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Regional assessment of groundwater vulnerability in the Snake river plain aquifer basin, USA

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RESUMEN

El sistema acuífero del río Snake en Idaho oriental es una de los más grandes e importantes fuentes regionales de agua en los Estados Unidos. Salvaguardar este sistema acuífero de la contaminación por el Laboratorio Nacional Ambiental y de Ingeniería de Idaho (INEEL) es de crítica importancia para el Depto. de Energía Norteamericano. Este trabajo contiene el resultado de las siguientes investigaciones: analizar el impacto de factores naturales sobre la vulnerabilidad de las aguas subterráneas; desarrollar el mapa de vulnerabilidad acuífera a la contaminación, indicar sitios contaminados de riesgo de contaminación acuífera usando el mapa. Se puso especial atención a la zona vadosa (zona de aeración) que determina el peligro potencial de penetración de un contaminante desde la superficie al agua subterránea. La evaluación del papel de la protección a la zona vadosa fue basada en los siguientes factores de control: factores pasivos – profundidad al agua y propiedades conductoras del medio insaturado; factores activos – recarga incluyendo sus partes principales: precipitación e irrigación. La evaluación de la vulnerabilidad fue hecha paso a paso para compilar una serie de mapas. Combinando el mapa de la zona vadosa y el de recarga al oriente de la planicie del río Snake, el mapa resultante refleja todos los factores antes mencionados. El sistema Point Count constituyó un concepto principal de evaluación de vulnerabilidad. La influencia de cada factor fue especificado por diferentes números (rangos), los cuales fueron determinados por expertos. A menor el rango, más favorables la situación en relación con la vulnerabilidad del agua subterránea. La vulnerabilidad acuífera es caracterizada por la suma de rangos que puede variar de 8 a 40 en la región estudiada. La suma total de rangos caracteriza la vulnerabilidad acuífera a la contaminación.

PALABRAS CLAVE: Recarga acuífera, zona vadosa, evaluación de vulnerabilidad.

ABSTRACT

The Snake River Aquifer System in eastern Idaho is one of the largest and most important regional water supplies within the United States. Safeguarding the Snake River Aquifer System from pollution underlying the Idaho National Engineering and Environmental Laboratory (INEEL) is of critical importance to the U.S. Department of Energy. The present paper contains the results of the investigations. Its tasks were: analyze the impact of natural factors on groundwater vulnerability; develop the map of groundwater vulnerability to contamination; indicate contaminated sites for risk of groundwater contamination using the map. Main attention was paid to vadose zone (aeration zone), that determines potential danger of contaminant penetration from the land surface to groundwater table. Assessment of vadose zone protection role was based on the following controlling factors: passive factors – depth to water and conduct properties of unsaturated medium; active factors – recharge, including its main parts: precipitation and irrigation. Vulnerability assessment was done step by step by compiling a series of maps. Combining vadose zone map and the map of groundwater recharge at Eastern Snake River Plain, the resulting map reflecting all above mentioned factors were received. The Point Count System was a main concept of vulnerability assessment. Influence of each factor was specified by different numbers (Rank), which were determined by expert assessment. The lesser the Rank, the more favorable situation is with relation to groundwater vulnerability. Groundwater vulnerability is characterized by Rank's sum that could vary from 8 to 40 in region under investigation. Total Rank sum characterizes groundwater vulnerability to contamination.

KEY WORDS: Groundwater recharge, vadose zone, vulnerability assessment.

1. INTRODUCTION

Between 1954 and 1970, approximately 2 million cubic feet of transuranic wastes and 220 000 gallons of related organic contaminants were buried within Idaho National Engineering Laboratory (INEEL) in southeastern Idaho. In order to ensure that these radioactive wastes will remain isolated from the biosphere on time scales of centuries to millennia requires consideration of rates and directions of subsurface flow within the vadose zone and underlying aquifer system. For solving a problem of buried radioactive wastes influence on water quality both under modern and expected natural-climatic changes Idaho National Engineering Environmental Laboratory (INEEL) applied to Russian Academy of Sciences and Moscow State University.

