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RESEARCH ARTICLE

INFILTRATION AND COLMATATION DYNAMICS ON PHYSICAL MODELS STUDY BY INFILTRATION BASINS AT ARTIFICIAL GROUNDWATER RECHARGE

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ABSTRACT

The problem of the growing shortage of water resources in the world, including in the territory of South-East Kazakhstan, due to global warming and aggravated by long distances to natural sources of good quality water, requires the combined use of surface water and groundwater from local aquifers to supply the local population with high-quality drinking water. The application of methods of artificial groundwater spreading can be an effective way only if positive characteristics of soil and soil parameters of the aeration zone and productive aquifers are obtained in the processes of infiltration and colmatation, which are one of the decisive indicators for ensuring productivity and duration of operation of infiltration basins in the given mode. This work presents the main results of complex field studies of the processes of infiltration and colmatation in infiltration mini-basins at pilot sites within the Aksu, Lepsy and Koksu river valleys, taken as typical for the territory of South-Eastern Kazakhstan, which most needs to increase the water supply of rural population settlements and remote pastures. These studies were supplemented by a detailed assessment of the water-physical, hydrodynamic and filtration properties of the overburden and the upper layers of the aquifer. The new data showed that the infiltration rate varied from 15 m/day at the beginning to 0.75 m/day at the end and remained practically unchanged by the end of the experiment. This was largely facilitated by the values of the heterogeneity coefficient of the granulometric composition of all the examined soils obtained during the studies, which did not exceed 3.0 due to the uniform distribution of coarse fractions and a small proportion of loams and sandy loams. Approximately one month after the start of the tests, a colmatation layer began to be generated at the bottom of the mini-ponds, the thickness of which by the end of the test reached from 3 mm for clay silt to 6 mm for silty clay. However, as studies have shown, the generation of a colmatation layer due to the settling of suspended particles of surface water did not significantly impact on the infiltration processes, as evidenced by the rated values of specific flow rates, which in the final period of time ranged from 0.86 to 0.75-0.80 m3/day per square meter of reduced infiltration surface. Thus, the generated positive results of field studies can serve as a factual basis for design, and can also be recommended and accepted as design indicators both at the stage of a feasibility study and at the stage of detailed design of artificial groundwater spreading systems without additional labor-intensive and costly survey works, and the approved methodology for their implementation will be useful when conducting similar studies in other regions.

KEYWORDS

Processes of Infiltration, Water-Physical, Local Population, Mini-Basins

1. INTRODUCTION

Under the growing deficit of water resources, the issues of their depletion and deterioration of the condition of domestic water supply in arid and semi-arid regions around the world can be addressed through artificial groundwater resources spreading of (AGWRS), the essence of which is an infiltration or injection transfer into the surface water aquifer. This artificial spreading is usually targeted, focused on a small area of influence of the captation structure.

2. REVIEW OF DOMESTIC AND FOREIGN RESEARCHES OF ARTIFICIAL SPREADING OF GROUNDWATER RESOURCES AND COLMATATION PROCESSES IN THE BASES OF INFILTRATION BASINS

The potential of the regions suitable for artificial spreading has been covered by a comprehensive review and multi-year researches in the field of the artificial extraction of groundwater from surface sources, as well as a comprehensive analysis of geo-environmental variables using numerous qualitative and quantitative methods. Artificial extraction of groundwater

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from surface sources has known long time ago. Under shortage of water in ancient times (over two thousand years BC), rainwaters were collected in reservoirs. However, since the water deteriorated, they began to store the water in tanks filled with sand for preliminary water purification. In Venice, prior to installation of centralized water supply, water was received from 200 public and 1200 private cisterns filled with sand, with a total capacity of 200 thousand m3 of water. These tanks were filled with precipitation.

The first examples of such activities in the countries of Western Europe date back to the beginning of the 19th century (Bize et al., 1972). Thus, in France, a channel field infiltration water intake was built to supply Toulouse in the Garona River valley. This capacity failed to supply the required flow rate, and in order to increase it, flat-bottomed pits were erected – the ponds where water was supplied from the river and where filtration occurred, spreading groundwater (Bize et al., 1972). In fact, this scheme still underlies most artificial groundwater spreading activities. Then this method began to be quickly applied in England in the water supply of Nottingham, Derby, and Newark. There are data on the use of the infiltration basin method in Scotland, Germany, etc., related to approximately the same period.

Researches on AGWRS methods are being actively performed in various regions of the world experiencing water shortage. Artificial groundwater reserves in different countries account for 15-30% of the total amount of water supply consumed. Foreign experience works conducted in the USA, Germany, Hungary, Canada, Romania, Switzerland, Central and South Africa, India, Australia, Kenya, Holland and Sweden, on the use of artificial groundwater spreading deserve attention. A studied the quantification of the spreading contribution from both an ephemeral riverbed and an introduced artificial spreading system based on flood water spreading in arid Iran using the MODFLOW model (Aju et al., 2021; Dar et al., 2020; Ahani Amineh et al., 2017; Hashemi et al., 2013).

Infiltration basins have become very popular methods of managed aquifer spreading due to their low construction cost. A detailed assessment of the water-physical, hydrodynamic and filtration properties of the covering sediments and the upper layers of the aquifer, especially when designing open infiltration basins, play a very important and decisive role in the AGWRS researches. Christy and Lakshmanan assessed the feasibility of erecting an infiltration basin in a saline aquifer to the north of Chennai, Tamil Nadu, India, to increase resources and improve groundwater quality (Christy and Lakshmanan, 2017). These researches showed that simple earthworks without slope support and embankment paving facilitated to improve groundwater quality. It is necessary to clean the pond removing accumulated colmatation sediments once a year (Christy and Lakshmanan, 2017). A group researchers executed a spatiotemporal assessment of suspended solids colmatation during laboratory soil column tests followed by numerical simulations to investigate the colmatation problem (Chu et al., 2019).

