Digital Technologies for Monitoring and Forecasting the Environmental Situation in Siberia

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Abstract—This article is dedicated to ecological monitoring of Siberia. The regional features of environmental problems are presented, and an integrated approach to the organization of digital monitoring as a tool for understanding what is happening and its forecasting is proposed. An approach to the digitalization of environmental monitoring based on digital platforms, which provide the collection, storage, and processing of large amounts of data in a distributed network of sensors, and satellite information, as well as services for modeling and forecasting, is considered. The results of digital monitoring in the Baikal natural territory are presented. This article is based on a report heard at the RAS Presidium meeting on June 22, 2021.

Keywords: ecology, anthropogenic impact, digital monitoring, digital platform, WPS service, modeling, forecasting

The Siberian Federal District (SFO) includes a huge territory (of a total area of 4 361 800 km²) with amazing and unique nature; it is rich in natural resources and minerals. The population of the Siberian Federal District is about 17 mln people; the population density is low, 3.9 per 1 km². The gross regional product is ₽7134 bln.

The rapid development of industry, active mining, and ill-conceived methods of farming in the region have had a detrimental effect on nature and have led to an increase in risk to the life and health of the population [1, 2]. The ecological situation in the district has great contrasts. In the northern and central parts, it is relatively satisfactory (local pollution of rivers can be noted); in the southern part, it is acute (due to salinization and deflation of soils and degradation of forests); and in areas where large cities and administrative centers are located, it is very acute (due to industrial pollution of the atmosphere, waters, and soils). The cities of Krasnoyarsk, Noril’sk, Abakan, Angarsk, Iskitim, Irkutsk, Zima, Bratsk, Kyzyl, and Lesosibirsk are recognized as environmentally unfavorable.

Despite the fact that the SFO is sparsely populated, the region has a whole range of environmental problems. Among the most acute are the following.

- Anthropogenic technological impact and pollution of the atmosphere, water resources, and soil cover by industrial enterprises of the metallurgical, fuel and energy, mining, timber, and oil and gas extraction complexes.
- Environmental accidents and disasters. Problems of natural and anthropogenic safety of strategic, critically important, and potentially dangerous objects of the technosphere and hydraulic structures.
- Problems of the boreal forests of Siberia (increase in the area of fires, epidemiological damage and growth of diseases, illegal logging, low level of reforestation).
- Significant environmental and landscape changes, pollution of and changes in the genesis of soils, wind erosion, and an increase in the area of disturbed and degraded lands.
- Problems of collection, recycling, and disposal of household and industrial waste, including radioactive waste.
- Increased danger of geodynamic processes (seismicity, landslides, avalanches, mudflows, etc.).
- Water use problems (excessive pollution of water bodies, unregulated consumption, etc.).
• Aggravation of the sanitary and epidemiological situation.
• Changes in the species composition of flora and fauna despite the large areas of protected territories.
• Problems of the Siberian Arctic (climate change and ice melting, pollution of the waters of the northern seas, reduction in the population of arctic animals, and changes in their habitat).

The increase in anthropogenic loads on the environment to a scale that threatens the reproduction of natural resources and the growth of risks to the life and health of the population due to their inefficient use make up one of the seven big challenges identified in the Strategy for Scientific and Technological Development of Russia. Table 1 shows data on the danger of natural emergencies in the subjects of the Siberian Federal District. In most cases, they are the result of accumulated environmental damage. Note that Irkutsk oblast is one of the few in which all three types of natural emergencies are observed—floods, forest fires, and earthquakes.

The foregoing suggests the following conclusion: the problems of natural—anthropogenic and environmental safety are a result of the destabilization of the “society—technosphere—natural environment” (S–T–N) system caused by ignoring the requirements of the concept of sustainable development. Today, the contradictions of scientific and technological progress are exacerbated: the high growth rates of the technosphere lead to the emergence of new threats to man, society, and the natural environment. Sustainable development of the fragile natural system requires the following:

• moving from solving individual environmental problems to a comprehensive provision of natural and anthropogenic safety of the region;
• organizing the monitoring of natural and anthropogenic safety, which will make it possible to stabilize crisis phenomena in the economy, ensuring the safety and functioning of fixed production assets, as well as protecting the population and territories from natural and anthropogenic emergencies;
• assessing the level of natural, anthropogenic, and environmental risks to form the basis for economic mechanisms of regulating natural and anthropogenic safety and reducing the likelihood of negative consequences.