2. METHODOLOGY

2.1. General approach to groundwater vulnerability assessment and mapping

Assessment of natural groundwater vulnerability to contamination is a hydrogeological assessment of measures for groundwater protection under different natural and maninduced conditions. According to experience of some countries, such as Russia, USA, Germany, Italy, etc it is possible to make regional assessments and map the natural vulnerability of aquifers used for water supply and irrigation. This assessment is usually based on the analyses and processing of all the available hydrogeological data including the data that characterizes the protective properties of the vadose zone.

Most of the methodologies are based on either quantitative or qualitative (using computation formulas) conditions that consider the effect of some factors on groundwater vulnerability. An intermediate position involves the determination of the degree of protection by a sum of numbers corresponding to the contribution of a certain factor. The methodologies based on this principle can be grouped with semiquantitative approaches. The quantity and types of vulnerability factors considered by different investigations vary.

On the whole, groundwater vulnerability depends on many factors that can be divided into three groups: natural, man-induced, and physic-chemical. It is governed by natural factors that include depth to groundwater; presence of semipermeable layers; composition, thickness, and permeability of rocks covering groundwater; sorption properties of rocks; hydrodynamic conditions determining the direction and velocities of seepage; rates of water exchange between main aquifers. Man-induced factors comprise: presence and storage of contaminants on the land surface; wastewater disposal; sewage irrigation; character of disposal and penetration of contaminants into aquifers. Physic-chemical factors include sorption and migration properties of contaminants, the character for the interaction between contaminants, rocks and groundwater. All these factors should be considered when assessing groundwater vulnerability to contamination. However, the selection of the principal factors for consideration will depend on the scope of the investigation and the scale of the assessment maps.

2.2. The methods for groundwater vulnerability assessing and mapping in the Snake River Plain Aquifer Basin

For assessing groundwater vulnerability to contamination, available actual data, characterizing geologic-hydrogeological, geomorphologic, hydrological, and climate conditions of the region under investigation were collected and analyzed. A particular attention was paid to analyze of thickness and hydraulic properties of vadose zone (aeration zone), that determines potential danger of contaminant penetration from the land surface to groundwater table in total. The next main natural factor of groundwater protection is groundwater recharge (mean value for perennual period).

Thickness of vadose zone of the Snake River Plain Aquifer Basin was determined from the map of depth to groundwater table compiled by Lindholm, G. F. *et al.* (1988). On the map the thickness of vadose zone is given in hatching according to the next gradation: less than 100; 100-299; 300-599; 600-900; more than 900 feet.

Analyses of structure and hydraulic properties (first of all, permeability) of vadose zone are the most important for assessing groundwater protection. However, data on permeability of rocks in vadose zone are often very limited or absent. In this case, for regional assessment a lithological composition of rocks in vadose zone is analyzed. To characterize hydraulic properties of vadose zone the analyses of the ratio between thickness of basalt and sedimentary rocks in the upper unsaturated zone have been done. Such analysis was made by comparison of maps of depth to regional water table (Lindholm, G.F. *et al.*, 1988) and sedimentary rock distribution, characterizing depth to uppermost volcanic rocks (Subsurface geology. Map ...). Such analyses allowed determining areas in each region with specific range of total vadose zone thickness where:

- content of sedimentary rocks is less than 10 %, that is fine permeable basalt rocks (more than 90 %) predominate in plan and hence, aquifers in such regions are lesser protected from contamination under the same conditions (vulnerability is larger);

- content of sedimentary rocks is 10-50 % from the total thickness of vadose zone (groundwater is better protected in comparison with the first mentioned territories under the same conditions);

- content of sedimentary rocks is more than 50 % in the total plan of vadose zone (groundwater protection is the best under the same conditions).