A group researchers presented the results of a one-dimensional experiment performed on a gravel filter column (Siriwardene et al., 2007). Physical colmatation has been studied at both constant and variable water levels, as well as at various concentrations of sediment influx (Siriwardene et al., 2007). Siegrist studied wastewater soil contamination, wastewater composition and loading rate in a structured silty loam soil under pilot infiltration cells (Siegrist, 1987). It was found that the development of soil colmatation was highly correlated with cumulative mass loads of total biochemical demand in oxygen and suspended solids (Siegrist, 1987). A group researchers conducted laboratory and field tests to identify colmatation mechanisms and quantitative assessment of the filtration efficiency reduction as a function of sediment load in California, USA (Conley et al., 2020). Small infiltration ponds have been erected to assess the infiltration rate. The results of laboratory and field tests showed that the initial and final infiltration rates in the sediment varied depending on the area of the infiltration surface and the initial soil saturated hydraulic saturation (Conley et al., 2020).

Field studies and water level monitoring conducted to evaluate the effectiveness of storm flow infiltration trenches showed a wide variation in colmatation rates (Toran and Jedrzejczyk, 2017). There is still insignificant percentage of the use of artificially created groundwater in the territory of Russia and CIS countries. Research in the field of colmatation processes and parameters to a greater extent relate to the seventies - eighties of the last century and was on a one-time basis. This is true for the works of Plotnikov N.A. [12] on designing of the structures of artificial groundwater spreading for water supply, Burdayev V.A. and Medvedev M.I. [13], who conducted research and analysis of the factors impacting the rate of sand colmatation in water infiltration intake structures (Plotnikov, 1983; Bogomolova and Burchak, 1976). A group researchers on determining the dirt capacity and characteristics of the properties of the silt film in open infiltration structures (Bogomolova and Burchak, 1976). As noted by N.I. Plotnikov, despite the importance of the issue under consideration, today there are no guidelines that would cover the hydrogeological basis of artificial spreading of fresh groundwater reserves (Plotnikov et al., 1978). In our opinion, since the appearance of this book, the state of the issue has changed insignificantly.

Meanwhile, artificial spreading of groundwater, or induced recharge, can be an effective way to address this problem. In the process of spreading, regulation of groundwater reserves is achieved, allowing subsequently obtaining the required amount. In addition, this is the only way in arid conditions to save the aquifer from depletion, increase its capacitive reserves with the expansion of the area of distribution of the level with water natural self-purification, which will meet the needs of the population in drinking water (Mukhamedzhanov et al., 2017; Mirlas et al., 2015). The concept of research should be based on the world practice theoretical and technological approaches to this issue.

Research on the study of the issue of water supply and the efficient use of natural water resources was made by scientists from the U.M. Akmedsafin Institute of Hydrogeology and Geoecology, structural subdivisions of the Ministry of Agriculture of Kazakhstan. Groundwater use technologies were developed (Absametov et al., 2013; Mukhamedzhanov et al., 2016). However, the current condition of irrigated agriculture and the growing water needs of rural producers have mainstreamed the issue of using overflows and caused floods, considering them as a natural water resource in the agricultural sector of the economy. In this regard, we consider the scientific substantiation and implementation of the accumulation method of the river runoff of overflows into storage ponds (small water reservoirs of seasonal regulation) of melt water with their subsequent use for the needs of the agricultural sector as one of the decisive incentives for careful attitude to scarce surface sources for irrigation.

The simplest AGWRS schemes in Kazakhstan began to be used in the sixties of the last century, which was largely caused by drying up of coastal infiltration wells due to the uneven seasonal distribution of surface runoff in the driest years. The AGWRS methods are used to some extent at the Ayaguz, Zhangiztoba, Taldysai, Zharatas and other infiltration water intakes. Especially in the last ten to fifteen years (from 2008 to the present), large-scale scientific research works have begun to be actively carried out, including the territory of the South-Eastern region of the Republic to study the AGWRS prospectives for domestic and drinking water supply of rural settlements, oasis and pastures irrigation.

Antonenko collected and summarized material, both archives and publicly published; his analysis in terms of identifying zones and areas with favorable conditions for artificial groundwater spreading; general criteria for identifying perspective areas have been formulated (Antonenko, 2008). This work was the starting point and the initial stage in a large-scale expansion of detailed scientific and applied research to study the AGWRS prospectives for drinking water supply in South-East Kazakhstan (Antonenko, 2008). A group researcher within the framework of the project grant, given by the Ministry of Education and Science of the Republic of Kazakhstan, performed zoning of the study area and made a map of the prospectives for artificial groundwater spreading (Antonenko et al., 2014). A method of hydrogeological and meliorative zoning has been developed based on the study of the geomorphological conditions of the region, which were very important in substantiating the optimal placement of infiltration basins of open type seasonal regulation under AGWRS (Antonenko et al., 2014).

One of the topical studies determining the future efficient operation of infiltration structures is identification of the filtration process hydrodynamics features. In modern science, this issue is debatable and requires in-depth study. Experimental studies and forecast of filtration medium colmatation in the Sary-Arka alluvial collectors, made by were of scientific and practical importance (Zhumatayev, 2011). Field pilot and filtration studies allowed identifying the infiltration capacity of the aeration zone; establishing regulations of colmatation development; determining the parameters of infiltration structures for AGWRS, assessing the groundwater operational reserves, taking into account their artificial spreading (Zhumatayev, 2011). But one should note that the small areas of device infiltration and a small number of tests did not exclude elements of chance in identifying the probabilistic-statistical nature of the change in the rate of infiltration both by area and in depth.

The theoretical analysis of groundwater movement under infiltration basins, trenches, channels ("open" infiltration structures in artificial spreading systems) is based on the classical theory of saturated flows (Mirlas et al., 2013). At the same time, in many cases, the forecast of the infiltration structures return failed to be proved, as well as the forecast of the groundwater level surface. As a rule, they explain that by an insufficiently complete consideration of the factors impacting the nature of filtration under the ponds. Such factors primarily include the formation of a poorly permeable silt film at the bottom of the pond, its compressibility, colmatation of the upper part of the filter layer, temperature difference between groundwater and filtering water, etc. (Kulagin et al., 2015).

Kuldeyeva during the research, chose an innovative and unified approach to simulate the natural conditions of water penetration until complete saturation of the tested thickness of the overburden rocks, taking into account the infiltration flow spreading under a close occurrence of the groundwater level on the created physical model of the mini basin (Kuldeyeva, 2015). On the basis of the obtained results of the field studies of the AGWRS process, a one-dimensional model of moisture transfer was created, which together made it possible to study the main parameters specifying this process for the conditions of the Karatal experimental site. For this purpose, the Visual MODFLOW Pro software package, often used by Western scientists and specialists, was applied (Kuldeyeva, 2015)

A group researchers believe that the deficit of water resources in the south-east of Kazakhstan, aggravated by long distances to natural sources of good quality water, requires the combined use of surface and groundwater from local aquifers to supply the local population with quality drinking water (Mirlas et al., 2015). According to a detailed assessment of the water-physical, hydrodynamic and filtration properties of the overburden and the upper layers of the aquifer plays a very significant and decisive role for studying the processes of infiltration and colmatation (Kuldeyev et al., 2015 ; Zavalei et al., 2015; Ismagulova et al., 2016).