Monitoring and forecasting of the environmental situation in regions across the world, in Russia, and, in particular, in Siberia are extremely topical, given that the interaction between man and nature and the impact of the consequences of technological development and other anthropogenic factors on the environment are global challenges of the 21st century. Today, such monitoring is dispersed among dozens of departments using hundreds of methods, which hinders improving its quality and obtaining comprehensive information. For example, Lake Baikal has been studied for more than 100 years, its environmental monitoring being provided by Roshydromet, the Federal Agency for Fishery, and many other structures. However, when the crisis began in the coastal zone of Lake

| Subjects of the region | Floods | Forest fires | Earthquakes | Total degree of danger of emergency situations of the subject |
|------------------------|--------|-------------|-------------|-----------------------------------------------------------|
|                        | Flood area, thou. km² | Population in flood zones, thou. people | Fire area, thou. km² | Population in fire zones, thou. people | Seismic area, thou. km² | Population in earthquake zones, thou. people | |
| Altai Republic         | 0.5    | 13          | 12          | 5               | 40               | 60               | 3            |
| Tyva Republic          | 0.5    | 30          | 40          | 9               | 110              | 160              | 3            |
| Republic of Khakassia  | 6      | 95          | 10          | 7               | 20               | 70               | 2            |
| Altai krai             | 20     | 120         | 8           | 10              | 120              | 90               | 1            |
| Krasnoyarsk krai      | 3      | 140         | 1500        | 40              | 60               | 150              | 1            |
| Irkutsk oblast        | 0.9    | 70          | 180         | 30              | 160              | 300              | 1            |
| Kemerovo oblast       | 2.7    | 70          | 16          | 15              | 130              | 120              | 1            |
| Novosibirsk oblast    | 13     | 300         | 20          | 15              | 107              | 320              | 1            |
| Omsk oblast           | 4.0    | 16          | 2.5         | 18              | –                | –                | 1            |
| Tomsk oblast          | 3.5    | 40          | 0.9         | 70              | –                | –                | 1            |
| Total                 | 54.1   | 894         | 1789.4      | 219             | 747              | 1270             | –            |
Baikal in 2003, it turned out that no one was monitoring the situation there.

The ecological state of a number of regions of Siberia is of deep concern to both the scientific community and the population living there, and its fundamental improvement requires close cooperation between the Russian Academy of Sciences; the Russian Ministry of Education and Science; the Russian Ministry of Natural Resources; the Rosatom State Corporation; and other departments, interested organizations and business structures, and regional government bodies and local authorities. To improve the quality of environmental monitoring, it is necessary to create an information system for observing, assessing, and predicting changes in the state of the environment to identify the anthropogenic component of these changes against the background of natural processes. Such a system should help not only to accumulate, systematize, and analyze the huge array of data but also to assess the admissibility of certain loads on the environment as a whole and on the reserves of the biosphere.

At present, much attention is paid to the study of basic and applied environmental problems. In this regard, the use of integrated digitalization\(^1\) becomes relevant, particularly for digital monitoring of the ecological state of natural areas. It is applicable both for specially protected objects like Lake Baikal, the Vasyugan Swamp, or Siberian boreal forests, the state of which significantly affects weather conditions and the ecological situation in Siberia, the Urals, and the Far East, and for industrialized regions, for example, the Kuzbass mining complex.

