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On Knowledge-Based Forecasting Approach for Predicting the Effects of Oil Spills on the Ground

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Abstract. The oil industry carries enormous environmental risks and can cause consequences at different levels: water, air, soil, and, therefore, all living things on our planet. In this regard, forecasting the environmental consequences of oil spill accidents becomes relevant. Moreover, forecasting of oil spill accidents can be used to quickly assess the consequences of an accident that has already occurred, as well as to develop a plan of operational measures to eliminate possible accidents, facilities under construction, associated with the transportation, storage or processing of petroleum products. Consequently, the aim of this paper is to present a knowledge-based approach and its implementing system for forecasting the consequences of an accidental oil spills on the ground and groundwater. The novelty of the proposed approach is that it allows us to forecast the oil spill in a complex and systematic way. It consists of components for modelling geological environment (i.e., geological layers, oil spill form, the oil migration with groundwater), forecasting component for an oil spill and pollution mitigation component. Moreover, the forecasting component is based on experts' knowledge on oil spill. In addition, the paper presents a general architecture for the implementation of the proposed knowledge-based approach and its implementation into a prototype named SoS-Ground.

Key words: ecology, oil products, decision-making, forecasting, knowledge-based system, architecture, scenario

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Основанный на знаниях подход прогнозирования последствий нефтяных разливов на поверхность земли

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Аннотация. Нефтяная промышленность сопряжена с огромными экологическими рисками и может привести к последствиям на самых разных уровнях. Это имеет отношение как к воде, воздуху, почве, так и ко всем живым существам на нашей планете. В этой связи прогнозирование экологических последствий при аварийных разливах нефти является весьма актуальным. Кроме того, прогнозирование аварийных разливов нефти может быть использовано для быстрой оценки последствий в рамках уже произошедшей аварии, а также для разработки плана оперативных мероприятий по ликвидации возможных аварий, строящихся объектов, связанных с транспортировкой, хранением или переработкой нефтепродуктов. Таким образом, цель данной работы - представить подход, основанный на знаниях, и систему его реализации для прогнозирования последствий аварийных разливов нефти на земле и в грунтовых водах. Новизна предлагаемого подхода заключается в том, что он позволяет комплексно и системно прогнозировать нефтяные разливы. Подход состоит из компонентов для моделирования геологической среды (т.е. геологических слоев, формы разлива нефти, миграции нефти вместе с грунтовыми водами), компонента по прогнозированию разлива нефти и компонента, смягчающего последствия загрязнения окружающей среды. Помимо этого, компонент, позволяющий осуществлять прогнозирование, основан на экспертных знаниях о нефтяных разливах. В дополнение, в данной статье представлена общая структура реализации предложенного подхода, основанного на знаниях, и его осуществление в виде прототипа SoS-Ground

Ключевые слова: внутренний банковский риск, концепция, менеджмент, цифровые технологии

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Introduction.

Oil occupies a leading position in the global fuel market, it is produced in 80 countries of the world, 40% of the oil produced goes to the market. The largest oil producers are Venezuela, Canada, Iran, Iraq, Kuwait, the United Arab Emirates, Russia, Libya, Nigeria, and the United States. According to statistics for 2019, at the end of 2018, Venezuela is the leader in proven oil reserves, which accounts for 47 billion tons of oil reserves or 17,7% of world reserves (BP, 2019).

The most common and dangerous consequence of the oil industry is oil pollution, which is associated with almost all activities at all stages of oil production, i.e., from research to refinement. Other environmental impacts of the oil industry are reflected in an increase in the greenhouse effect, the appearance of acid rain, a decrease in water quality, pollution of groundwater, etc. (Zhou, et al., 2019; Nyssanbayeva et al., 2020).

Moreover, a high technogenic load of the world oil complex causes risks associated with spills of oil and oil products. In this regard, forecasting of the environmental consequences of such accidents becomes relevant. At the same time, forecasting can be used to quickly assess the consequences of an accident that has already occurred, as well as to develop a plan of operational measures to eliminate possible accidents and facilities under construction related to the transportation, storage or processing of petroleum products (Feng, et al., 2019).

Therefore, a number of authors have proposed oil spill forecasting systems. However, the biggest part of existing systems are developed for oil spill on the sea but not on the ground, what is completely different by its nature. For this reason, we need an approach, which takes into consideration the nature of oil spill process on the ground and implement it into forecasting system.

The aim of the paper is to present a knowledge-based system, which allows us to make a forecast of oil spill on geological layers and to find out the concentration of pollution in soil, ground and groundwater.

The novelty of the proposed approach is that it allows us to forecast the oil spill in a complex and systematic way. It consists of components for modelling geological environment (i.e., geological layers, oil spill form, the oil migration with groundwater), forecasting component for oil spill and pollution mitigation component. Moreover, the forecasting component is based on experts' knowledge on oil spill.

The rest part of the paper is structured as follows. In section 2, we review the related works on knowledge-based systems for oil spill. In section 3, we consider a knowledge-based approach to predict the pollution of the geological environment as a result of an accidental spill of oil products. In section 4, a prototype in the form of web application of the proposed knowledge-based system is presented.

Related Works.

Existing systems for oil spill forecasting. In this section, we review some of the existing forecasting and decision-making systems for oil spill. According to (Davies, Hope, 2015), authors have proposed a Bayesian environmental decision support system based on logical inference for the selection of oil spill response strategies. This can minimize the potential for non-optimal response strategies that cause additional environmental and socio-economic damage beyond the initial pollution. However, these scenarios for the elimination of pollution are presented only for the aquatic environment.

According to (Zhuk et al., 2017), the developed Black Sea Geographical Information System (GIS) provides automated data processing and visualization on-line. New numerical models can be incorporated in the GIS environment as individual software modules, compiled for a server-based operational system, providing interaction with the GIS. The system architecture is similar to the knowledge-based system presented, but it is also designed to predict hydrosphere pollution.