Field studies of infiltration basins, as well as an assessment of their impact on colmatation processes, were performed using a physical model of a mini-basin in the Karatal River basin of South-Eastern Kazakhstan (Ismagulova and Mirlas, 2019). During these studies, the natural conditions of water infiltration were simulated until the complete saturation of the studied thickness of the overburden, taking into account the spreading of the infiltration flow at a low level of groundwater occurrence. The thickness of the resulting colmatation membrane at the bottom of the mini-basin was only 0.9 mm, while the turbidity of the surface waters of the Karatal River was up to 30 mg/l. Pilot studies carried out at the Karatal experimental site made it possible to assess the processes of infiltration at the infiltration mini-basin, to study the processes of colmatation and silting in the infiltration profile under the mini-basin (Ismagulova and Mirlas, 2019).

Thus, a comprehensive review of literature from foreign and domestic sources, accompanied by a targeted discussion and argumentation on possible solutions to the issue of depletion and deterioration of the drinking water supply of high quality in arid and semi-arid regions under the growing shortage of natural water resources, led to a reasoned conclusion that artificial groundwater spreading can be an effective way to address this issue. This is the only way in arid conditions to save the aquifer against depletion, increase its capacitive reserves with the expansion of the area of distribution of the level with water natural self-purification, which will meet the needs of the population in drinking water. It is argued that one of the topical studies that determine the future effective operation of infiltration structures is to identify the features of the filtration process hydrodynamics. In modern science, this issue is debatable and requires in-depth study.

A perspective region of practical importance for increasing the water supply of rural settlements and remote pasture areas is the river valleys of South-East Kazakhstan, where the presence of an open groundwater surface and the absence of impermeable sediments that overlap the aquifer make the free infiltration method the most effective. The sites perspectives for AGWRS are mainly confined to sites composed of Quaternary alluvial sediments of mainly Modern and Upper Quaternary ages (Kuldeyev et al., 2015). Aquifers are lithologically represented by sediments of gravel, scree, sand, gravel-pebbles and boulders and common in the valleys of the Karatal, Aksu, Lepsy, Keskenterek, Koksu, Tentek, Bizhe Rivers (Kuldeyev et al., 2015).

Taking into account the prospectives for erection of AGWRS installations for their further practical use in South-East Kazakhstan, the need for comprehensive field studies to study the processes of infiltration and colmatation in pilot sites becomes obvious. In this regard, the main objectives of this research were the development and execution of comprehensive field studies to assess the infiltration and colmatation processes in pilot sites within the Aksu, Lepsy and Koksu River valleys in South-Eastern Kazakhstan, mostly needed to increase the water supply to rural settlements and remote pastures. These studies have been aimed at developing the necessary measurements and methods applicable to local conditions. A more objective and larger and more detailed description of the processes of water infiltration and actual colmatation is a real opportunity for unification and applied use of the data obtained for the arid zone of Kazakhstan under a growing shortage of natural water resources.

It is necessary to emphasize that the following research aimed to develop necessary measurements and methods applicable to local conditions. More realistic and detailed area characterization of water infiltration processes and actual colmatation were the initial in-situ information during the performance of the corresponding part of the project on "Assessment of fresh groundwater resources, as the main source and long-term reserve of the sustainable drinking water supply of the Republic of Kazakhstan", financed by the Committee of Science of the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. BR10965134). The authors express special gratitude to rural and district Akimats for the given possibility to conduct research at the realization of the project on the territory of South-Eastern Kazakhstan, for the allocated sites for the arrangement of infiltration mini basins and organization of complex experimental grounds, and for the practical help in carrying out field experiments, and also for installation and equipment of observation piezometers.

3. Research Site Organization

Based on the results of analysis of very limited library, reporting and published materials, it was established that research regions by level of supply with groundwater resources mainly with mineralization of up to 3 g/l belong to regions with poor and satisfactory level of water supply. Groundwater exploitable resources modules equal to 30-250 m^3/daily with uninterrupted water extraction process (Bakirova, 1978). Therefore, while organizing sites, large-scale complex studies for obtaining reliable pilot characteristics and parameters were included and arranged into the list of topical and high priority tasks (Mirlas et al., 2013; Mukhamedzhanov et al., 2017). Field observations were made in three prospective regions of South-East Kazakhstan: in valleys of Aksu and Lepsy rivers and in piedmont plain under boundary conditions of Karatal river main inflow – Koksu river. Locations of research sites in the territory of the Republic of Kazakhstan in Almaty oblast is shown in Figure 1.

The following main and determining criteria were used (Kuldeved et al., 2015; Kuldeyeva, 2015):

- availability of potential consumers of accumulated water on the sites of groundwater resources artificial spreading;
- availability of water-bearing beds (aquifers) having sufficient potential for adopting respective volume of accumulative groundwater reserves, of required quality and in required quantity;
- possibility of using the selected site of groundwater resources artificial spreading as a standard one for dissemination of obtained data to similar regions for further implementation and use of research results;
- possibility of organizing experimental works on the site;
- value and other technical-economic indicators.

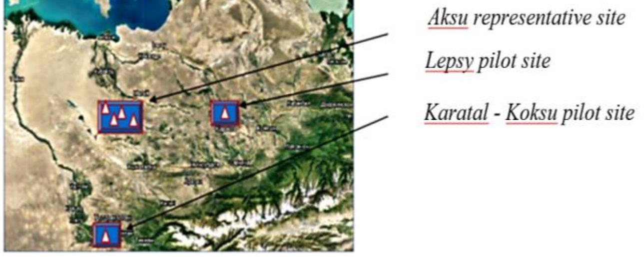


Figure 1: Tile of satellite map of the territory of South-East Kazakhstan with locations of pilot research sites

In the selected sites, exploratory shafts were drawn and rigged. These shafts simulated scaled-down daily runoff infiltration basins, where main types of experimental-filtration works were provided: experimental fillings of shafts and experimental-filtration studies in mini-basins' physical models (Figure 2-3).