Such approach is new and at present stage of investigations is the only possible method for permeability assessment, and hence, danger of contaminant penetration from the land surface to aquifer. In this case, according to separate data the basalt rocks matrix hydraulic conductivity is 10^{-8} m/day, but in fractured basalt is more than 30 m/day, and the porosity varies from 0.2 to 0.4 (Faybishenko *et al.*, 2000). Values of vertical hydraulic conductivity of sedimentary units range from 10^{-3} to 10^{-2} m/day, horizontal hydraulic conductivity range 5 – 6 m/day, and the porosity may range up to 0.53 (Rightmine and Lewis, 1987). At the same time, a central tendency of aquifer hydraulic conductivity estimates near the INEEL range from $3 \cdot 10^{-3}$ to 7,320 m/day (Anderson *et al.,* 1999). So, hydraulic conductivity of sedimentary units is essentially lesser than that of volcanic one. Besides, last experiments (Faybishenko *et al.,* 2000) show the main conducting role of basalt fractures. In accordance with above mentioned the analyses of sedimentary and volcanic units ratio was carried out (Table 1).

Assessment of vadose zone protection role was based on the next controlling factors:

- active factors – recharge, including its main parts: precipitation and irrigation;

- passive factors – depth to water and conduct properties of unsaturated medium.

Concerning passive factors, it should be noted that they reflect the property of geological medium to conduct the water and pollution. In regional scale this characteristic depends on relative quantity of sedimentary deposits composing vadose zone. The rest of vadose zone components are the volcanic unit.

This approach allowed receiving a new factor, based on relative quantity of sedimentary deposits in vadose zone. Thus, the more gradation is, the more groundwater is vulnerable.

According to this factor all the Snake River Plain Aquifer Basin can be subdivided on three gradations (Figure 1):

- I gradation corresponds to maximal vulnerability and occupies the most part of the region (~60 %);

- II gradation corresponds to mean vulnerability and occupies north-eastern and edges of the region (~20 %);

- III gradation corresponds to minimal vulnerability and occupies only edges of the region (~20 %).

Summarizing groundwater recharge by precipitation and irrigation, one can obtain the map where some zones are determined. These zones reflect total recharge values coming to aquifer. Groundwater recharge due to precipitation, infiltration at irrigated lands and losses from river runoff is one of the main factors determining groundwater natural protection from contamination coming from the land surface. That is why mapping of groundwater recharge in the eastern part of the Snake River Plain Aquifer Basin is essential part of vulnerability assessing.

Table 1

Ratio between sedimentary and volcanic units in vadose zone

Depth to uppermost volcanic unit, feet	Depth to water, feet					Relative quantity of sedimentary deposits, per cent	Gradations
	<100	100-299	300-599	600-900	>900		
<10	**<10**	**3-10**	**1.6-3**	**1.1-1.6**	**<1**	<10	I
10-50	**10-50**	**3-50**	**1.6-16**	**1.1-8.3**	**1-5**		
50-100	**50-100**	**16-100**	**8-33**	**5.5-16**	**5-11**		
100-500	**-**	**33-100**	**16-100**	**11-83**	**11-55**	10-50	II
						>50	III

*Note: all values are given in percentage.

