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Chapter

Global and Regional Aspects for Genesis of Catastrophic Floods: The Problems of Forecasting and Estimation for Mass and Water Balance (Surface Water and Groundwater Contribution)

Tatiana Trifonova, Dmitriy Trifonov, Dmitry Bukharov, Sergei Abrakhin, Mileta Arakelian and Sergei Arakelian

Abstract

Traditionally torrential rains are considered to be the main factor of flood emergence. But with some examples of disastrous floods in absolutely different parts of the world, the rough estimation of the water balance results in the necessity to suggest a correct alternative hypothesis. Our simplest model (taking into account precipitation, evaporation, and soil permeability) clearly points out the significant discrepancy in several events between potentially accumulated and observed water masses. This observation puts forward the idea that precipitation is necessary, but it is not often a sufficient factor for disastrous flood emergence and for the water flow budget. Thus, another available water source, i.e., groundwater, should not be ignored. We consider the reasons and conditions for such phenomena. In this chapter, we will focus only on the causes and forecast of dangerous dynamic phenomena in rock masses. Of particular interest here are water flows through various granite massifs and geological rocks of magmatic origin using nonlinear dynamics approaches.

Keywords: catastrophic floods, groundwater contribution, seismic factors, hydrodynamic pressures, modeling of the topology cracknel fractal structure

1. Introduction

The principal goal of the present chapter is to consider the existing uncertainty and discrepancy for floodwater balance estimation in the area under heavy rain. The problem arises because of, on the one hand, the theoretical approach and reasonable database about the rainfall going from atmosphere and, on the other hand, the real observable surface water flow parameters measured by some methods and/or fixed by some eye-witness [1]. We do not take into consideration the spring runoff and seasonal patterns [2].

The key item of our discussion is that the last characteristics may sometimes be noticeably greater than the first ones [3]. We carried out such analysis, mostly, for torrential rain and catastrophic floods in Louisiana (USA) on June 16–20, 2015. Our estimations show a greater (up to 75%) water mass discharge observation during the event than it could be expected from the rainfall process estimation only in the area under study. The fact gives us grounds for taking into account a possible ground-water contribution to the event [4]. This is especially true for long-standing water on the land surface during the events. In this aspect the principal item of the present chapter is to discuss the reasons of the existing uncertainty and discrepancy for the flood/debris water balance estimation in the area under heavy rain and recognize the impact of different phenomena, providing some meaning for such.

Groundwater flood of a river terrace is also considered in many works. In [5], e.g., the subject was discussed in respect to when the rise of the water table above the land surface occurs due to the intensive rainfall (and being as a relatively rare phenomenon). Many fundamental results have been obtained from the problem, e.g., the contribution of groundwater to surface runoff is very well known in any field of hydrology. But in general, a steady-state behavior is often under study.

In fact, the processes of interaction of groundwater and surface water through the systems of deep karst caves, artesian basins, etc. were widely discussed by specialists in various publications. However, we focus on sudden violations of such stable states when a sudden catastrophic release of large masses of groundwater to the surface occurs, which, in our opinion, can be caused by endogenous transformations of the underground space. Violation of the underground regime stability can occur, in particular, as a result of increased seismic activity, which can lead to the restructuring of the crack organization, to the redistribution of internal pressure and water masses. Meanwhile, the availability of karst rocks is not a prerequisite. It is these possible factors that are the subject of our analysis.

In this chapter, we will focus only on the causes and forecast of dangerous dynamic phenomena in rock masses. Of particular interest here are water flows through various granite massifs and geological rocks of magmatic origin by using nonlinear dynamics approaches [6, 7]. We are speaking about universal, induced by external influences, topological/fractal features of structures for any rock (granites and other types/subtypes of water-bearing rocks). Rather, we are considering nonlinear solid-state physics in terms of strength/fracture and breaking of the continuous structure of underground monolithic blocks and/or their modification under the influence of changing external conditions, including seismic processes.

But the problem is that physics-based modeling of karst systems remains almost impossible without sufficient accurate information about the inner physical characteristics. Usually, the only available hydrodynamic information is the spring discharge at the karst outlet. Numerous works in the past decades have used and proven the usefulness of the time-series analysis applied to spring discharge, precipitations, or even physicochemical parameters, for interpreting karst hydrological functioning [2, 8].

In [9] complementaries of karst hydrology and hydrogeology, the results are indicating a fast passage of a flood wave along a well-developed conduit system.

