Designing and producing a geographic information system to forecast vegetation fire danger according to weather conditions

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Abstract. The article is concerned with the research and development of a geo information system for forecasting fire danger according to weather conditions. A structured approach is used to introduce the workflow process of the system in IDEF0 technique: generating data files/array, assessing the current fire danger, a spatial fire danger forecasted information and fire breaking-out, verifying the forecast index reliability and fire probability. The two-tiered architecture of a distributed data system and functional modules consisting of presentation logic, domain logic and database logic is focused on. Generation of meteorological data arrays is organized in a hypercube form and rated values of fire danger index. The surface planes of a hypercube include the month of fire danger season as well as the title and index of the weather station number, meteorological parameters and fire danger characteristics. The system is tested in the territory of the Jewish Autonomous Region in order to construct fire probability maps according to weather conditions using the developed geographic information system based on MapInfo Professional 15 and programming environments MapBasic and RAD Studio Delphi 2010. Forecast verification of fire danger index of three days lead-time amounts to 85% on the first day, it is 80% on the 2nd day, they are 70% and 65% on the third and fourth days respectively. The probability of vegetation fires in the territory of Birobidzhan subdivision of the JAR Forest Department is calculated depending on weather conditions. The forecast success rate is 75%.

1. Introduction

Vegetation fires are considered to be one of the most dangerous processes initializing in large areas over a number of years, and have a great influence on the ecological state of biosphere development. Forest stands are damaged and die. Soil landscape, hydrological conditions, atmospheric chemistry change as well as solar energy capacity does. Fire and post-fire greenhouse gas emission are the main processes of tremendous changes in the main geosphere components. Therefore, the development of systems that make the forecast fire damage possible aimed at ensuring timely detection. Hence, fire overhaul, forest
resource conservation, and economic and environmental damage mitigation caused by fires are focused on in much research, especially in those countries covered by forest lands.

The forecast of vegetation fire breaking-out is based on operational processing of large data arrays for long-term periods. This requires properly designed geographic information systems (GIS).

These systems have been developed for some countries, for example, the USA [1], Canada [2], Russia [3], and in Europe [4]. Despite the factual structure of data collected and reviewed, the methods for their processing and presentation of the results are different. Each of them contains modules of meteorological parameters and fire characteristics.

For example, the present-day forest fire monitoring system used throughout Russia consists of subsystems for collecting information on forest fire frequency based on ground and aerial observations in strongly protected forest areas, and distant monitoring according to NOAA satellites [5] from Russian and foreign centres for receiving and processing satellite data; a radio range finding of lightning strikes; collecting information about the meteorological situation according to the Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet) data.

Canadian Forest Fire Danger Rating System (CFFDRS) [2] and the US National NFDRS (National Fire Danger Rating System) [1] are based on the analysis of meteorological and satellite data taking into account the condition of forest fuel and land configuration. In Europe, EFFIS (the European Forest Fire Information System) was arranged, which operated based on regional calculating methods of meteorological indices: ORIEUX [6], I87 [7], NumRisk [8] in France, ICONA [9], IREPI [10] in Spain; PORT [11] in Portugal. The result of the operating system is index distribution electronic maps based on soil mantle wetness data, wind velocity, cloud amount, atmospheric moisture capacity, etc.

The developed systems make it possible to collect information on vegetation fires as well as on the environment condition, perform a spatial assessment of fire danger index and forecast energy parameters of forest fires; design information software to support taking situational management decisions. Their analysis allows the authors to emphasize the following disadvantages, such as non-justified selection of techniques for assessing and forecasting fire danger index for various climatic patterns; the use of a limited set of meteorological data when developing software systems for calculating the current fire danger or making forecasts, the lack of spatial forecasting units for fires.

The aim of the study is to develop a spatial forecast system for vegetation fire breaking-out considering the characteristics of a particular climate type.

The following stages are required for this: calculation of actual and forecasted fire danger parameters of a certain lead time, spatial forecast of fire danger index, calculation of fire conditional probability in cells of an established scale regular network or in a net of rides in forest estate lands for a definite period, and the development of a geographic information system for making electronic maps of the vegetation fire breaking-out probability of a particular fire danger class.

2. Materials and methods
To achieve this aim, it is necessary to form a module structure and provide a description of the system business processes.

GIS fire danger forecast of the territory under the conditions consists of the following subsystems: collection of meteorological data and distant testing data; data storage; forecast of fire danger parameters; constructing electronic maps. Subsystem interaction organization works in practice as a two-tiered architecture of distributed data processing applications. Functional modules of applications are divided into the following groups [12].

The design and development of GIS in this paper is based on IDEF0 (Integration Definition Methodology) [13] of SADT functional model (Fig. 1) using various types of development support systems: MapInfo Professional spatial information software presented, MySQL data management systems, MapBasic object-oriented environment programming, Embarcadero RAD Studio 2010.