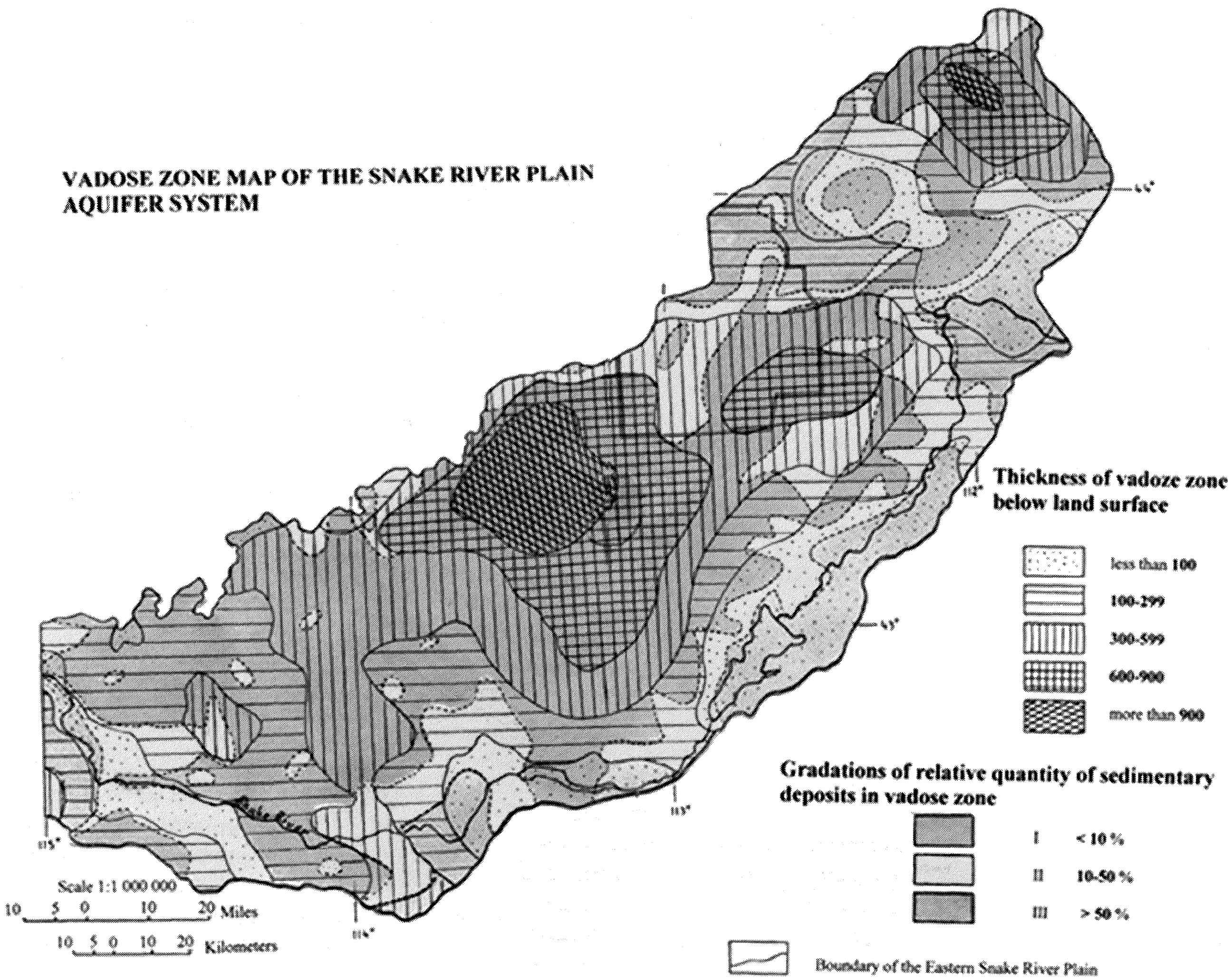

Fig. 1. Vadose zone map of the Snake River Plain Aquifer System.

2.3. Assessment and mapping of groundwater recharge

We would like to produce recharge mapping using the relationship between the rate of available for recharge water comes to top soil due to precipitation and irrigation and recharge rate. To obtain this relationship modeling of vadose zone flow for natural conditions and irrigated areas are performed.

At INEEL site and surrounded areas a lot of works for study flow in vadose zone including unsaturated flow modeling have been done (Wood and Norrell, 1996; Manguson and Martian, 1995, Martian, 1995, Faybishenko B *et al*, 2000) and other. We develop own methodology of assessing groundwater recharge in Eastern Snake River Plain using unsaturated zone modeling. The outline of this methodology is following: 1) estimation of the relationship between annual precipitation and annual recharge for natural condition, 2) estimation of the relationship between annual precipitation plus irrigation and recharge at the irrigated area, 3) mapping of recharge using precipitation map, irrigation map and obtained relationships.

For estimation recharge relationship with precipitation the following preconditions are used:

- Natural groundwater recharge is result of precipitation redistribution between evapotransipration and runoff.
- Groundwater recharge is assumed to be deep percolation of 1-D flow in vadoze zone to groundwater level.
- Due to deep groundwater level the depth of groundwater does not affect on recharge value.