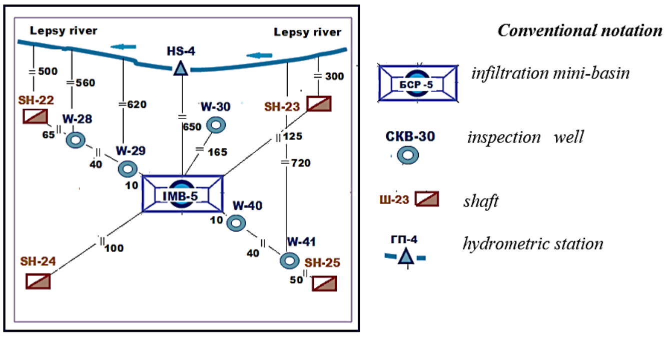
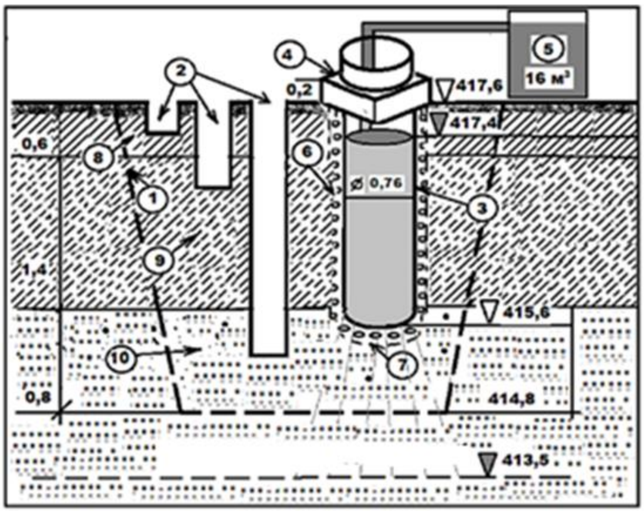


Figure 2: Standard layout of sample location of hydrogeological, geotechnical and hydrometric stations on the example of Lepsy pilot site

Full complexes of field operations of engineering geology soil mechanics with sampling of aeration zone rock specimen were carried out in shafts.

Physical models of mini - infiltration basins were divided into two sections

- in the left part in the mini-basin conventional boundary, three shafts were rigged for consistent study of filtration features of all geological and lithological varieties of blanket and aquifer bottomset bed rocks with undisturbed structure;
- in the right part, with the purpose of ensuring the largest area of infiltration (0.44 m^2), with maintaining constant level (0.2 m) and water head (1.8 m), asbestos-cement pipe with inner 760 mm diameter and 2,200 mm long metal core was used as infiltrometer (Figure 3).



Groundwater baseline level

Figure 3: Scheme of composition and parameters of rigging for pilot research of infiltration rate and colmatation processes

On the scheme: **1 -** infiltration open-type mini-basin; **2 –** shafts to study water-physical and mechanical-and-physical properties of aeration zone soil; **3 –** tube well to carry out studies of infiltration rate and colmatation processes; **4 –** tube well head with installed equipment of river water supply automatic management; **5 –** reservoir for river water filling and settling; **6 –** tube well borehole drilling for a casing pipe; **7 –** gravel filler for casing cement-asbestos perforated pipe; **8 –** average density clay loam, light; **9 –** loamy light sand; **10 –** inequigranular sand with rare inclusions of gravel.

To ensure automated and fixed water supply to mini-basins and with constant water level (water column 1,800 mm), unique own original design dripping systems with a set of floating valves were mounted on the head wall with check valves. To study groundwater hydro chemical conditions within the total hydrocycle of daily runoff infiltration basins operation under conditions of continuous filling with river water, temporary observation piezometers were drilled and rigged (Methodical Guidelines, 2002). Observation piezometers were located so that observation data from them might give a regional characteristics of groundwater hydrochemical conditions formation peculiarities not only in daily runoff infiltration basin zone of influence but also along boundaries and throughout the total area of the research pilot sites. To study river runoff hydrological conditions, arranged were temporary hydrological stations at rivers' stations (Figure 2), attached to the sites of the most promising in terms of designing systems of groundwater resources artificial spreading. Study cross-sections were arranged on sites straightened by terrain and length as well as possible use of rope-boat crossing site.

4. Experimental Studies Procedure

Experimental studies procedure was determined by the set tasks and objectives, and the study of aeration zone actual parameters and colmatation processes was carried out with the use of up-to-date diagnostic devices and laboratory equipment that are based on the existing in the global practice of advanced technological approaches to this issue. To obtain required parameters while carrying out studies of colmatation processes in open infiltration basins, selected was an innovative and unified approach of water infiltration natural conditions simulation until complete saturation of the tested thickness of blanket deposits and dynamics of infiltration flow formation into upper water-saturated sediments strata of the first from surface unconfined aquifer in case of groundwater level close occurrence in the generated physical models of infiltration mini-basins (Kuldeyeva, 2015).

The studies were carried out with account to actual value of rivers' main runoff that starts every March and ends in the end of October with different water content of a hydrologic year: from 25% to 75% exceedance probability, due to which, total duration of infiltration period with the use of groundwater artificial spreading systems is up to 8 months every year. For arid conditions of South-East Kazakhstan, leading role is played by mechanical colmatation conditioned by river flow-induced transfer, especially by floodwater, physical weathering products (Kuldeyeva, 2015). Therefore, special importance was given to performing long-term monitoring of river runoff turbidity value in study sites in South-East Kazakhstan and evaluating its impact upon colmatation processes while using as a source of groundwater resources artificial spreading.

With river turbidity less than 50 gr/m^3 according to our data, cumulative method was applied – samples taken in two points on each vertical line merging together, and henceforth average turbidity was identified. If a river turbidity was less than 20 gr/m^3, samples were merged from all points of effective cross-section, and then river average turbidity was identified. Field observations of river runoff turbidity values are given in accordance with RD 52.08.104-2002 by photometric method - spot measurements with portable turbidity meter manufactured in Russia. Part of them are doubled with check measurements of turbidity by conventional weight method (Siegrist, 1987). Laboratory equipment, chemical glassware and materials provided by the Republican State Institution "Zonal Hydrogeological Ameliorative Center" of the Republic of Kazakhstan Ministry of Agriculture were used for that.