In our hypothesis, the principal part of a possible groundwater exit to the land surface is related to the crack-net system state in the Earth's crust (including deep layers) being a natural water transportation system. The reasons for that are, first, the pressure field variation for groundwater basin and, second, the modification of the crack-net itself by different factors occurring both suddenly (e.g., may be probably associated with the Krymsk city flash flood event, July 6–7, 2012, Russia) and smoothly (e.g., is hypothetically associated with the Amur River flood event, August to September 2013, Russia/China)) [4, 10, 11]. Such reconstruction of a 3D crack-net water system under different external influences, significant even in any

local crack section and resulting consequently in variation of the water flow pressure distribution, is a principal item for the presented approach.

A separate area of research tackles on the impact of external fields on the properties of rocks with different/variable structures and compositions of minerals in different combinations that determine the classification of rocks by physical properties, in particular, their hydraulic properties under the action of elastic vibrations in the massif. Underground runoff/discharge is determined by the type/subtype of water-bearing rocks, classified on different territories [7].

We believe that in some cases, the interconnection of floods (due to triggering restructuration of the crack-net system as a transportation system for groundwater exit to the land surface) and preceding earthquakes may occur. We discussed such problem in certain event such as the September 2013 Colorado flood (USA)) [10].

Thus, we think it is time to make a transition from the "surface view," i.e., observation of the beholders and consequences of the water events, to "fundamental approach," i.e., measured physical parameters during the continuous monitoring of water budget and possible mechanisms of their variation, especially for a flash process.

In the chapter we discuss the existing problems and basic principles of the concept, the evaluation of the sources and amounts for catastrophic floods, and comparison and analysis of flood characteristics being observed and measured, the disastrous flood in Louisiana, USA, in 2015 being taken as an example. The key part of the concept is related to the impact of fractured bedrock (as the natural transport ways for groundwater contribution) on the water balance in the 3D system of the river basin. Finally, we consider a possible role of tectonic stresses in the Earth's crust in the dynamics of the groundwater basin functioning. The analysis of its state for identifying significant factors in the formation of the water balance in mountain ranges shows that there are some controversial issues and policy challenges in forecasting.

More precisely, we are speaking about the fundamentals of rock physics, as physical-technical properties and physical processes in the rocks depend on a great number of random factors.

It is practically impossible to take these factors into consideration within the framework of a single model. Therefore, it is necessary to develop some hierarchy of models, where each of them describes certain laws and correlation dependences for various physical processes and vibrational phenomena of changes in the physical properties of rocks, which include the influence of seismic waves and the occurring deformations and tensions in the rocks and their destruction [12].

We present our concept as a whole by its sequential functional blocks. This is our hypothesis, which, in our opinion, is original and based on sufficient factual/numerical materials we have applied within the framework of the relevant approaches and models that we have developed.

2. Existing problems and basic principles of the concept

In general, the important circumstance emphasizing the role of groundwater in the river basin system is that its volume is comparable to the whole surface water volume and greatly exceeds the total volume of annual precipitation on the Earth [5, 7]. According to the World-wide Hydrogeological Mapping and Assessment Programme, the worldwide resources of groundwater are assessed at $1.1 \cdot 10^{16}$ m^3. And this is true for free liquid water only. It is supposed that the resources of water contained in hydrated minerals playing the most important role in the Earth water balance might be much bigger [7, 10].

Usually, when the water balance of the river basin is estimated, the soil permeability and its percolation component are considered as the key characteristics [13].

Percolation processes of different scales are considered. On the one hand, it is a small-scale percolation, defined by the properties of specific soils, prevailing in the considered river basin. On the other hand, it is a large-scale percolation, defined by the fracturing of the Earth's crust. Without going into details of the forming of a river basin's geological structure [11, 14], we highlight the fracturing of the Earth's crust which makes the intense interaction of surface water and groundwater possible. The infiltration component of the soil permeability (and deeper rock layers) is characterized by a significantly slower vertical and lateral movement of water masses.

The commonly recognized concept of the river water balance and a hydrological dynamic model during the disastrous floods are based on the simple principle that the river regime development is only associated with runoff due to rainfall [13, 14]. Moreover, a heavy rainfall spatial distribution in watersheds is practically completely determined by some ensemble of selected functions (both regular and stochastic) [14]. The units are being adjustable for the measured discharge of the water flow in such complex system with different orographies, slopes, land covers, soil types, and some meteorological factors during wet and dry periods [1, 3].

Although karst aquifers constitute some of the most important water resources worldwide, generally accepted methods for reliably characterizing their hydraulic properties are still elusive [15].