Thus the following equation of water balances in vadoze zone we applied for recharge estimating:

$$W = P - ET - R - \frac{\Delta V}{\Delta t}\,, \qquad (1)$$

where W is groundwater recharge, P is precipitation, R is surface runoff, ET is evapotranspiration, $\frac{\Delta V}{\Delta t}$ is change of water capacity in unsaturated zone.

For calculation water balance Eq. (1) the program HELP (Schroeder *et al.*, 1994) was used. This program includes very well tested blocks for calculation of evapotranspiration and surface runoff. This program calculates vertical redistribution of water in unsaturated zone column using simple model of downward gravity-dominated flow. The flow rate at the low boundary of column is assumed to be recharge value. Comparison of this model with a model that solve Richard's equation in unsaturated zone shows that both model give similar result for water redistribution (Gogolev, 2002)

At the territories like a crater of Moon where basalt rock forms the topsoil profile recharge value should be different from recharge at sedimentary soils. To estimate the value of recharge at basalt topsoil we assumed that due to roughness of basalt surface, the runoff from these areas much less than runoff from sedimentary topsoil, while total evapotraspiration is similar to evapotraspiration from sedimentary topsoil profile. Using this precondition we modeled recharge for sedimentary topsoil without surface runoff. The result of modeling indicates that in average recharge obtained without runoff in 1.5 times exceeds recharge with runoff. This coefficient later was used for mapping recharge at basalt plateaus.

For mapping of recharge the annual precipitation map of Eastern Snake River Plain was created. This map was made using gridded meteorological data obtained from the Surface Water Modeling group at the University of Washington produced following the methodology described in Maurer *et al.* (2001).

13 weather stations with more that 50 years of meteorological records were selected for estimating the relationship between precipitation and recharge in natural conditions. These stations are located within the Eastern Snake River Plain and nearest mountain areas. Measured precipitation in these station 7.5-15.5 inches per year covers typical range of precipitation in studied area (Climatography of the Idaho National Engineering Laboratory, 1989). For the each station 100 year of daily precipitation and temperature values were generated and correspondently series of recharge were calculated by HELP model for seven different topsoil profiles. Averaging over the series gives the mean annual precipitation and averaging over the series and over the profiles gives the mean annual recharge for the each station. Figure 2

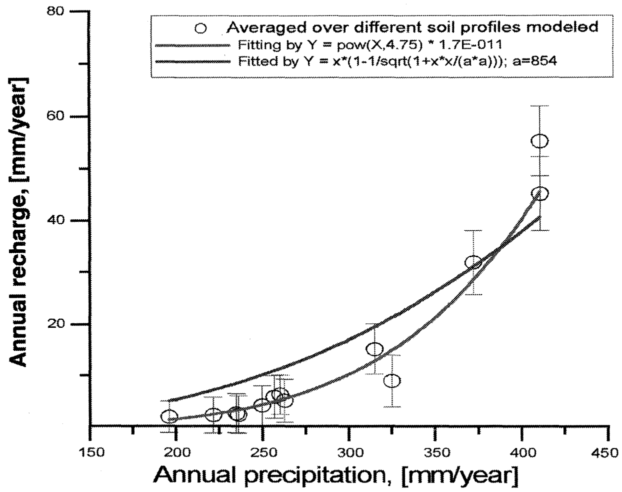

Fig. 2. Averaged over different soil profiles recharge versus average annual precipitation.

shows averaged over topsoil profiles recharge values for each station. The curves at this figure are fitting modeled recharge versus precipitation.

The precipitation map and selected dependence of recharge from precipitation were used for generation the map of recharge in sedimentary topsoil.

To create the final map of recharge that takes into account recharge at basalt plateaus and recharge under irrigated areas supporting base map that shows spatial distribution of irrigation and basalt plateaus was done. The final actual map of groundwater recharge at Eastern Snake River Plain was compiled using mentioned maps. Under the irrigated area recharge was increased on 90 mm/year and under basalt plateaus the recharge values were increased in 1.5 times. As the result the map of groundwater recharge was created (Figure 3).

