STRUCTURE OF ENVIRONMENTAL INDICATORS AND INDICES

It can be assumed that an indicator is an attributive characteristic of impact (pollution, resource 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 relations. Indicators and index 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 indices, in terms of a system of PSR indicators (i.e. Pressure-State-Response), has been adopted as a working base (Friends of the Earth Europe, 1995).

The first indicator, characterizing an impact in the PSR system states all the time peculiarities environmental impact and particularly on the underground hydrosphere. 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.

Pressure indicators (PI) These should be subdivided into two as follows:

- available pressure indicator (API), representing an impact that has already occurred, and,
- a retarded pressure indicator (RtPI), 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 pollution, as well as predicted ecological and anthropogenic events), a foresight indicator.

Foresight indicator (FI) This is so called to avoid confusion in assessing ecological consequences at present, in the near and 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. Sub-Index Groups (I1), characterizing pressure and foresight indicators must quantitatively describe the sources of pressure.

State indicators (SI) These characterize changes in a studied sphere under negative phenomena pressure. Like pressure indicators, state indicators must be subdivided into two as follows:

- available state indicator (ASI), and,
- future state indicator (FSI).

The latter describes changes that will occur under the impact of a source as a result of retarded (or delayed) pressures. Sub-Index Groups (I2) characterizing indicators of state must quantitatively describe those changes in a studied sphere that have already occurred or will occur under the impact of accomplished or retarded pressure.

Response indicators (RI) These characterize political-social-economic decisions made in response to environmental changes (and groundwater in particular). They provide an elaboration of measures for improving the characteristics for sustainable development. They should represent the level of a political decision as follows: international (IRI), national (CRI), regional (RRI), and also specify the terms of its realization as follows: operative (OIRI, OCRI, ORRI), and perspective (in both near and remote time (PIRI, PCRI, PRRI). Sub-Index Groups (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 forming ecological indicators and indices of the environment is given in Fig. 1.

STRUCTURE OF ECOLOGICAL INDICATORS AND INDICES OF THE UNDERGROUND HYDROSPHERE

The below ground hydrosphere, containing fresh groundwater is a thin layer of water, not universally spread inside the lithosphere. The fresh groundwater portion of the