To obtain a reliable characteristic of water-physical, water-chemical, hydrodynamic and filtration properties of aeration area rock, the studies were carried out individually for each horizon of blanket deposits for the entire penetrated thickness (Shestakov, 1974; Ismagulova et al., 2016; Zavalei et al., 2015). To identify fine-gravelly and anisometric sandy soil grain composition, and also coarse part of silty-clayed soil, a sieve method was used (Kulagin et al., 2018; Kozhnazarov, 2010). In the evaluation of aeration zone rock filtration properties based on the results of pilot loading for low permeability soil, N.S. Nesterov method was used, and for permeable soil – A.K. Boldyrev method. Based on the results of water loading to shafts, filtration coefficient of aeration zone blanket soil and aquifer bottom set sediments was found by formula (1):

$$K = \frac{QZ}{W(H_k+Z+h)} \quad (1)$$

where: Q – filtration discharge, m^3/daily; Z - wetted depth after the experiment, m; H_k - capillary pressure value, m; W - filtration section area, m^2; h – water column height in the ring (sump), m.

In the existed and partially restored wells used as the reference observation network, in the course of the year, level was measured every ten days with calculation of the average weighted monthly value of groundwater level with the use of a standard classical method – electrical level gage (Kosheleva and Pashkovsky, 1986; Sychev and Volosevich, 1973; Babushkin et al., 1974; Plotnikov et al., 1978).

Groundwater chemical composition was determined by the content of the most common anions: HCO_3, SO_4, Cl and cations - Ca, Mg and Na, that were expressed in gr/l or meq/l. Sum of anions and cations determined water mineralization or salts quantity. Chemical composition and water mineralization were expressed by salt composition formula. Chemical composition and groundwater mineralization were identified in accredited laboratories of the Republican State Institution "Zonal Hydrogeological Ameliorative Center" of the Ministry of Agriculture, U.M. Akmedsafin Institute of Hydrogeology and Geoecology and K.I. Satpayev Kazakh National Research Technical University by laboratory analysis of samples taken from all wells and observation piezometers simultaneously within fixed period. Experimental studies of infiltration rate, specific yield of infiltration surface and study of colmatation processes were carried out in each of four Aksu sites and one in Lepsy and Karatal-Koksu regions each individually depending on hydrologic year water content (Shestakov, 1974; Plotnikov et al., 1978; Plotnikov, 1983; Burdayev and Medvedev, 1972).

Infiltration rate based on the results of experimental field observations was identified by generally accepted formula (2) (Ismagulova and Kulagin, 2016):

$$V = \frac{Q}{F} \quad (2)$$

where: V - infiltration rate, m/daily; Q – river water discharge supplied to infiltrometer to maintain constant level, m^3/daily; F – area of circle of infiltrometer basis, m^2.

Quantitative determination of elementary mechanical particles content in the formed sediments on the bottom of infiltrometers upon filtration cycles completion, was carried out by pipette method in the accredited laboratory of U.M. Akmedsafin Institute of Hydrogeology and Geoecology. In dust and silt fractionation, particles water fall velocity was taken as basis, i.e. their hydraulic size that is determined by Stokes formula (Vadyunina and Korchagina, 1961). To classify soils by mechanical composition, method of N.B. Sibirtsev was used, who introduced division of particles into physical sand – particles larger than 0.05 mm and physical clay – particles less than 0.05 mm widely used nowadays (Vadyunina and Korchagina, 1961). While processing data of mechanical analysis of formed sediments fraction percentage composition in the base of mini-infiltration basins physical models infiltrometers, classification of N.A. Kachinsky was used (Vadyunina and Korchagina, 1961). Calculations of % fractions content were carried out by formula:

$$X = \frac{100000a}{bm}\% \quad (3)$$

where: X – sought fraction in % smaller than required size (for instance: smaller than 0.05 mm; smaller than 0.01 etc.); a – weight of fraction that is smaller than the sought size, gr; b – pipette volume, ml; m – weight of absolute dry weighed portion taken for analysis, gr.

Weight of fractions of certain size (0.05-0.01 mm; 0.01- 0.005 mm; 0.005 – 0.001 mm and less than 0.001 mm) was found by deduction from the weight or percentage composition of previous weight fraction or percentage composition of the next one (Vadyunina and Korchagina, 1961).

Based on results obtained for dirt capacity and sand established experimentally on physical models of open-type infiltration basins, duration of in-depth colmatation period was identified for all penetrated and tested geological and lithologic horizons by dependence (4) (Kuldeyeve, 2015):

$$T_k = \frac{G}{V_{cp}M} \quad (4)$$

where: T_k- duration of soil in-depth colmatation period, days; V_{cp} – average infiltration rate for the given period determined by plotted diagram of results of desk study of colmatation processes field experimental studies in the basins of rivers Aksu, Lepsy and Koksu, m/daily; M – inflow water turbidity, kg/m^3, G - dirt capacity of rock underlying the first from the surface water-bearing unconfined aquifer, kg/m^2.

Dirt capacity of rocks or the value of soil specific areal saturation with silty and clayey mass while turbid water filtration was identified based on the overall balance of mass of particles suspended in water supplied to mini-infiltration basins by dependence (5) (Bogomolov and Burchack, 1976):

$$G = \frac{QTM}{1000F} - 1000m_0\gamma \quad (5)$$

where: Q - average discharge for infiltration, m^3/daily; T – total duration of water supply, daily; M – average turbidity, mg/l; F – soil filtering surface, m^2; m – average actual thickness of slime, m; γ – slime skeleton volume weight, gr/cm^3.

Skeleton volume weight is determined in an accredited laboratory by thermostatic-weight method on sediment layer samples taken without disturbance to its structure in three replications upon filtration cycle completion and discharge of residual raw water from base surface from infiltrometers with the help of a steel cutting ring and subsequent transportation in sealed and pressurized labeled weighing bottles for performing laboratory and analytical studies (Verigin et al., 1977).

Slime volume weight was found by formula (6) (Bogomolov and Burchak, 1976):

$$\gamma = \frac{P_1 - P_2}{V} \quad (6)$$

where: P_1 – weight of wet ground with a weighing bottle and cap. gr; P_2 – weight of empty weighing bottle with cap, gr; V – slime volume, cm^3.