3. RESULTS

Assessment of groundwater vulnerability in the Snake River Plain Aquifer Basin was based on the methodology, discussed in Chapter 2. The Point Count System was a main concept of vulnerability assessment. The next factors are suggested in this system: recharge; thickness of vadose zone; influence of rocks composition, forming aeration zone. The latest is new and not used in other systems for regional groundwater vulnerability assessing. It represents gradations of relative quantity of sedimentary deposits in vadose zone.

Influence of each factor was specified by different numbers (Rank), which were determined by expert assessment (Table 2).

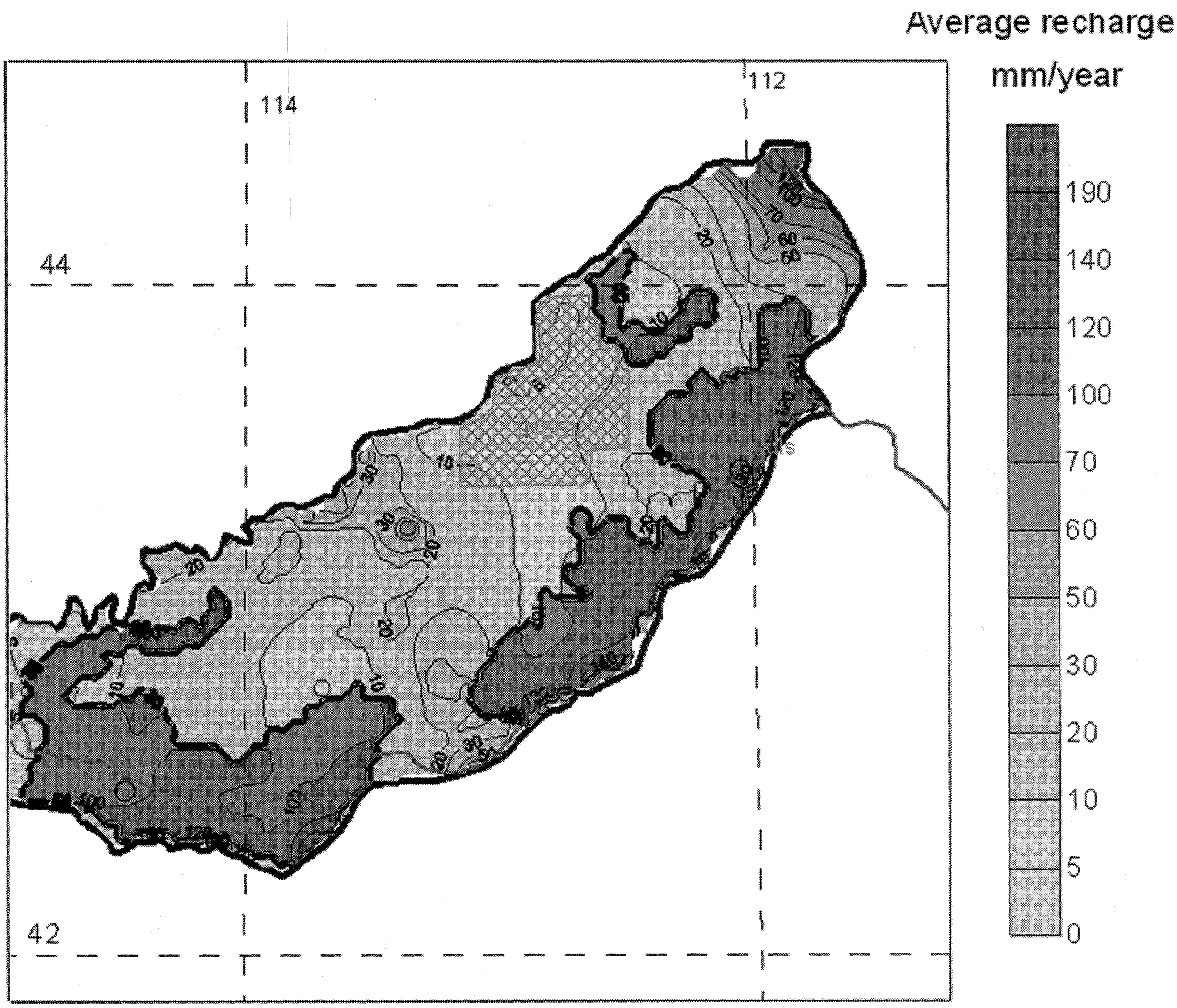

Fig. 3. Actual map of groundwater recharge at Eastern Snake River Plain Basin.