Information systems to support certain aspects of environmental monitoring are developed and maintained in Krasnoyarsk krai (http://gis.krasn.ru/) [3], in Kemerovo oblast (http://biodiv.ict.sbras.ru:8080/red-book/welcome) [4], and in some other regions of Siberia. In real time, they accumulate meteorological and climatic information and collect data on atmospheric air pollution, hydrological observations, the state of biodiversity, bottom sediments, and soil. Among the foreign ones, noteworthy is the Group on Earth Observations Biodiversity Observation Network (GEO BON) (https://geobon.org/). It is designed to improve the collection of biodiversity observational data and related user services that are of interest not only to the scientific community but also to environmental decision makers. Also note the national biodiversity monitoring system in Mexico, based on remote sensing data and a ground network for collecting information from 2150 sites.

In the context of the development of the digital paradigm in the world, the implementation of digital platform principles and the methodology and tools to create application modules in solving environmental problems is becoming a priority. This is also associated with large volumes of thematic and spatiotemporal data of environmental monitoring, with a significant number of software and hardware systems, as well as the improvement of data transmission systems.

In the past, institutes of the RAS Siberian Branch have been actively involved in the digital transformation of environmental monitoring in Siberia, in particular, in the creation of basic types of new digital platforms, digital twins for forecasting, and thematic WPS\(^2\) services, which make it possible to simulate scenarios of events. A digital platform is a medium for accumulating, exchanging, and managing data in a structured form, as well as a system for calling business functions with services connected to it through technological interfaces of participants in the digital ecosystem—a regional partnership of participants in monitoring Siberia, supporting open information-computing and telecommunication data exchange, processing services, models, and digital tools and services. In the approach under development, there are three basic types of digital platforms: instrumental, infrastructural, and applied (Fig. 1).

The instrumental target platform provides access for participants in the target monitoring ecosystem of Siberia to the development and debugging of applied information and software and hardware, providing them with instrumental services for processing spatio-temporal data and their interfaces. The infrastructural digital platform provides for the creation of applied software and hardware for monitoring Siberia, thematic WPS services for processing and distributed data storage based on an information and analytical environment and service-oriented and end-to-end technologies. The applied digital platform operates with processed data at the level of a separate group or type of monitoring as a whole and also supports the algorithmic exchange of services between participants in the digital ecosystem using the information and analytical environment and technological infrastructure.

An important component of the digital transformation of environmental monitoring is providing it with powerful information and computing resources. Today, a distributed data processing center for environmental monitoring is being created at the RAS Siberian Branch (SB RAS) (Fig. 2). In addition to increasing the total disk space, participants combine regional data processing centers into a single infra-

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\(^1\) Digitalization is understood as the process of introducing a systematic approach to the use of digital resources, the introduction of digital technologies, cyber-physical systems, the integration of sensors into all components of equipment, and the replacement of physical or analog resources with digital data (Author’s note).

\(^2\) WPS (Web Processing Service) is a standard for implementing geoprocessing services. Geoprocessing can include any algorithm, calculation, or model that operates on spatially referenced vector or raster data. The WPS standard is being developed by the Open Geospatial Consortium (OGC) (Editor’s note).
structure, which provides researchers with reliable storage of accumulated data and the ability to access information about the state of various objects in the Siberian Federal District. SB RAS Supercomputer centers are connected to this infrastructure.

The use of digital instrumental and infrastructural platforms, the service-oriented paradigm, end-to-end technologies, and big data and their filling with content in the form of mathematical and computer models of individual processes and ecosystems as a whole, supplemented by tools for collecting and analyzing ecosystem monitoring data, including those obtained using remote Earth sensing and terrestrial sensor networks, substantiate the achievability of the expected results.

The approach considered was tested during the implementation of the major scientific project “Fundamentals, Methods, and Technologies of Digital Monitoring and Forecasting of the Ecological Situation for the Baikal Natural Territory.” The conceptual
foundations of the six scientific directions of this project are formed by a consortium of 13 SB RAS institutes from Irkutsk, Angarsk, Ulan-Ude, Tomsk, and Novosibirsk. The first of them concerns the basics of the instrumental, infrastructural, and applied digital platforms for environmental monitoring; the second direction is the monitoring of extreme natural phenomena and anthropogenic emissions into the atmosphere; the third deals with monitoring the hydrological regimes of water bodies; the fourth is assessment of environmental risks associated with the state of the vegetation cover; the fifth concerns monitoring of extreme geological and ecological—geochemical processes; and the sixth is medical—ecological and epidemiological monitoring.