Authors of (Lehikoinen et al., 2012) has developed a prototype for risk assessment and decision support model, applying Bayesian Networks, for the evaluation of environmental risks arising from the oil transport. The proposed model can be used to compare the effectiveness of some preventive management actions and oil recovery against the accident risk. However, as authors state, the results presented are only indicative on how the tool could be utilized in choosing an optimal risk control option. The modelling of the effects of preventive actions on the maritime traffic risks needs to be further developed.

In (Denzer et al., 2011), authors have presented a support system based on cismet's geospatial application suite. It integrates several tools and models into a holistic, user-centred application. However, authors have not presented any architecture of the proposed application.

Other decision support systems (DSS) also known as the following. A web-based decision support system proposed to facilitate emergency management in the case of oil spill accidents, called WITOIL (Where Is The Oil) and applied to create a forecast of oil spill events, evaluate uncertainty of the predictions, and calculate hazards based on historical meteo-oceanographic datasets in (Liubartseva et al., 2016). In (Amir-Heidari & Raie, 2019), a general DSS is proposed for passive and active response planning in Persian Gulf, before and after a spill. It is based on NOAA's advanced oil spill model (GNOME), which is linked with credible met-ocean datasets of CMEMS and ECMWF. The developed open-source tool converts the results of the Lagrangian oil spill model to quantitative parameters such as mean concentration and time of impact of oil. The tool was tested in both deterministic and probabilistic modes, and found to be useful for evaluation of emergency response drills and risk-based prioritization of coastal areas.

In (Ribotti et al., 2019), an oil spill forecasting system have been presented to support the management of emergencies from the oil fields in the Italian seas. The system provides two online services, one automatic and a second dedicated to possible real emergencies or exercises on risk preparedness and responding. The automatic service produces daily short-term simulations of hypothetical oil spill dispersion, transport, and weathering processes from each extraction platform. The hazard estimations are computed by performing geo-statistical analysis on the daily forecasts database.

Summing up, the existing proposed decision-support and forecasting systems for oil spill are used for oil spills on water mainly, but not on the ground. Moreover, some of the information systems presented are designed only for forecasting of oil spill or only for supporting decision-making. Therefore, there is a need for a complex knowledge-based system for oil spill forecasting on the ground.

Forecasting modelling for oil spills. In this section, we analyse models and techniques used for oil spill forecasting.

According to (Chiu et al., 2017), authors used vector summation of the ocean current velocity and 3% of the wind speed to determine the trajectory of the oil slick on the water.

In order to reveal the major errors sources and improve the accuracy of the forecasting system, the authors of (Li et al., 2019) designed five numeric simulation scenarios. But the error of wind and the inaccuracy released time of oil were the major error sources of the oil spill forecasting.

In (Wang, 2017), authors used the method of polynomial chaos to quantify the uncertainty in the forecast of circulation in the Gulf of Mexico caused by uncertain initial conditions and data on wind exposure. The input uncertainties consisted of the amplitudes of the perturbation modes, the spatiotemporal structure of which was obtained from the expansions of empirical orthogonal functions. However, a model built on the basis of this method is quite sensitive to parameter variations. According to (Hou, 2017), an oil spill forecast is quantified by comparing a forecast probability map with a corresponding simulation of reverse gears. This approach implements Monte Carlo simulations to provide parameters for creating forecast probability maps. A simple statistical model based on HyosPy was developed to assess the reliability of the oil spill forecast in terms of confidence. In (Janeiro,2014), a set of nested models was implemented in the philosophy of downsizing caused by external operating products. According to (Hodges, 2015), authors used the real-time forecast uncertainty, which are added in each modelling step and the new parameters are introduced.

Summing up, the analysis of the used approaches and techniques for oil spill forecasting are suitable for water, but not on the ground. According to the specifics of the aquatic environment, the distribution of oil products will occur in a different way compared to the geological environment. Moreover, the analysed models are built for a rather narrow problem, for example, to calculate the shape and area of a spill, or only the probability of a spill in certain situations, which does not give a complete view of the pollution and its consequences.

Therefore, it is found that the topic of protecting the geological environment is insufficiently covered, which makes our knowledge-based approach viable.

A knowledge-based approach for forecasting of oil spill on the ground

The main concept of the approach. The main idea of the knowledge-based approach for forecasting of oil spill on the ground is presented in Fig. 1. It consists of four main parts corresponding to layers of the geological environment as the following: the surface layer (Surface), the soil layer (Soil), the ground layer (Ground) and groundwater layer (Underground water). At each part, certain parameters, used for future prediction, are calculated. Based on those parameters, the proposed approach allows us to predict the following: 1) the depth of penetration of oil products into the soil and ground, 2) the mass of oil product adsorbed by the ground and its concentration, 3) the residual mass of the oil product that can reach groundwater, 4) the time to reach the maximum concentration at the groundwater level, and 5) describe the horizontal redistribution of oil product with groundwater.

The knowledge-model used for forecasting is presented as the following. In many cases, it is impossible to collect complete and reliable data of all parameters in the approach used to calculate and forecast the pollution. Therefore, the knowledge of qualified specialists are used. First, each case of oil spill we express as a vector (see eq. (1))

$$\langle \text{TypeOP, TypeGr}, V_0, S_1, \alpha, H_2, H_3 \rangle , \tag{1}$$

where TypeOP is the type of oil product (OP), TypeGr – type of ground, V_0 – volume of spilled oil expressed in m^3, S_1 – stain area in m^2, α – surface angle, H_2 – maximum depth of penetration of OP into the soil in m, H_3 – maximum depth of penetration of oil products into the ground expressed in m.