Slime gravimetric humidity was identified by sample drying to constant weight. Then, calculated was the slime skeleton volume weight by formula (7) (Verigin et al., 1977):

$$\gamma_{ск} = \frac{\gamma}{1 + \frac{W}{100}} \quad (7)$$

where W – soil gravimetric humidity, %.

The value of formed clay coating thickness was identified by instruments immediately after completion of raw water supply to physical models infiltrometers and raw water natural runoff from infiltration mini-basins. Dynamics of clay coating formation on the bottom of basins throughout the whole duration of filtration cycle and upon its completion was tracked and subsequently calculated by main parameters based on the following dependence (8) (Bogomolov and Burchak, 1976):

$$\delta = \frac{Mqt}{\gamma_{ск}} \quad (8)$$

where: δ — coating thickness, m; M - suspended particles content (its turbidity), kg/m^3; $\gamma_{ск}$ – coating skeleton volume weight, kg/m^3; t - time, days; q - infiltration rate (discharge assigned to area unit), m/daily.

To compare results of identification of value of clay coating formed within the total time of maintaining constant level (hydraulical pressure head) in minibasins infiltrometers, two methods were used – immediate sampling with undisturbed structure on the meter base and subsequent measurement of its thickness, and by calculation by the above detailed calculation with the use of full-scale parameters obtained in the process of experimental studies

5. Experimental Studies Results

As the result of desk study and analysis of carried out field studies, the following was established.

From hydrogeological point of view:

- for all rivers of the region under study, characteristic is large asymmetry of river runoff in hydrological cycle, making in multiannual section – 9 years on average: one year high-water, two years in a row – medial by dryness, and 3-5 years may be low-water in a row (Figure 4);

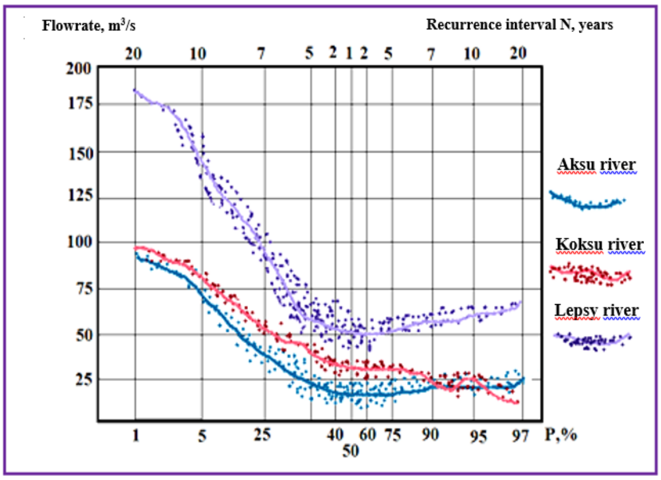


Figure 4: Curves of exceedance probability for annual water flow of Aksu, Lepsy, and Koksu rivers for the period of 1970 - 2020

- rate of gain or decline of Aksu, Lepsy, and Koksu rivers runoff in main-stream stations has considerably changed, as natural decrease of river water content was intensified by losses caused by the impact of economic activities in catch basin, global warming and decrease in glacial-snow feeding of rivers in the region under study;
- water consumption in the region under study must be orientated to river runoff of 75% exceedance probability;
- water of Aksu, Lepsy, and Koksu rivers belong to “clean” rivers (mineralization of water 0.3 – 0.5 gr/l, composition - hydrocarbonate calcium); all rated indicators are within allowable values and can be used for water supply, irrigation and stockwater development.

Data of field and laboratory studies of water-physical and filtration properties shows quite high water-carrying capacity of Aksu, Lepsy, and Koksu rivers valleys sand-and-gravel-pebbly deposits at account of relative homogeneity of their grain composition which is characterized by more or less uniform distribution of coarse fraction and small share of clay loam and sandy clays. Medium and coarse-grained sand with grain size of 0.5-2 mm represents a prevailing faction. Soil heterogeneity factor varies from 1.10 to 1.70. Molecular moisture capacity: minimum for sand (1.5-10%), maximum for loam and clay (15-20%). Filtration factors of the studied soil depend on lithological composition of reservoirs and are equal for gravel-pebbly formation from 5.6 to 8.5 m/daily, for sand – from 1.5 to 4.5 m/daily, for sandy clay: 1.1 – 1.2 m/daily, for clay loam: 0.11 – 0.79 m/daily.

As the result of detailed study of present-day groundwater hydrogeological and hydrochemical conditions, it was established that on study sites the following obtained dissemination and prospectives:

a) for artificial spreading of groundwater reserves by construction of seasonal regulation, open-type infiltration basins - aquifers of alluvial, poorly defined, recent and Upper Quaternary deposits (aQ_{III-IV}) represented by sand, sandy clay, sand-gravel-pebbly deposits with interlayers of clay loam, clay and aleurolites.

Unconfined groundwater level occurrence depth is 3 to 5 m in spring and 5 to 7 m in summer with dryness of the year with 75% exceedance probability; 2 to 3 m and 4 to 5.5 m respectively with dryness of the year with 25% exceedance probability.

Aquifer thickness is 15-25 m. Flow rates of wells while carrying out experimental air-lift pumping-out and data of previously executed filtration works made values of 0.6 – 0.9 l/s with water level decrease by 1.5 – 2.5 m. Specific yield is 0.4 – 0.35 l/s per 1 m of level drop. Filtration factor: 3.15 – 4.5 m/daily. Water-transmitting capability of aquifer deposits: 50 - 115 m^2/daily.

Groundwater mineralization throughout the year almost does not change and makes values of up to 1 gr/l with prevailing sodium bicarbonate-sulphate composition.

b) for distant-pasture cattle rearing stockwater development – aquifer of alluvial-lymnetic Middle Quaternary deposits (alQ_{II}), represented by fine- and inequigranular argillaceous sand, arenaceous, slightly cemented sandstone with interlayers of thin clay loam and clay.

Unconfined groundwater level occurrence depth is 3-4 m in spring and 4-5 m in summer with dryness of the year with 25% exceedance probability; 4-5 m and 5-7 m, respectively with dryness of the year with 75% exceedance probability.

Aquifer thickness is 60-70 m closer to the upper water-parting boundary – Aksu river bed and up to 100 m as it gets closer to the lower southern water-parting boundary – Akozek river temporary bed.