The main objects of this model consist of the major and descendant/derived flow charts (decompositions/partitioning). The interface and modular units are located inside them.
The derived chart contains modules.

Module I. Forming data arrays allows one to prepare multidimensional data for storage and processing [14]. When constructing a logical structure of meteorological database, On-Line Analytical Processing algorithms were performed based on preselection of long-time information from the database, their mathematical processing, data and rating value structuring in the form of multidimensional hypercubes [15, 16]. There is a hypercube for describing meteorological data and rating values of fire danger index below. It consists of three faces. They stand for a month of the fire danger season, hydro meteorological station, meteorological parameters and fire danger index.

Module II. Assessment of the current fire danger. The forest fire calculation (algorithm for assessing the current) and integrated (algorithm forecasting fire danger according to weather conditions) parameters are carried out.

Module III. Spatial forecast of fire danger parameters and fire breaking-out. Business processes are completed in two stages: first, fire danger index is forecasted according to the data of each weather station, and then a spatial forecast of calculated parameters and possible fire breaking-out on the days with certain fire danger classes is made.

Module IV. Verification of the forecast index and the potential of fire reliability. The mean square deviation of the change in the forecasted value for the forecast lead time period \( \sigma_{\Delta i} \), the permissible forecast error \( \delta \), the root mean square error of the test forecasts \( S \) and forecast correctness \( \rho \) are calculated [17] for every day. The distribution fidelity of fire danger classes for every day forecast is assessed by A.V. Katz’s method [18].

Module V. Regulatory actions of forest conservation measures selects fire measures depending on the forecasted fire danger class and the conditional probability of vegetation fires, for example, the number of daily desired track flights/ routing to monitor the fire danger situation in a protected area is determined for Aerial Forest Fire Center.

The review of present-day fire danger assessment techniques in Russia showed that the main criteria for assessing daily fire danger are three interrelated parameters: forest fire drought one \( L \); the integrated factor of drought \( CP \); drought class \( CL \). To select the equation for calculating the daily actual fire danger parameters, an analysis of equations 1 and 2 is carried out according to the actual data of weather stations over a long-term period:

\[
L = t \cdot (t - \tau) \tag{1}
\]

\[
if \ (x < 3.00 \text{ mm/day}) \ then \ CP = \sum_{1}^{n} t \cdot (t - \tau) \ \ else \ CP = t \cdot (t - \tau) \tag{2}
\]
where: \( t \) is the daily air temperature, \( r \) is the daily dew point temperature, \( x \) is daily amount of rainfall mm per day. The drought class on the current day is determined by \( CP \) value on a regional scale [19].

To make short-term forecasts of fire danger indices, a technique was developed with two forecasted elements (average daily air temperature and synoptic term of precipitation) and equations of dependence of \( L_{i+n} \) on temperature for each month of the fire danger season of each weather station:

\[
L_{i+n} = C_0 + C_1t
\]

where \( t \) is forecasted air temperature; \( C_0, C_1 \) are factors of correlation equation, \( n = 1,2,3 \).

Then, the calculation results are used to make up electronic maps of the current and forecasted fire danger. To do this, a regular network is put on the map of the explored area. The nodes of it determine the fire danger indices by interpolation and are transferred to GIS for theme-based visualization [19].

The calculation of conditional probability of fires and the construction of maps is carried out for every \( q \) days of the fire danger season. The conditional probability \( P_{j|q}^{CL} \) of fires in \( j \)-cells of the regular network in \( q \)-timeframe for a certain \( CL \) is calculated according to (4):

\[
P_{j|q}^{CL} = \frac{Y'}{Y} \cdot \frac{N_{CL}}{N}
\]

where \( N_{CL} \) is the number of fires on the days of a certain drought class and \( N \) is the total number of fires in \( j \)-cell of the regular network in the \( q \)-timeframe; \( Y' \) is the number of fire danger seasons with fires and \( Y \) is the number of fire danger seasons for the whole period observed.

3. Result
The system was tested in the territory of the south of the Russian Far East to design maps of fire probability according to weather conditions using the geographic information system developed.

The choice of the region is caused by the high annual fire frequency and complicated weather conditions characterized by poor spring-autumn humidity and long time periods of high temperature, low soil and air humidity, dry/hot winds [20]. Weather conditions combined with the climate determine the basic mechanisms of developing fire danger seasons. They are long time (from April to October), three different danger periods, ununiformed time and territory of fire distribution [21].

The input data were the actual weather data obtained from five hydro meteorological stations of the Jewish Autonomous Region (JAR), including daily database from 1960 to 2016, and forecasted ones from The Hydro meteorological Centre of Russia sites [http://meteoinfo.ru]. The daily database on vegetation fires [22] was performed based on the research letters from the Far East Air Base from 1970 to 2016, JAR Forestry for the period of 1997 till 2016, and satellite images from NASA sites [http://rapidfire.sci.gsfc.nasa.gov] and Aerial Forest Fire Center [http://aviales.ru].