In the general case, n cases can be given in the form of a matrix (see eq. (2)).

$$\begin{bmatrix} \text{TypeOP}^1 & \text{TypeGr}^1 & V_0^{\,1} & S_1^{\,1} & \alpha^1 & H_2^{\,1} & H_3^{\,1} \\ \text{TypeOP}^2 & \text{TypeGr}^2 & V_0^{\,2} & S_1^{\,2} & \alpha^2 & H_2^{\,2} & H_3^{\,2} \\ \text{TypeOP}^3 & \text{TypeGr}^3 & V_0^{\,3} & S_1^{\,3} & \alpha^3 & H_2^{\,3} & H_3^{\,3} \\ \dots & \dots & \dots & \dots & \dots & & \dots \\ \text{TypeOP}^n & \text{TypeGr}^n & V_0^{\,n} & S_1^{\,n} & \alpha^n & H_2^{\,n} & H_3^{\,n} \end{bmatrix} . \tag{2}$$

In the case if a particular attribute is unknown, it is defined as *undefined*. For example, in the first case in the matrix (3), the type of oil product is unknown, in the second case – the volume of spilled OP, in the third case – the area of spilled OP, and in the last case – the type of OP and the amount of spilled OP.

$$\begin{bmatrix} \textit{undefined} & \text{TypeGr}^1 & V_0^{\,1} & S_1^{\,1} & \alpha^1 & H_2^{\,1} & H_3^{\,1} \\ \text{TypeOP}^2 & \text{TypeGr}^2 & \textit{undefined} & S_1^{\,2} & \alpha^2 & H_2^{\,2} & H_3^{\,2} \\ \text{TypeOP}^3 & \text{TypeGr}^3 & V_0^{\,3} & \textit{undefined} & \alpha^3 & H_2^{\,3} & H_3^{\,3} \\ \dots & \dots & \dots & \dots & \dots & \dots & \\ \textit{undefined} & \text{TypeGr}^n & \textit{undefined} & S_1^{\,n} & \alpha^n & H_2^{\,n} & H_3^{\,n} \end{bmatrix} . \tag{3}$$

In the simplest case, only one component is unknown as presented in eq. (3).

Second, main forecasting rules based on expert's knowledge are defined as the following:

1. IF the type of OP is unknown, but it is known that the OP has reached the ground, THEN the case is as follows eq. (4):

$$\langle \textit{undefined}, \text{TypeGr}, V_0, S_1, \alpha, H_2, H_3 \rangle . \tag{4}$$

First, based on eq. (4), we express the value of the surface tension of the oil product (5):

$$\delta_0 = \frac{M_3 \times \delta_w}{h_3 \times S_1 \times m_3 \times w_3 \times \rho_w} , \tag{5}$$

where δ_0 is the OP surface tension coefficient measured in kg/s^2, M_3 – ground mass adsorbed by the ground layer in kg, δ_w – surface tension coefficient of water in kg/s2, h_3 – ground layer height in m, m_3 – soil porosity (from 0 to 1), w_3 – capillary moisture capacity of the soil (from 0 to 1), and ρ_w – water density in kg/m_2.

Second, we determine the type of OP be searching for an extremum (see eq. (6)):

$$| \delta_0 - \delta^i_0 | \to \min, \; i = 1, \dots, k, \tag{6}$$

where δ_0^i are reference values of the surface tension of petroleum products.

2. IF it is known that the OP was completely adsorbed in the soil and did not enter the ground, THEN the density of the OP can be expressed by eq. (7):

$$\rho_0 = \frac{M_2}{h_2 \times S_1 \times u_2} \qquad (7)$$

where ρ_0 – OP density, in kg/m^3, M_2 – ground mass adsorbed by the soil layer in kg, h_2 – soil layer height in m, u_2 – the amount of OP that the soil can absorb.

We determine the type of OP be searching for an extremum (see eq. (8)):

$$| \rho_0 - \rho^i_0 | \rightarrow \min, i = 1, ..., k, \qquad (8)$$

where ρ^i_0 are reference values of the density of petroleum products.

3. IF the type of ground is *unknown*, THEN eq. (9)

$$\langle \text{TypeOP}, \textit{undefined}, V_0, S_1, \alpha, H_2, H_3 \rangle\ . \qquad (9)$$

First, a quantity characterizing the type of soil can be expressed as in eq. (10).

$$m_3 \times w_3 = \frac{M_3}{h_3 \times S_1 \times \rho_w \times \frac{\delta_0}{\delta_w}} \qquad (10)$$

Second, the type of ground is determined by finding an extremum in eq. (11).

$$| m_3 \times w_3 - m^i_0 \times w^i_0 | \rightarrow \min, i = 1, ..., k, \qquad (11)$$

where m^i_0 and w^i_0 are reference values of porosity and capillary moisture capacity of the ground. By defining m^i_0 and w^i_0, minimizing the difference $| m_3 \times w_3 - m^i_0 \times w^i_0 |$ you can find out the type of ground.

4. IF the angle α of inclination of the surface is *unknown*, THEN see eq. (12).

$$\langle \text{TypeOP}, \text{TypeGr}, V_0, S_1, \textit{undefined}, H_2, H_3 \rangle. \qquad (12)$$

5. IF the area of the strait and the type of OP are unknown, THEN see eq. (13).

$$\langle \textit{undefined}, \text{TypeGR}, V_0, \textit{undefined}, \alpha, H_2, H_3 \rangle. \qquad (13)$$

The type of oil can be determined by eq. (5). In the event that the OP was completely adsorbed in the soil. The type of OP is reduced to the case described above in eq. (7).

6. IF the area of the spilled OP and the type of ground are not known at the same time, THEN see eq. (14).

$$\langle \text{TypeOP}, \textit{undefined}, V_0, \textit{undefined}, \alpha, H_2, H_3 . \rangle \qquad (14)$$

For this case, the calculation of unknown quantities reduces to eq. (10).