Within the framework of the first direction, the concept of digital transformation of scientific research on environmental problems of the Baikal natural territory (BNT) [5] was proposed using a digital platform as an open system of algorithmic network interaction, accumulating the latest methods and technologies and providing access to large volumes of spatiotemporal data, processing services, and digital tools and services. To date, the architecture of the system for storing information about the object of study and the means of access to it and the infrastructural component of the digital platform for displaying spatiotemporal data in the form of tables, diagrams, and maps have already been developed, and a prototype of the service management subsystem has been created.

In the second scientific direction, the results of continuous automatic monitoring (the resolution level ranges from minutes to days) of the transfer of gaseous impurities—SO$_2$, NO/NO$_2$, CO, and Hg, as well as meteorological parameters recorded by the Listvyanka atmospheric station [6], were obtained. It is shown that the most severe pollution of the atmosphere in the central ecological zone in the southern part of the lake occurs during the transfer of air masses from the northwest in winter. In addition, a continuous series of data has been obtained from round-the-clock measurements of the concentration of greenhouse gases (ground-level ozone, nitrogen oxide, nitrogen dioxide, sulfur dioxide), aerosol microphysical characteristics, the chemical composition of aerosols, the aerosol optical depth of the atmosphere, and the meteorological and turbulent parameters of the atmosphere using unique modern equipment (Fig. 3). The energy objects of the Baikal natural territory have been studied. An information structure is proposed to determine their ecological characteristics. Methods and models for determining the indicators of the wind, helio-, geo-, and biopotential used in substantiating plans for the construction of renewable energy sources are described mathematically. The results of this work make it possible to form a correct structure of the developed information and analytical system and requirements on its information content for further research on the project.

Within the third direction (monitoring of the hydrological regimes of water bodies), a pilot network of stations for digital monitoring of the hydrological situation on Lake Baikal and its inflowing tributaries has been developed and put into trial operation [7]. Among them is an autonomous complex for measuring the hydrophysical, hydrochemical, and hydrooptical parameters of the littoral of Lake Baikal, located near the village of Bol’shie Koty [8]. The data obtained make it possible for the first time to follow in detail the daily and monthly variations of these parameters during the transition period from summer to winter. A prototype station for monitoring the thickness of the ice cover has been developed and manufactured. The accumulated data from monitoring the level of Lake Baikal, obtained by the Limnological Institute, SB RAS, in 2015–2019, have been analyzed, processed, and verified. Comparison with the data of the Yenisei Basin Water Administration and the average daily indicators of observation posts of the Irkutsk and Trans-Baikal departments for hydrometeorology and environmental monitoring reveals significant discrep-
ancies in the indicators, the causes of which are not yet clear.

The assessment of environmental risks associated with the state of the vegetation cover (the fourth scientific direction) made it possible to identify areas with the highest species diversity and to propose a concept for a monitoring network of climatically important parameters with account for the zonality and landscape diversity of the coast of the Baikal mountain frame. The key indicators of forest pathology monitoring have been determined, and a technology for reflecting the environment-forming functions of the forest ecosystems of the Baikal natural territory (carbon uptake and oxygen production) has been developed. Under laboratory conditions, the duration of the development of the generation of an invasive stem dendrophage of the Siberian fir, new for the BNT, has been established. An algorithm for the model of the potential distribution of biocenoses and their bioproductivity has been proposed. A monitoring system for forest fires and a method for identifying burnt areas have been developed. Importantly, these scientific studies will certainly give a tangible forestry and environmental effect. The quality of decision making in the field of the protection of forests from diseases and pests can be improved with the start of the functioning of the system, which should provide automated collection, storage, and processing of environmentally significant information for assessing the state and forecasting the development of forests and identifying trends both in time and in space.