Table 2

The main hydrogeological factors affecting on ground water vulnerability in the Snake River Aquifer Basin

Recharge		**Vadose zone thickness**		**Relative quantity of sedimentary deposits in vadose zone**	
Value, mm/year	Rank	Value, ft	Rank	Value, per cent	Rank
< 10	0	> 900	3	> 50	5
10 - 20	2	600-900	6	10 - 50	10
20 - 30	4	300-599	9	< 10	15
30 - 50	6	100-299	12		
50 - 100	8	< 100	15		
100 - 150	10				

It was shown in Table 2 that Ranks sum could vary from 8 to 40 in region under investigation. Total Rank sum characterizes groundwater vulnerability to contamination. The more Rank sum, the more vulnerable territory is.

Vulnerability assessment was done step by step by compiling a series of maps. The Map of vadose zone (Figure 1) reflects total protective role of aeration zone. Combining this map and the map of groundwater recharge (Figure 2), the resulting map reflecting all factors were received. According to Table 2 Ranks sum was calculated and ranged from 8 to 40. Analyzing received data, it can be noted that for territories with obvious high protective properties of aeration zone the sum is ≤20 (e.g., under recharge <30 mm/year, vadose zone thickness >600 feet and sedimentary rock composition 10-50 %; or any properties, giving in total 20). Basing on above mentioned, values range 8-20 was given to territories with category "well protected". So, all received range was subdivided in the next way (Table 3).

Table 3

Groundwater vulnerability categories

Cumulative rank	Categories
8-20	Good protected
21-25	Protected
26-30	Conditionally protected
31-35	Poorly protected
36-40	Unprotected

Final map (Figure 3) reflects separate areas with different groundwater vulnerability to contamination. From this map it's obvious that basins of the Big Lost River, the Birch Creek, and the Salmon Falls Creek are well protected. Groundwater in these regions receives small recharge from the surface (<10 mm/year) and is protected by sedimentary vadose zone. Then, territories with moderate recharge, where sedimentary cover protects groundwater them from contaminant penetration, are called conditionally protected. And, finally, territories situated mainly on basalt plateau and irrigated land, are poorly protected and unprotected. Besides, hazardous areas of groundwater contamination due to losses of river runoff are situated along this river.

4. CONCLUSION

The results of the investigations within the Snake River Plain Aquifer Basin in the eastern Idaho are: analyze of the natural factors impact on groundwater vulnerability; assessment of groundwater recharge under modern climate conditions; development the map of groundwater vulnerability to contamination; indication of contaminated sites for risk of groundwater contamination using the map.

For assessment and mapping of groundwater recharge the methodology of creation of regional groundwater recharge map for Eastern Snake River Plain was applied. The powerful method for estimating of groundwater recharge was used in groundwater modeling is calibration of regional groundwater flow model taking into account vadose zone study and modeling in key points. This method is applied for solving groundwater management problem for studied area. The ground water recharge map obtained using this approach is conditioned on groundwater level data available for calibration and as usual it consists of zones. As the result the map of recharge can agree with measured groundwater level.

As a result of the investigations, the methodology of regional assessment of the modern groundwater recharge was developed. The map of groundwater vulnerability to contamination in the Snake River Plain Aquifer Basin was firstly compiled. Unprotected and poorly protected from contamination areas were separated out on the map basing on carried out calculations.

Results of assessment and mapping groundwater vulnerability to pollution are of great practical value. They can be used to develop a strategy for groundwater use and protection in areas with differing natural vulnerability; to verify the plans for placing and development of large industrial and agricultural projects that will generate hazardous wastes and wastewater; to verify the groundwater use for water supply and irrigation and places for potable-water supply well fields; to give a hydrogeological proving for different water-protecting measures.