7. IF area of spilled OP and the depth of penetration of OP into the ground is unknown, THEN see eq. (15):

$$\langle \text{TypeOP}, \text{TypeGr}, V_0, \textit{undefined}, \alpha, H_2, \textit{undefined} \rangle. \qquad (15)$$

Additional equations used for calculations are presented in Annex 1. For more details about the mathematical model also see (Smelov et al., 2018; Burmakova et al., 2018).

The general architecture of knowledge-based forecasting of oil spill on the ground system. In this section, we present a general architecture to implement the proposed approach. The knowledge-based forecasting system consists of six main components as the following (see Fig. 2). Component F (forecasting component) receives initial data on the amount, type and location of the oil spill. The result of this component is a report on the effects of pollution and is placed in the database. Component F operates as presented in the described approach. Component P (component for assessing the predicted state) receives data from Component F and compares the values of the forecast result with the standards for maximum permissible concentrations. Component C (component for the classification of the predicted state) is developed to classify the conditions of the geological environment. Component R (component for choosing rehabilitation technologies) generates a final report that contains a list of rehabilitation technologies. Components O and H are reference components developed to store information about technologies objects whose activities are associated with the handling of petroleum products and information on the chemical composition of petroleum products, respectively. These components are part of the database as reference data**.**

Components F, P, C and R are the implementation of the proposed approach that allows to predict the consequences of an incident involving a spill of oil products (component F), to evaluate (compare with standard values) the predicted values of the degree of pollution of soil and groundwater

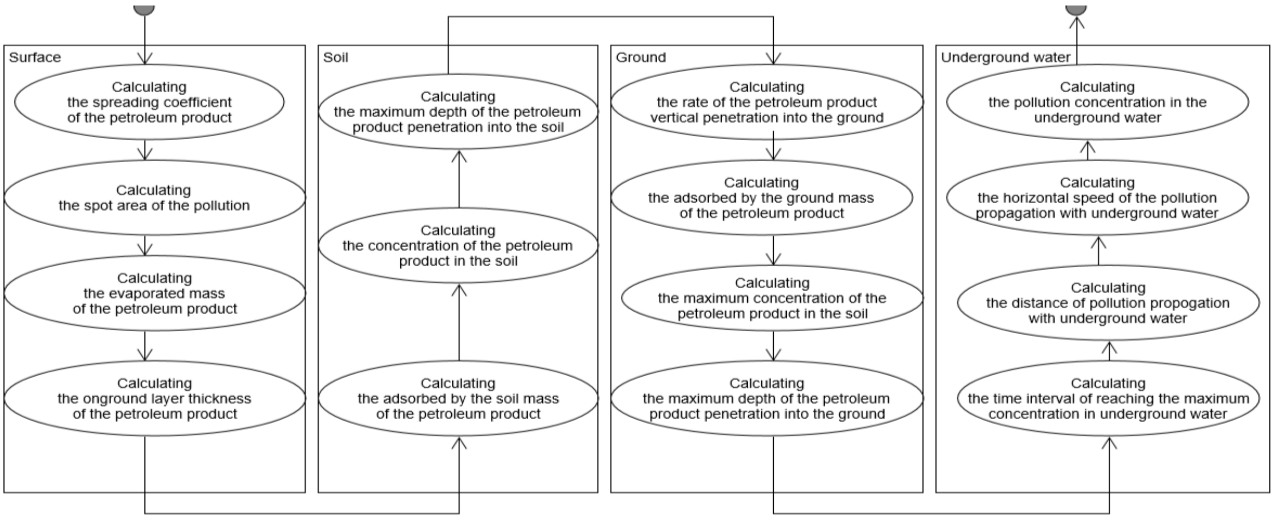


Fig. 1. The knowledge-based approach for oil spill forecasting on the ground
Рис. 1. Основанный на знаниях подход к последствию загрязнения геологической среды в результате аварийного пролива нефтепродуктов.