Filtration factor: 1.65 – 2.5 m/daily. Water-transmitting capability of aquifer deposits: 120 - 250 m^2/daily.

Flow rates of wells while carrying out experimental air-lift pumping-out and data of previously executed filtration works equal to 0.2-0.9 l/s with level decrease by 1.0 – 3.2 m. Specific yield is 0.2 – 0.28 l/s per 1 m of level drop.

Groundwater mineralization is 1-2 gr/l in the northern part and with distance from Aksu river to the southern water-parting boundary – Akozek river temporary bed and 2 – 2.5 gr/l with prevailing, respectively, sodium bicarbonate-sulphate composition and chloride - sodium bicarbonate composition.

In the utmost of the study object eastern part, in the valley with hummocky-ridgy aeolian relief, lacustrine-alluvial Lower Quaternary deposits are represented by very fine, fine, less often medium sand and pulverescent sand clay with interlayers of clay.

Unconfined groundwater level occurrence depth is 2-3 m in spring and 3-5 m in summer with dryness of the year with 25% exceedance probability, 3-5 m and 5-7 m, respectively with dryness of the year with 75% exceedance probability.

Aquifer thickness is 0-75 m, filtration factor 1.32 – 1.5 m/daily, water-transmitting capability of aquifer deposits 75 -120 m^2/daily. Flow rates of wells are up to 0.5 l/s with level decrease by 2.0 m.

Groundwater mineralization varies from 1 to 2 gr/l with prevailing chloride - sodium bicarbonate composition.

All the above defined aquifers have hydraulical connection and form a single flow of unconfined groundwater as a whole.

Pilot studies of infiltration rate, infiltration surface specific yield and study of colmatation processes were carried out individually and in differentiated manner depending on hydrological year water content.

Experiment results are recorded in record books and in the form of combined diagrams of infiltration rate dynamics, infiltration surface specific yield, cumulative infiltration, average monthly flow rate and values of river runoff turbidity for studying colmatation processes in the region under study (Figure 5).

By nature of dynamics of determined values based on data of measured water flow rates for infiltration per unit of time and curves of infiltration rates change for the whole period of carrying out pilot-experimental studies, three main stages in the operation mode of all four infiltrometers were established.

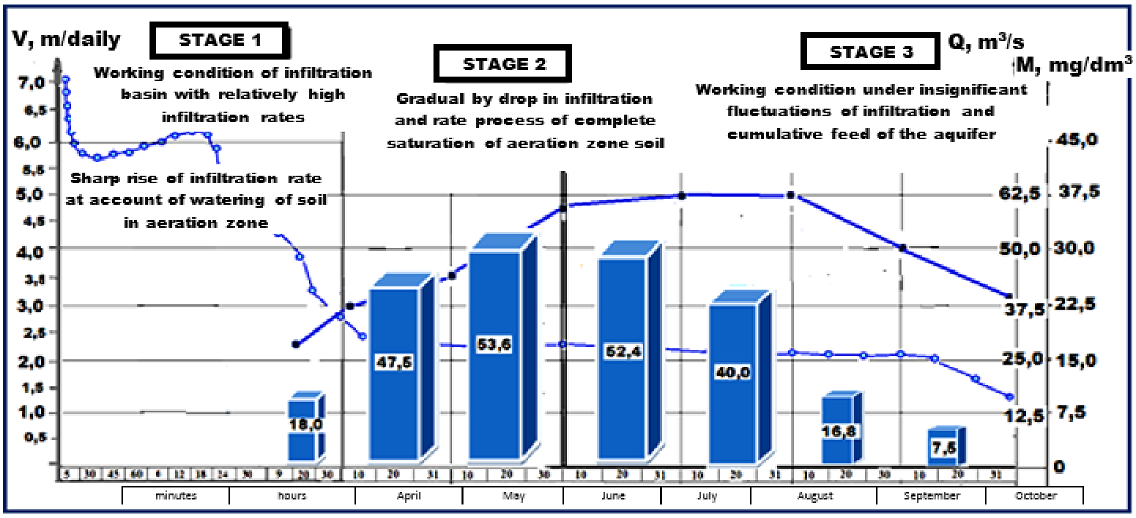


Figure 5: Diagram of river runoff surface water infiltration rate dynamics, average monthly flow rates and turbidity based on the results of pilot studies of colmatation processes in infiltration basin physical model at Aksu representative site (БСР-2)

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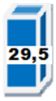
CONVENTIONAL NOTATION: V – average daily infiltration rate, m/daily, Q – river runoff average monthly flow rate with 75% exceedance probability, m^3/s, M – river runoff average monthly turbidity with 75% exceedance probability, mg/dm^3

- isolines of average daily infiltration rate, m/daily,

- isolines of river runoff average monthly turbidity for Aksu river, mg/l,



- block and river runoff average monthly flow rate of Aksu river with 75% exceedance probability, m^3/s,

First – initial stage – is characterized by transient behavior of infiltrometers including saturation period and achieving of complete moisture-holding capacity with the highest infiltration rates, and its duration and values of infiltration initial rate have certain differences in the results of studies in four mini-basins carried out in different years and for different by composition soil. It was commonly established that in the very beginning of experiments, after sharp drop in flow rate for infiltration and respectively of infiltration rate, it boosts which is conditioned by soil in aeration zone watering processes under infiltrometer and forming of so-called “water curtain”. This is visually demonstrated on combined diagrams of infiltration rate dynamics, infiltration surfaces specific yield and cumulative infiltration, built based on the results of pilot studies of colmatation processes in infiltration basin physical model БСР-2 at Aksu representative site (Figure 5).