The main result obtained within the fourth scientific direction is the creation of a pilot network of the Listvyanka, Bugul’deika, and Priol’khon’e test sites, which provides real-time monitoring of dangerous geological processes in the western part of the central ecological zone of the Baikal natural territory (Fig. 4). Analyzing the observation results will make it possible to assess effectively the dynamics of processes affecting the state of the unique ecosystem of Lake Baikal and its water resources. Importantly, the quality of the forecast of extreme manifestations will also increase.

At the Bugul’deika test site, using drilling and mining operations, stations were created for constant measurements of the speed of the Earth’s crust, seismic and microseismic vibrations, the radon concentration in the soil, and the temperature regime of rocks, and for periodic measurements of the electrical resistivity of the rock mass in the upper part of the Earth’s crust. Similar monitoring is carried out at the Priol’khon’e and Listvyanka test sites.

To predict hazardous geological processes of an endogenous nature, models of deformation of the earth’s surface, principles for predicting strong earthquakes based on the analysis of the radon field, and a method of monitoring the deformation of rocks on small (a few meters) and medium (a few hundred meters) voltage measurement bases have been developed, as has a technique for detecting signs of the preparation of close, moderate, and strong earthquakes based on a detailed study of microseismic fields. A method is proposed for assessing the temperature regime of rocks based on analysis of the monitoring data with account for the dynamics of the manifestation of hazardous processes within the central ecological zone of the Baikal natural territory. In this context, the base is the distance from the measurement instrument to the measurement point. For example, for medium bases, this is the distance from the laser rangefinder to the point to which the beam is directed.
ecological zone of the Baikal natural territory. Hydrogeochemical test sites are located have been collected and analyzed; a hydrogeochemical method for assessing the penetration of South Baikal waters into active coastal faults has been proposed; and theoretical foundations of the method for assessing the regime, chemical composition, and quality of groundwater within the area under study have been developed.

The analysis made it possible to reveal new regularities in the manifestation of hazardous geological processes in Southern Cisbaikalia associated with the migration of groundwater and the intensification of seismic activity. The phenomenon of propagation of deep water in the South Baikal reservoir with the characteristic values of the activity ratios $^{234}\text{U}/^{238}\text{U} = 1.95–1.99$ and the concentration $\text{U} = 0.44–0.46 \, \mu\text{g/dm}^3$ under the coast of Lake Baikal was discovered [9]. Time-varying ratios of groundwater components due to the manifestation of the Cherdynets-Chalov deformation effect, chemical interaction of water with evaporites, and mixing of groundwater with contrasting U-isotope characteristics were revealed. A comprehensive analysis of the biomedical, structural—tectonic, deformometric, emanation, and hydrogeochemical effects that preceded and accompanied the Bystrinskoe earthquake (September 21, 2020, $M_w = 5.4$) [10] was conducted, its seismological parameters were established, and the effects of interest for further research of forerunners of strong earthquakes in Cisbaikalia were identified.

The team of the Vinogradov Institute of Geochemistry, SB RAS, identified chemical elements and compounds that require constant monitoring, which will form the basis of the database “Inorganic Pollutants in the Runoff of Lake Baikal (the source of the Angara River, the Irkutsk Reservoir, and the upper part of the Bratsk Reservoir).” The concentrations of $\text{SO}_4^{2-}$, $\text{Cl}^-$, $\text{Mg}^{2+}$, $\text{Na}^+$, $\text{NO}_3^-$, $\text{NO}_2^-$, $\text{NH}_4^+$, $\text{F}$, $\text{P}$, trace elements ($\text{Hg}$, $\text{Cd}$, $\text{Pb}$, $\text{Zn}$, $\text{As}$, $\text{Br}$, $\text{Ge}$, $\text{Al}$, $\text{V}$, $\text{Cr}$, $\text{Mn}$, $\text{Co}$, $\text{Ni}$, $\text{Fe}$, $\text{Cu}$, $\text{Mo}$, $\text{U}$, $\text{Th}$), and the physical and chemical parameters of water determined by the sampling network, optimized to assess the quality of and predict possible changes in aquatic ecosystems of the Baikal natural territory, will be introduced there.