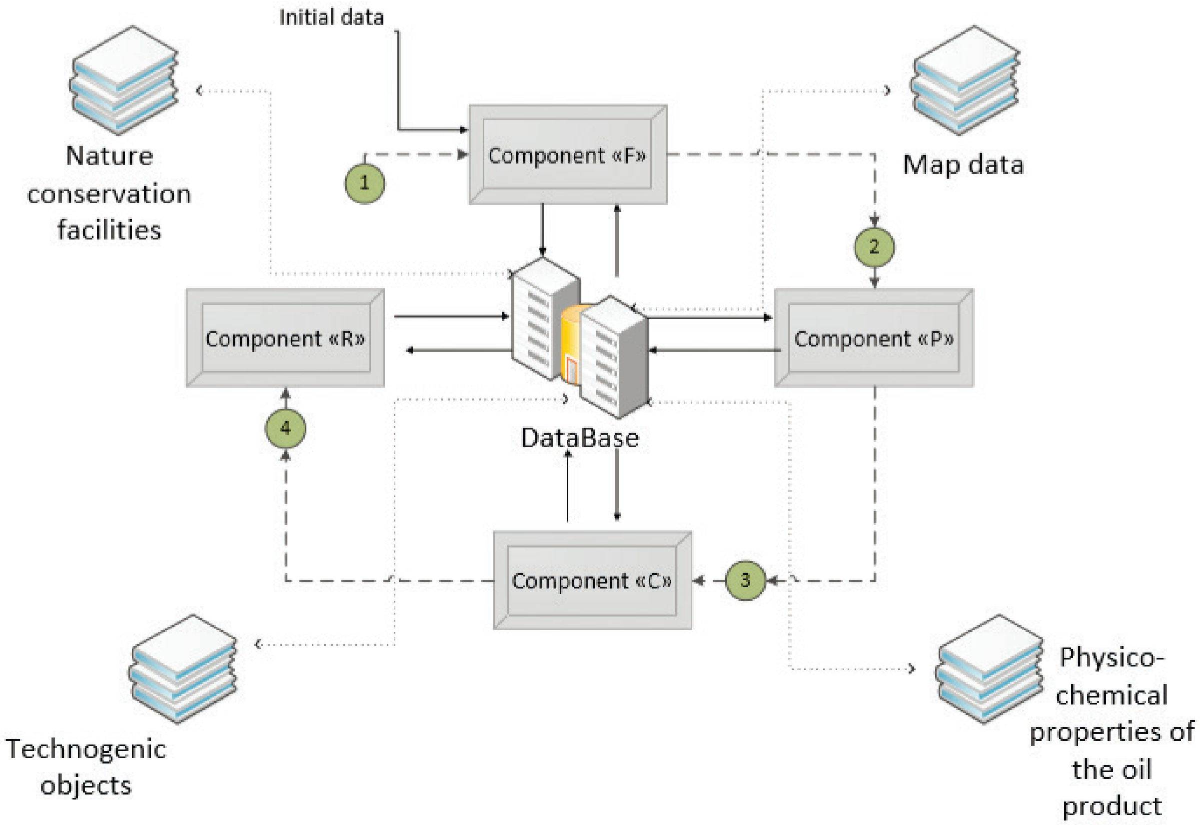


Fig. 2. The architecture of knowledge-based forecasting system for predicting the effects of geological pollution due to oil spills
Рис. 2. Архитектура системы последствий загрязнения геологической среды в результате аварийного пролива нефтепродуктов.

(component P), and also classify the predicted state of the geological environment (component C) and propose technologies and technical means for rehabilitation of the geological environment (component R). Each of these components in its work uses reference information presented in the form of electronic reference books and generates a report containing calculated predicted values. In Fig. 3, a scenario in the form of a sequence diagram of Components communication through messages during the forecasting process is presented.

As presented in Fig. 3, the user through an interface enter or select calculation parameters, as well as receive a report reflecting the results of the

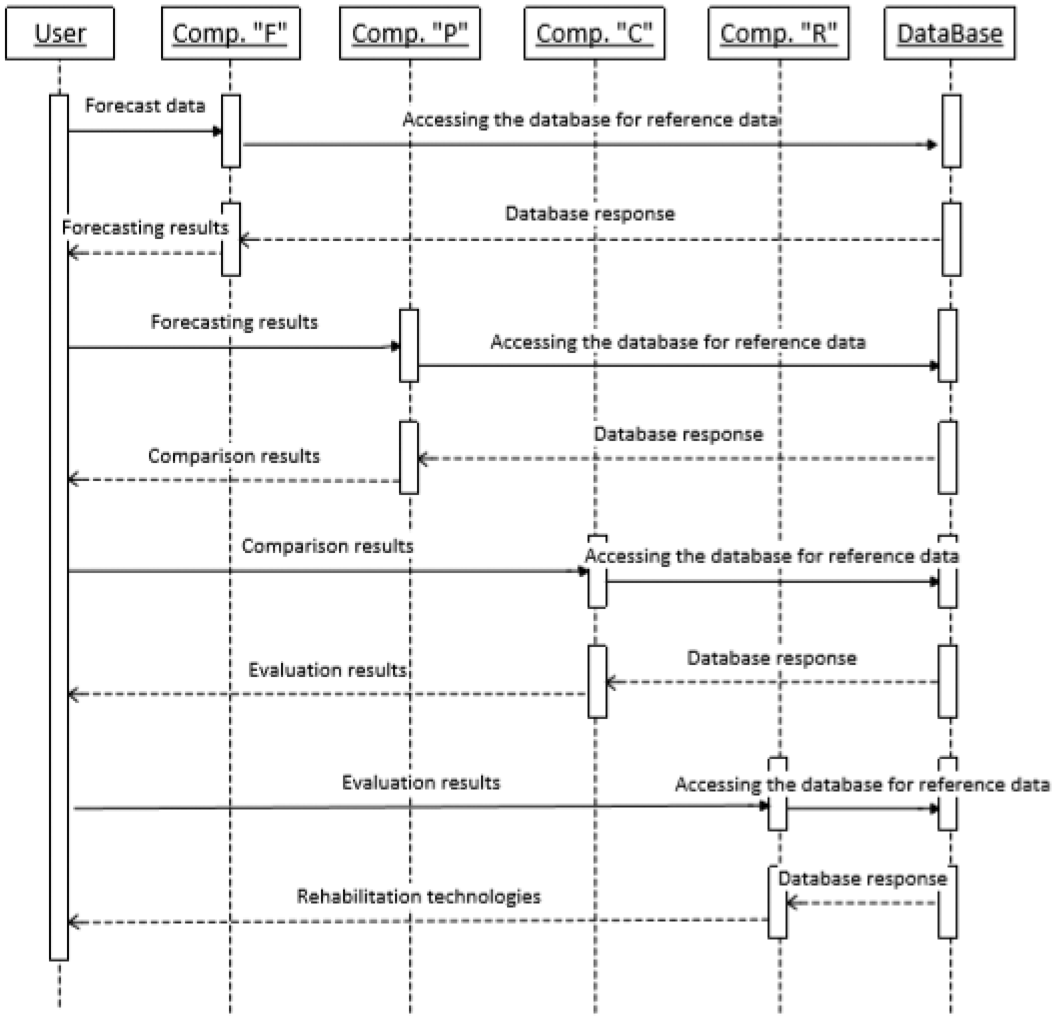


Fig. 3. The scenario of forecasting process
Рис. 3. Сценарий процесса последствий загрязнения геологической среды
в результате аварийного пролива нефтепродуктов.