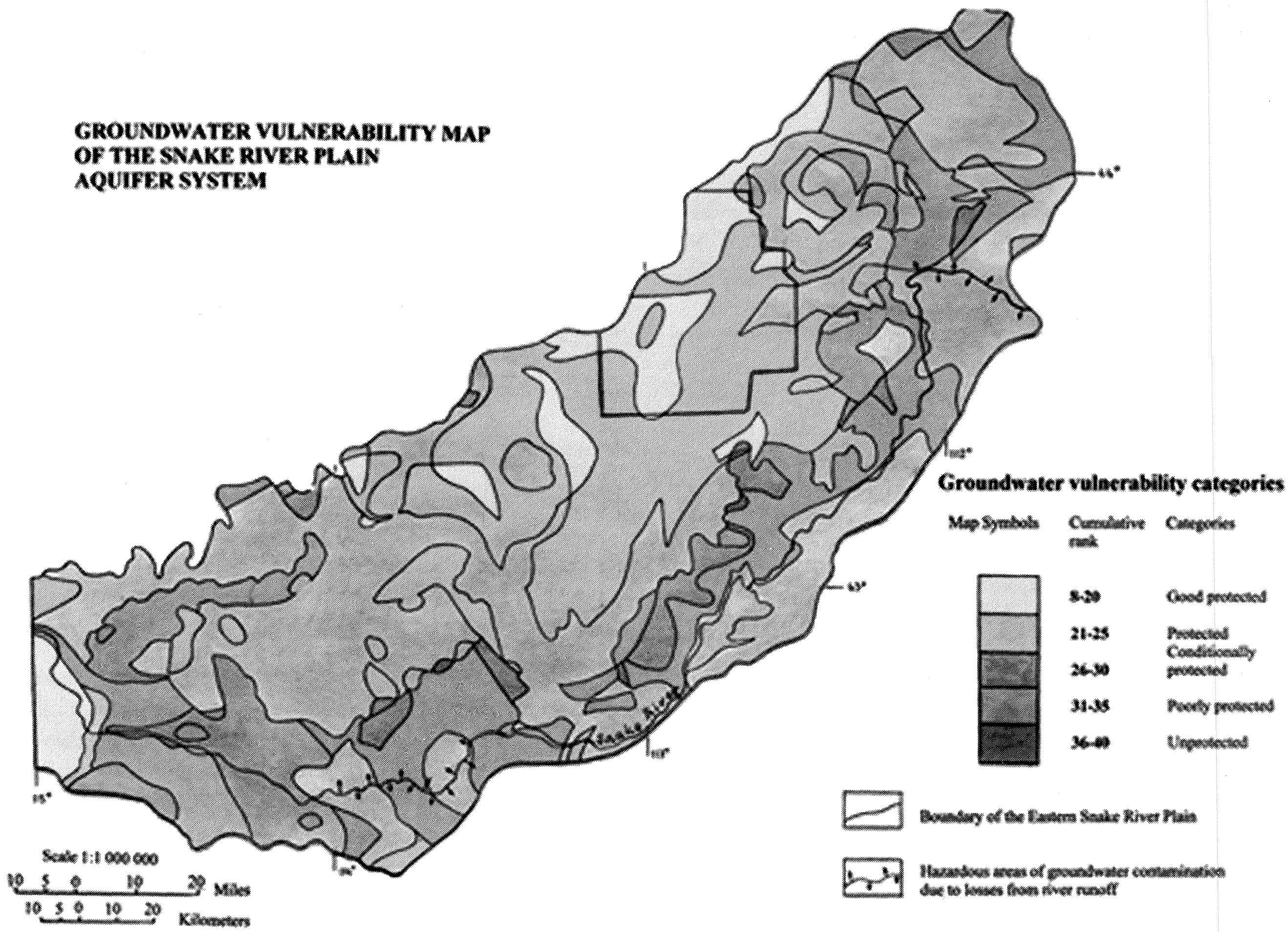

Fig. 4. Groundwater Vulnerability Map of the Snake River Plain Aquifer Basin.

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