To forecast the forest fire index \( L_{i+1} \), correlation equations of the form \( L = f(t) \) are used, where \( t \) is the air temperature at 1-3 p.m. local time, which are obtained for a particular month of the fire danger season according to the most dangerous dry days in each weather station for the base period (Table 1).

| Month    | \( C_0 \) | \( C_1 \) | \( R^2 \) | \( R \)    | \( R/\sigma \) | \( A \) |
|----------|-----------|-----------|-----------|-----------|-------------|-------|
| April    | 2.78      | 0.05      | 0.63      | 0.79      | 154.43      | 0.56  |
| May      | 9.30      | 0.03      | 0.47      | 0.68      | 92.94       | 0.17  |
| October  | 2.41      | 0.05      | 0.59      | 0.77      | 138.28      | 0.57  |

Linear equations are chosen for the forecast, since they correspond to Fisher's variance ratio/\( F \)-test, have a correlation coefficient \( R \geq 0.7 \) and a ratio \( |r|/\sigma_r \geq 2 \) that corresponds to the regulation documents in effect for hydro meteorological phenomena [23] and can be used to make forecasts in the most stressful
months of the fire danger season (April, May, October). The equations for calculating the forecasted value of the integrated index $C_{P_i+1}$ on $i + 1$ day depend on the precipitation intensity rate (Table 2).

**Table 2.** Calculation of the forecasted value of the integrated index $C_{P_i+1}$ depending on the precipitation rate intensity within three-days (part).

| No | Synoptic term for rainfall intensity | Equation $C_{P_i+1}$ |
|----|-------------------------------------|----------------------|
| 1  | without precipitation, dry weather  | $C_{P_i+1} = C_P + L_{i+1}$ |
| 2  | No rain largely, light rain, a couple of showers | $C_{P_i+1} = (C_P + C_L + C_{CL_{i+1}})/2$ |
| 3  | Rain, precipitation, drizzle, rainy weather | $C_{P_i+1} = (C_P + C_L + C_{CL_{i+1}})/2$ |

4. Discussion

214 forecasts of fire danger indices for a three-day lead time were made during the fire danger season in 2010. Reliability on the first day was 85%, 80% was on the second day, and 70% and 65%, respectively were on the third and fourth days. In addition, the probability of vegetation fires in the territory of Birobidzhan subdivision of the JAR Forestry Department was calculated depending on weather conditions. The correctness of it was 75%. A part of the calculation is given in Table 3.

To construct electronic maps, the JAR Forestry Department net of rides was used with unambiguously identifiable parameters: subdivision, district forest service and a quarter of a year number. The distribution of fire danger parameters was performed by interpolating the actual and forecasted values of the integrated factor and the fire danger class in the center of quarters.

**Table 3.** Forecast of fire danger indices in the territory of Birobidzhan subdivision of the JAR forestry according to the data of Birobidzhan weather station (part)

| Date | Actual | Forecasting | Fire breaking-out probability at a particular fire danger class (I / II / III / IV / V) | Accuracy of forecast |
|------|--------|-------------|----------------------------------------|---------------------|
| 28.04 | 3      | 1           | 0.0 / 0.0 / 0.2 / 1.0 / 0.0             | -                   |
| 29.04 | 3      | 3           | 0.1 / 0.0 / 0.0 / 0.7 / 1.0             | +                   |
| 30.04 | 3      | 3           | 0.0 / 0.1 / 0.5 / 0.1 / 0.4             | +                   |

a. Note: + forecasted and actual data are the same; - forecasted and actual data run counter to.

The probability of vegetation fires is calculated according to the selected timeframe: between 1 day to a month. In the latter instance, fire probability in each quarter is determined by the sum of the probabilities of fire breaking-out for all fire danger classes per each day of the month.

The examples of constructing maps of the territorial distribution of an integrated index and the fire probability on the first day of the forecast are presented in Fig. 2.

**Figure 2.** Map of distribution of the integrated fire danger index (a) and fire breaking-out probability in the territory of the Jewish Autonomous Region (b), October 18, 2010.
The greatest fire danger in April and October was forecasted in the blocks of the City of Birobidzhan, Zheltoyarovsky and Bobrikhinsky districts of Birobidzhan subdivision of the JAR Forestry. The forecast validity is 70%.

5. Conclusion
In conclusion, the performed system makes it possible to forecast the vegetation fire probability according to weather conditions. It can be used to identify the most dangerous temporary seasons and periods, find areas in advance where fires are possible influenced by various changes of weather conditions, and construct maps necessary to hold protective forest conservation measures in order to prevent fires.

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