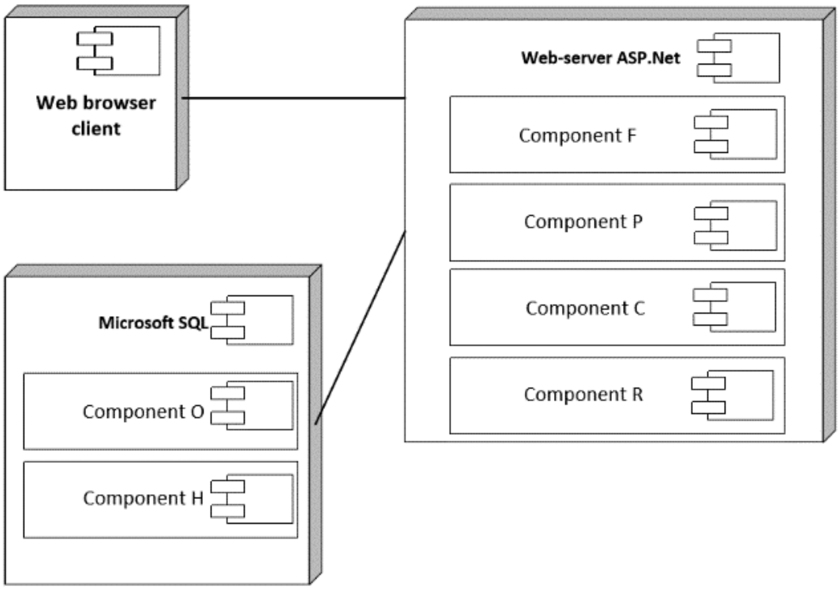
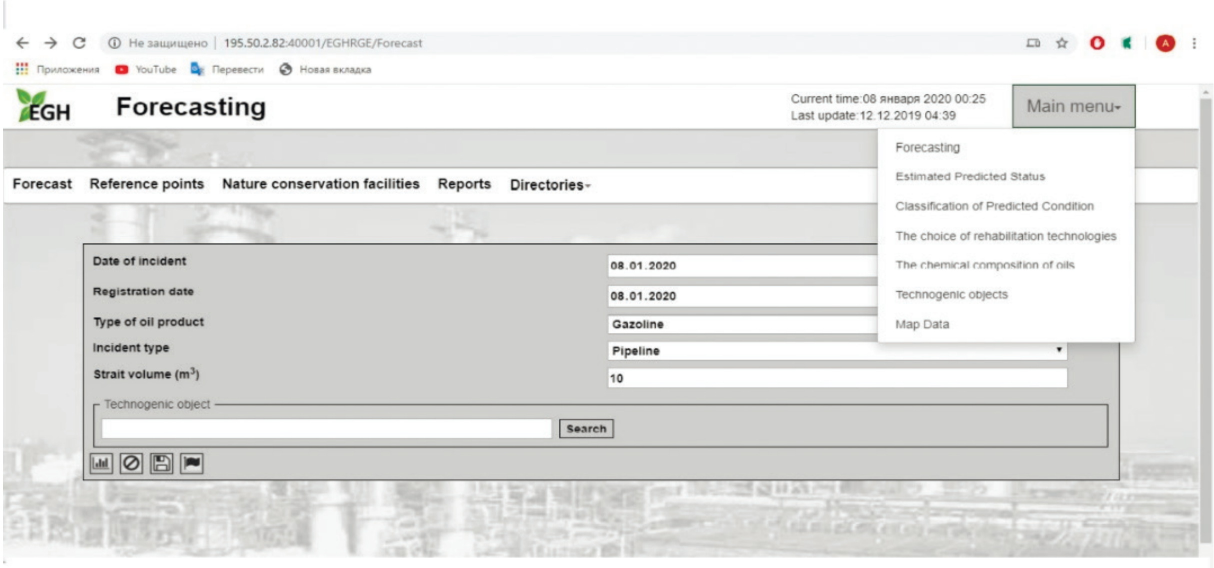


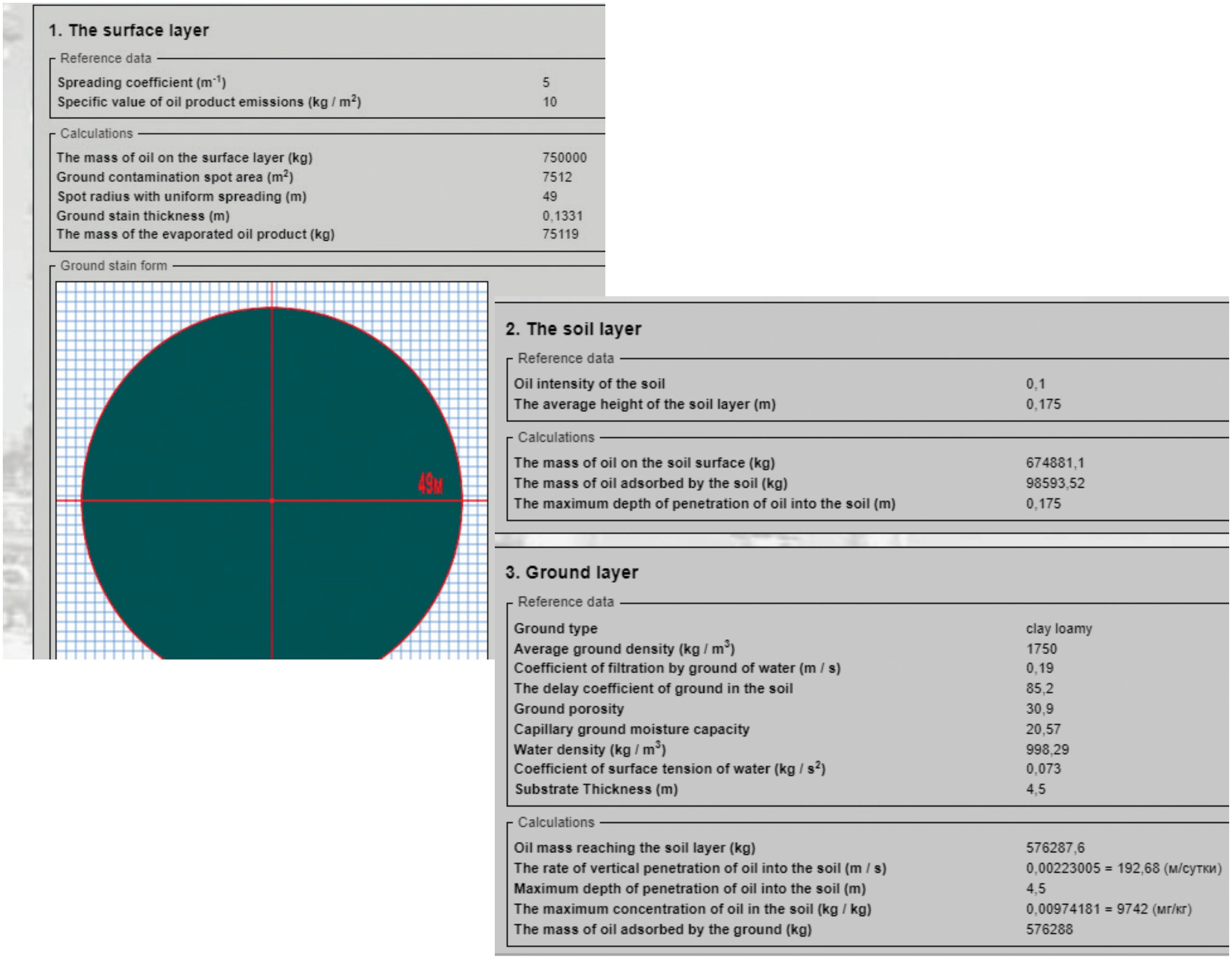
Fig. 4. The deployment diagram of the proposed architecture
Рис. 4. Схема развертывания предлагаемой архитектуры.