Table 1: Consolidated Characteristics of Key Evaluation Parameters While Performing Field Observations in Infiltration Basins Physical Models

No.	Pilot studies cycle stage	Average water flow rate, m^3	Duration of in-depth colmatation and pilot studies cycle, days	Water average turbidity, mg/l	Infiltration rate as of the end of pilot studies cycle, m/daily	Slime thickness, m
1	2	3	4	5	6	7
# 1 infiltration basin physical model (Aksu river)						
1	I	1.76	46	19.5	4.00	0.0021
2	II	0.49	61	29.0	1.12	0.0012
3	III	0.42	92	20.0	0.95	0.0010
4	IV	0.25	31	21.1	0.57	0.00022
5	colmatation period	0.49	114	23.0	1.12	0.0017
6	filtration cycle (average specific)	0.75	230	23.0	1.66	0.00529
# 2 infiltration basin physical model (Aksu river)						
7	I	30	30	19.2	5.62	0.0021
8	II	61	61	38.0	2.91	0.0012
9	III	92	92	24.5	1.45	0.0010
10	IV	31	31	25.2	0.58	0.00022
11	colmatation period	98	98	29.0	2.01	0.0017
12	filtration cycle (average specific)	0.75	213	29.0	1.36	0.00494
# 3 infiltration basin physical model (Aksu river)						
13	I	0.76	30	16.4	1.72	0.00050
14	II	0.55	61	23.2	1.25	0.0011
15	III	0.37	92	17.3	0.83	0.00080
16	IV	0.24	31	16.2	0.55	0.00016
17	colmatation period	0.35	168	21.0	0.68	0.0017
18	filtration cycle (average specific)	0.45	214		1.13	0.00256
1	2	3	4	5	6	7
# 4 infiltration basin physical model (Aksu river)						
19	I	1.90	36	25.0	4.32	0.0023
20	II	0.89	117	17.4	2.03	0.0024
21	III	0.70	30	16.5	1.60	0.00046
22	IV	0.28	31	17.0	0.65	0.00017
23	colmatation period	0.79	155	21.1	1.80	0.0034
24	filtration cycle (average specific)	0.64	214	21.0	1.45	0.00533
# 5 infiltration basin physical model (Lepsy river)						
25	I	1.24	30	22.5	2.82	0.0023
26	II	1.02	61	35.0	2.31	0.0053
27	III	0.89	92	30.0	2.03	0.0069
28	IV	0.61	31	24.1	1.20	0.0011
29	colmatation period	0.62	195	30.0	1.40	0.0101
30	filtration cycle (average specific)	0.75	214	29.0	1.70	0.01257
# 6 infiltration basin physical model (Koksu river)						
31	I	2.65	30	17.2	6.02	0.0037
32	II	1.45	61	28.0	3.30	0.0058
33	III	0.93	92	30.2	2.12	0.0068
34	IV	0.31	31	24.1	0.70	0.00062
35	colmatation period	0.81	127	28.1	1.85	0.00795
36	filtration cycle (average specific)	1.08	214	26.8	1.83	0.01264

The second stage is characterized by continued transient behavior of infiltrometer and processes of complete saturation of soil of aeration zone layer under consideration under conditions of gradual and relatively equivalent drop in flow rate for infiltration and infiltration rate. In the third stage, observed was the formation of the established working conditions of infiltrometers under gradual and relatively even drop and insignificant changes in infiltration rate. In the final period of hydrocycle time, irrespective of hydrologic year water content and with mandatory preliminary decrease of turbidity value by settling of water used for studies, observed is the drop in infiltration rate and decrease of infiltration water flow rate. Thus values of infiltration rate and specific yield obtained by the end of pilot works, fully reflect positive filtration capabilities of aeration zone soil and underlying rock of the first from the surface aquifers throughout the whole filtration cycle of infiltration basins work. Consolidated characteristics of key parameters of infiltration dynamics formation, colmatation and silty layer thickness while performing field observations in infiltration basins physical models for artificial spreading of groundwater reserves are summarized in Table 1.

Results of silty layer thickness determination in the process of conducting of pilot studies are summarized in Table 2.

Table 2: Actual and Estimated Data of Silty Layer Thickness Value

Mini-basin #	Sediment description	Obtained values of silty layer thickness, mm			Correlation factor values
		Actually measured	by empirical formula	Difference with actual measurement (+, -)	
1	silty clay	4,04	5,00	+ 0,96	0.81
2	silty clay	6,00	4,90	-1,10	0.82
3	clayey silt	3,00	2,70	-0,30	0.90
4	silty clay	5,00	5,30	+0,30	0.90
5	clayey silt	6,40	12,50	+6,10	0.51
6	silty clay	11,20	12,60	+1,40	0.89

The above actual and estimated data shows that the obtained values of silty layer thickness are satisfactorily conform; almost all values of correlation factor are within permissible limits (variance up to 10-14 %); field observations are quite reliable and performed with considerably high degree of accuracy.

Field pilot-filtration studies allowed:

- quantitative evaluation of paramount hydrophysical functions of soil building up soil profile: dependency of moisture and saturation coefficient on buoyancy head;
- evaluation of volume of water inflowing into unsaturated area of soil profile;
- revealing aeration zone infiltration capability;
- characterizing water flow rate filtrated to aquifer from infiltration basin;
- establishing regularities of colmatation development;
- identification of infiltration facilities parameters for groundwater resources artificial spreading systems;
- analyzing balance components of infiltration flow in the area of incomplete saturation and calculation the volume of filtrated water that will subsequently proceed to groundwater reserves spreading of underlying aquifer.
- well-founded justification that in the creation of infiltration basins penetrating sandy deposits, formation of colmatation layer at account of sedimentation of South-East Kazakhstan rivers' runoff surface water suspended particles will not considerably impact infiltration process.

6. Findings

Academic and research value of studies carried out was in the fact that for the first time priority was given to full-scale field and laboratory works, results of which served as a primary characteristics of colmatation processes fundamental parameters forming and their physical activity. In the course of experiments, in addition to measurements of water flow rate, fed water turbidity was identified as well as slime thickness, slime skeleton volume weight that are baseline parameters for calculation of water filtration under conditions of colmatation. Experiments were carried out with account to actual value of rivers main runoff that starts every March and ends in the end of October with different value of hydrologic year water content: from 25 to 75% exceedance probability, due to which, the total duration of infiltration period while using groundwater artificial spreading systems every year was about 8 months for four years. Such large-scale and long-term experiments in domestic practice of research in Kazakhstan were carried out for the first time. Results of studies carried out allowed revealing of both nature of infiltration rate change, as well as its crossing certain control values that conventionally serve as quantitative landmarks for filtration cycle period estimation, and also exclusion of element of randomness in finding probabilistic-statistical nature of infiltration rate change both in terms of area as well as depth. The findings of colmatation processes study provide firm grounds to recommend using of the obtained data for similar regions for possible further implementation of small groundwater artificial spreading systems in the arid zone of the Republic of Kazakhstan as a real argument of effective control of aquifers depletion in hydrogeological and hydroeconomic practice, as well as for prevention of reduction of water supply to consumers.

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