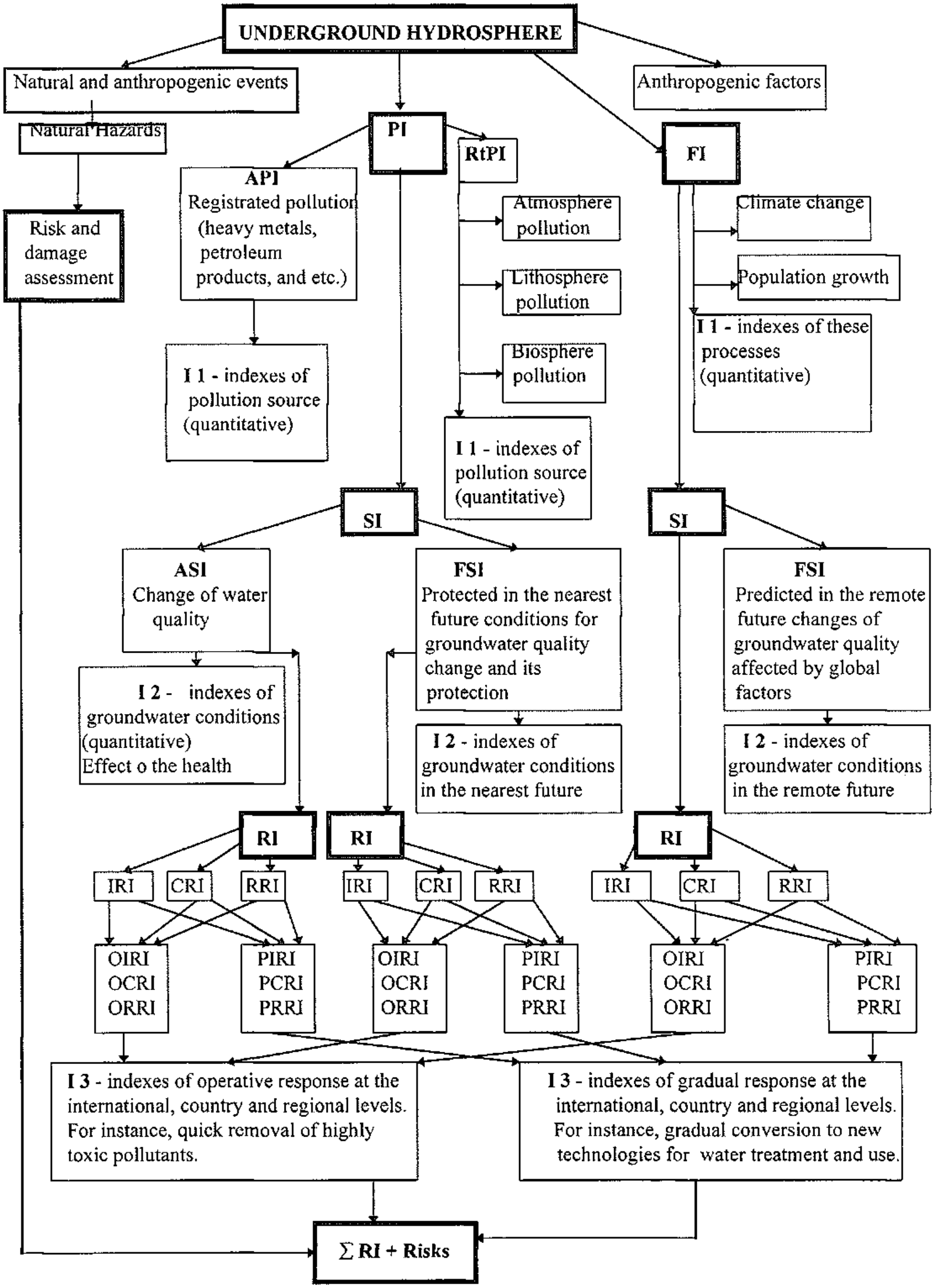

Fig. 1 The structure of indicators and indices for the underground hydrosphere: a schematic example.

total water reserve on the Earth is only about 2.6%, but in many regions it is the only source of water supply. Therefore, when assessing regional sustainable development, it is necessary to consider the role of groundwater along with surface supplies.

Fresh groundwater as a source of potable and domestic water supply, if compared with surface sources, has a number of advantages. It is, as a rule, characterized by a better quality state, is more safely protected from pollution and infection, but due to limited resources it cannot provide for the total potable water demand of many regions and big cities. According to confirmed data, more than a 1000 groundwater pollution sources have been revealed in Russia, with 759 being of a stable character. An overwhelming majority of pollution sources (75%) are found in the most polluted European part of Russia. An underground hydrosphere seldom has an immediate contact with pollution sources; these are usually located on the ground surface or in some neighbouring sphere; there is a lag before pollution reaches the groundwater. This is the essential argument for widening the PSR system. The impact of the polluted atmosphere, biosphere and lithosphere will collectively affect the underground hydrosphere after some time through complex interactions.

INDICES OF GROUNDWATER CONDITIONS

Groundwater condition 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) Indices of this group characterize an areal spreading of pollution and are expressed by a ratio between the area of spreading (S_s) and the total area of a studied object (S_0):

$$I_d = S_s / S_0$$

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

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

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

(where C_1, C_n are the 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:

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

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 values must not be outside the limit 6.5–8.5.

Group III – static indices (or hydrogeochemical indexes) (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 ($I_s^{HCO_3-Ca}$) as follows:

$$(I_s^{\mathrm{HCO_3-Ca}}) = C_e / C$$

where C_e is an experimental coefficient, depending on ion activity, their concentration and calcite solubility product. C is a constant of system equilibrium. If $(I_s^{\mathrm{HCO_3-Ca}}) > 1$, 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 undersaturated with carbonates and groundwater is characterized by carbonic acid aggressiveness.

Conditions of the sulphate-calcium system are determined by $(I_s^{\mathrm{SO_4-Ca}})$ as follows:

$$(I_s^{\mathrm{SO_4-Ca}}) = L_e / L_{\mathrm{CaSO_4}}$$

where L_e and $L_{\mathrm{CaSO_4}}$ are experimental and theoretically derived gypsum solubility products. 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 the groundwater is aggressive to gypsum. Assessment of ionic exchange equilibrium conditions $(I_i^{\mathrm{Ca\leftrightarrow Na}})$ is as follows:

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

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

Besides the indices given above, it is necessary to consider an index of decay for 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.

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. 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 rain 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 an ionic ratio 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;
$(HCO_3 + CO_3) / SO_4 \geq 1$;	$Cl / SO_4 \geq 1$	for arid areas.