Current time:08 января 2020 00:25
Last update:12.12.2019 04:39

Date of incident	08.01.2020
Registration date	08.01.2020
Type of oil product	Gazoline
Incident type	Pipeline
Strait volume (m^3)	10

Fig. 5. User interface of SoS-Ground
Рис. 5. Пользовательский интерфейс системы последствий загрязнения геологической среды в результате аварийного пролива нефтепродуктов.



1. The surface layer

Reference data

Spreading coefficient (m^{-1})	5
Specific value of oil product emissions (kg / m^2)	10

Calculations

The mass of oil on the surface layer (kg)	750000
Ground contamination spot area (m^2)	7512
Spot radius with uniform spreading (m)	49
Ground stain thickness (m)	0,1331
The mass of the evaporated oil product (kg)	75119

Ground stain form

2. The soil layer

Reference data

Oil intensity of the soil	0,1
The average height of the soil layer (m)	0,175

Calculations

The mass of oil on the soil surface (kg)	674881,1
The mass of oil adsorbed by the soil (kg)	98593,52
The maximum depth of penetration of oil into the soil (m)	0,175

3. Ground layer

Reference data

Ground type	clay loamy
Average ground density (kg / m^3)	1750
Coefficient of filtration by ground of water (m / s)	0,19
The delay coefficient of ground in the soil	85,2
Ground porosity	30,9
Capillary ground moisture capacity	20,57
Water density (kg / m^3)	998,29
Coefficient of surface tension of water (kg / s^2)	0,073
Substrate Thickness (m)	4,5

Calculations

Oil mass reaching the soil layer (kg)	576287,6
The rate of vertical penetration of oil into the soil (m / s)	0,00223005 = 192,68 (м/сутки)
Maximum depth of penetration of oil into the soil (m)	4,5
The maximum concentration of oil in the soil (kg / kg)	0,00974181 = 9742 (мг/кг)
The mass of oil adsorbed by the ground (kg)	576288

Fig. 6. SoS-Ground forecasting report
Рис 6. Отчет прогнозирования системы последствий загрязнения геологической среды в результате аварийного пролива нефтепродуктов.