To ensure medical, environmental, and epidemiological monitoring (the sixth scientific direction), the levels of exposure to chemical pollutants that cause acute, chronic, and long-term health problems when staying in a smoke source have been determined [11]. Thus, during mass landscape fires in the forests of the Baikal natural territory, the risks of acute inhalation exposure, calculated from the maximum recorded concentrations, are due to the pollution of the surface layer of the atmosphere with suspended solids (hazard coefficient, HQac = 11.3), formaldehyde (HQac = 1.4), and carbon monoxide (HQac = 1.2). The total contribution to the general toxic hazard index from these substances is $96.3\%$. The highest probability of a negative irritating effect during acute exposure is typical of CO (the risk is 0.999), $\text{SO}_2$ (0.945), suspended solids (0.919), and soot (0.864). Exposure to particulate matter (HQcr = 5.4), formaldehyde (HQcr = 4.7), and $\text{NO}_2$ (HQcr = 1.5) leads to high and medium levels of risk in chronic exposure to combustion products of coniferous forests. Long-term exposure to impurities, even at the level of average values, can lead to an increase in the pathology of the respiratory organs (hazard index, $HI_{cr} = 12.7$) and the cardiovascular system ($HI_{cr} = 6.3$) and to an increase in mortality ($HI_{cr} = 5.9$).

Methodological approaches to the creation of biological models of acute intoxication of the body with the smoke of natural fires are also proposed. The experimental model of a dynamic peat fire, developed for the first time, makes it possible to analyze in exposure chambers the composition of the gas mixture formed during the thermal decomposition of peat. Quantitative and qualitative characteristics of the main components of smoke, including the content of ultrafine solid particles (PM 2.5$^4$), CO, acetaldehyde, nitrogen oxides, aldehydes, heterocyclic compounds, terpenes, and phenol derivatives, showed its identity to the smoke factors during peat fires in natural conditions. The main criterion for such identity was the content of CO and PM 2.5 in the air, which amounted to $40.8 \pm 1.9 \, \text{mg/m}^3$ for CO and $0.92 \pm 0.34 \, \text{mg/m}^3$ for PM 2.5. The use of this model will make it possible to determine indicators of health disorders during wildfires in Cisbaikalia.

Let us mention still another development. This is a prototype of the inventory of natural focal infections of epidemiological significance for the population of the Baikal natural territory. The inventory contains a spectrum of tick-borne infections, including tick-borne viral encephalitis, ixodid tick-borne borreliosis, tick-borne rickettsiosis, tick-borne relapsing fever, human granulocytic anaplasmosis, and human monocytic ehrlichiosis, as well as a spectrum of other viral and bacterial infections: avian influenza virus A, hemorrhagic fever with renal syndrome, West Nile fever (virus), tularemia, anthrax, plague, and novel coronavirus infection (SARS-CoV-2). All these pathogens are of great epidemiological significance not only for the Baikal region but also for our entire country and for the world as a whole.

In conclusion, let us note that the methods and technologies developed within the framework of this project will make it possible to create an original distributed service-oriented digital platform for storing and processing large volumes of scientific data and knowledge in various formats to support the processes

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4 PM 2.5 is an air pollutant consisting of both solid microparticles and tiny droplets of liquids. The size of fine suspended particles reaches 2.5 $\mu$m.
of continuous monitoring of large natural objects, their interdisciplinary research, and forecasting of possible events. The most important component of sustainable development not only of the Baikal natural region but also of Siberia as a whole should be digital monitoring created on a single conceptual basis with an assessment of the state of the natural environment and technosphere objects, the organization of regional systems for the digital management of anthropogenic, ecological, natural, geodynamic, radiation, and, in a more global sense, territorial risks.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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