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

Group IV – dynamic indexes (I_d) Indices within this group characterize pollutant transport and migration behaviour. The Transport Characteristics of pollutants can be expressed by an index I_d^t, equal to the 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, 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 Characteristics of pollutants can be expressed by an 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 a coefficient of pollutant retardation (R_i):

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

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

Group V – indices of interaction (I_i). These are:

– Indices of Leakage, I_i^l, which in this group characterize aquifer interaction within the underground part of the hydrosphere:

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

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

– Indices of Penetration, I_i^{pn}, which characterize groundwater interaction with other components of the environment that has been polluted:

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

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

PRELIMINARY ASSESSMENT OF UNDERGROUND HYDROSPHERE ECOLOGICAL STATE USING SUSTAINABLE DEVELOPMENT INDEXES

In a Urals oil field region a preliminary assessment of the groundwater ecological state over a five year period of observation has been made, using the developed sustainable development indices. While assessing the impact of a global factor (acid rain) on the chemical composition of the higher level aquifer, the influence was also considered of a regional pollution factor (pollution by outflow from surface industrial brines and leakage of mineralized water from the lower aquifers) on the chemical composition of groundwater in both higher and lower aquifers as well as the effect of local factors such as spray blow-outs (Belousova & Krainov, 1998). Previous hydro-geochemical study of the oil field permitted consideration of pollution from low-level hazard pollutant macro-components.

The map of groundwater ecological conditions for the high level aquifer is shown in Fig. 2. There are categories of groundwater ecological state changes shown for both the right and left bank parts of the oil field. If it is assumed that all the sites singled out in the hydro-geochemical zoning map are similar, then the areal distribution of different ecological states of groundwater in the oil field will be as in Table 1.

It is clear from Table 1 and Fig. 2 that the right bank section of the oil field is characterized by more unfavourable ecological groundwater states with 53% falling within the highly and catastrophically unstable groups and 45% occurring on the left bank. The total area of unstable, highly and catastrophically unstable states are 67% and 95% for the right and left banks respectively. The latter is a somewhat excessive value as in 7 out of 11 sites, the range of groundwater conditions fluctuates between stable and unstable states. In general, both deposits can be characterized as territories exhibiting unstable to catastrophically unstable development (evolution) of groundwater chemical composition due to the impact of anthropogenic factors.

The impact of oil field exploitation and acid atmospheric precipitation has promoted transformations in groundwater chemistry in the higher level aquifer towards a catastrophically unstable development of the underground hydrosphere, and this process is irreversible. To revert to a fully sustainable development, a number of measures must be urgently worked out to improve the groundwater ecological state and applied in practice.

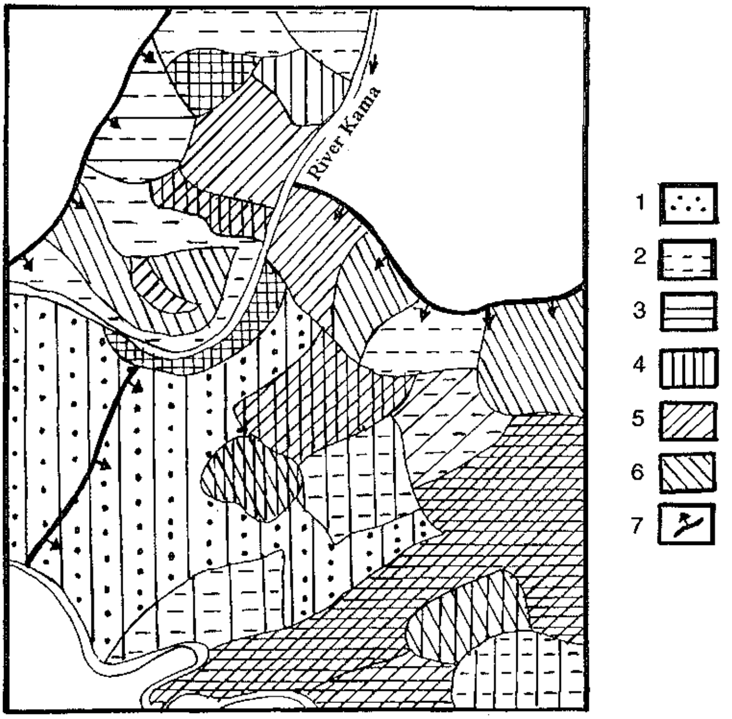

Fig. 2 Map of the groundwater ecological state for the higher level aquifer (scale about 1: 500 000). 1 - stable state; 2 - slightly unstable state; 3 - medium unstable state; 4 - unstable state; 5 - highly unstable state; 6 - catastrophically unstable state; 7 - boundaries of the oil field.

Table 1 Distribution of areas (%) with different ecological states of groundwater in the higher level aquifers in the oil field.

Category of stability	Right-bank part	Left-bank part
Stable state	0	0
Slightly unstable state	19	5
Medium unstable state	14	4
Unstable state	14	50
Highly unstable state	34	27
Catastrophically unstable state	19	18

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