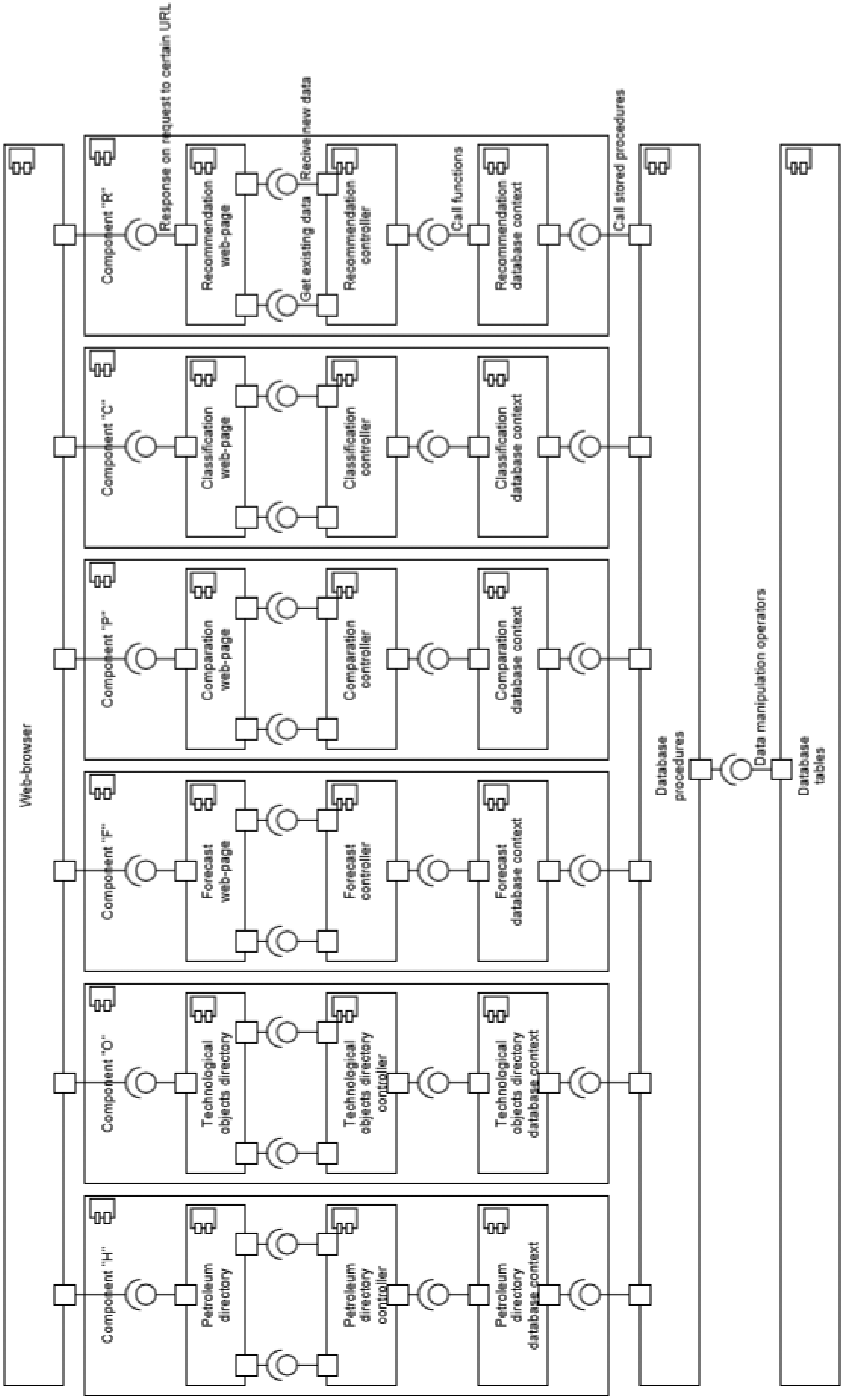


Fig. 7. The schema of the user interface implementation
Рис 7. Схема реализации пользовательского интерфейса системы.

forecasting. The results of data processing of each component are stored in the database for their subsequent use. The user can view the report of the forecast stored in the database.

Implementation of the proposed approach. The proposed knowledge-based forecasting architecture is implemented into a prototype, named the Knowledge-based Forecasting System for Oil Spill on the Ground (SoS-Ground) (Fig. 4). SoS-Ground is implemented as a web server based on ASP.NET 4.5 technology. MVC 5.0. For the implementation of the database of SoS-Ground, Microsoft SQL Server 2012 was used. Along with custom data, the database also stores a spatial data in the form of electronic maps with additional attributes (type of soil, groundwater depth, water protection zones, altitude, administrative division, etc.).

In Fig. 5, a user interface implementation in SoS-Ground is presented. In Fig. 6, an example of the forecasting report for oil spill on the ground is presented.

In Fig. 7, the implementation schema of the interface in web application is presented.

Conclusion. The analysis of the existing forecasting systems for oil spill shows that they are developed for the forecasting of oil spill on the water, but not on the ground. Moreover, because of the specifics of the aquatic environment, the existing forecasting approaches are not suitable for oil spill forecasting on the ground. As well, it is determined that the analysed models are built for a rather narrow problem, like, to calculate the shape and area of an oil spill, or only the probability of a spill in certain situations, which does not give a complete view of the pollution and its consequences.

In this paper, we propose a new knowledge-based approach for oil spill forecasting on the ground. Our main contribution is that the proposed approach allows us to forecast the oil spill in a complex and systematic way. It consists of components for modelling geological environment (i.e., geological layers, oil spill form, the oil migration with groundwater), forecasting component for oil spill and pollution mitigation component. Moreover, the forecasting component is based on experts' knowledge on oil spill.

According to the proposed approach, a general architecture for is put forth. This architecture was implemented into the SoS-Ground prototype and the case study shows correspondence to the forecasting of oil spill on the ground needs, as well as possibilities for decision-making based on the proposed forecasting approach for oil mitigation.

The topics for the future research are as follows: extending the proposed approach, detailed description of the knowledge part of the approach, improving SoS-Ground, making more detailed verification of the results.

Annex 1.

Here the main equations used in the calculations are presented as the following.

The area S1 of the pollution spot (m2) is calculated by eq. (A1).

$$S_1 = V_0 \times d_1 \tag{A1}$$

where V_0 – the volume of spilled OP (m^3), d_1 – the spreading coefficient of the NP (m-1).

The mass M_1 of the evaporated oil product (kg) is calculated by eq. (A2):

$$M_1 = S_1 \cdot q_1(T) \tag{A2}$$

where q_1 (T) is the specific value of oil product emissions (kg/m2).

Soil adsorbed mass M2 of OP (kg) is calculated by eq. (A3):

$$M_1 = S_1 \times h_2 \times u_2 \times \rho_0 \tag{A3}$$

The maximum depth of penetration of H_2 OP into the soil (m) is calculated by eq. (A4):

$$H_2 = h_2 \times \frac{M_0 - M_1}{M_2} \tag{A4}$$

where H2 – maximum depth of penetration of OP into the soil (m), M0 – the mass of spilled OP (kg).

The mass of M3 OP adsorbed by the ground layer (kg) is calculated by eq. (A5):

$$M_3 = h_3 \times S_1 \times \rho_w \times m_3 \times w_3 \times \frac{\delta_0}{\delta_w} \tag{A5}$$

The maximum penetration depth of H_3 OP into the soil (m) depends on the mass adsorbed in the ground is calculated by eq. (A6):

$$H_3 = \begin{cases} h_3 \times \dfrac{M_0 - (M_1 + M_2)}{M_3}, & M_0 - (M_1 + M_2) \leq M_3; \\ h_3, & M_0 - (M_1 + M_2) > M_3. \end{cases} \tag{A6}$$

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