Usually, the karst hydrological processes are the response of karst groundwater system to precipitation. The precipitation penetrates through the vadose zone. The subsequent groundwater pressure wave propagates to a spring outlet, and then, the spring discharge changes [16]. But sometimes in this case the uncertainty arises specifically as a consequence of variable water routing through the overlying soil, epikarst, and karst aquifer [15]. As it is shown in [17], poljes can be defined as depressions in limestone karst. They commonly occur as large-scale landforms in tectonically active karst areas. Their origin is generally polygenetic. From the hydrologic-hydrogeologic perspective, a polje is to be considered as part of a wider system. It cannot be treated as an independent system but only as a subsystem in the process of surface and groundwater flow through the karst massif.

But there are many questions about the adequate description under the above mentioned approach, and the subject is still not well understood especially for the debris flow-triggering and rainfall events in general [4].

If we are looking for the hypotheses about possible extra water contribution to the surface water flow, the groundwater is a good candidate for that as a driving factor. But the majority of hydrodynamic models are based on a stable and homogeneous shallower subsurface configuration (shallow groundwater table) with a maximum vertical depth of 5 m only [18].

It seems that a deeper groundwater with its long-term spatiotemporal responses makes much more contribution and is more predictable as a permanent process (less independent directly on precipitation) according to morphology of the Earth bowels/bedrock [19].

It is true, especially for a generalized extreme value of observable surface water flow in mountain river basin, when it is difficult to have a daily grid-point numerical data evaluation for correct absolute precipitation amounts (in particular, because a few hundreds of stations are required on a small territory of a few km length) [20]. Obviously, we can carry out a statistical performance evaluation for many years, but each used numerical algorithm is not universal and should be chosen as an appropriate one in accordance with the other complementary models for the study areas [10].

The principal fact is that in some cases, particularly, for stony soils (composed of fractions of rock fragments and fine soil with different hydrophysical characteristics), the infiltration process of rainfall at a lower rate is weaker than infiltration capacity acting in an opposite way. Thus, the highest vertical outflow occurs from

the bottom of the profile in soils (in contrast with the case without rock fragments) under the ponding infiltration condition [21].

Both interaction and water exchange between the groundwater and surface water are very important for flood forecasting and flood detection. But even using many hydrological gauging stations for database and global early flood warning (taking into account the space and/or radar monitoring), there is a big discrepancy between different models and real events, especially for a historical flash flood [22]. In fact, for real water events, were obtained by hydrograph, that a peak flow of the flood (coming from the river basin including many tributaries) occurs sometimes earlier than rainfall fields become maximum. The possible reason is due to vertical hydraulic gradients resulting in groundwater upwelling into stream value [23]. On average, the correspondence between the rainfall peak and debris flow location causes a systematic discordance underestimation for triggering rainfall whenever rainfall is measured away from the debris flow location [24].

3. Dynamic processes and the surface and groundwater coupling

The key question is how groundwater dynamics affects the stream flow in the unified system of the hillslope-riparian interface of a mountain catchment. Even in the case of high-resolution monitoring of hydrometric components on a 10-min daily basis, taking into account a precipitation level discharge process and groundwater state (controlled usually by both the shallower (not more than 1 m) and deeper (up to a few meters and as an exception—several tens of meters) wells), there has not been observed a direct correlation between precipitation and the groundwater dynamics during the storm events for both dry and wet periods [24, 25]. Therefore, the response of surface water and groundwater to meteorological factors is often not obvious in correlation aspect.

In [26] it was reported that the hydrological regime of the spring had a strong natural variability, and it was recommended that detailed interdisciplinary investigations of the spring water should be carried out to ensure its sustainable use and facilitate further development. Moreover, in a unique hydrological analysis of overflow discharges measured in the Rječina spring, the available data included average daily overflow discharges measured in the period from January 1, 1948, to December 31, 2015. In addition, numerous studies have been carried out in [27] in karst aiming at the investigation of groundwater regime. The karst spring hydrograph can reflect the groundwater regime, and consequently the analysis is based on them. A simple conceptual rainfall-runoff model is used for the estimation of groundwater balance components including the influences of time invariant catchment boundaries. The proposed parameter estimation procedure merges the soil moisture balance and the groundwater balance approaches to obtain the complete groundwater budget. The effective rainfall is calculated by using a mathematical model based on soil moisture balance equations, i.e., Palmer's fluid mass balance method.

The problem is that the driving factors for water events (and especially to estimate the water balance in dynamics on the land surface) are more complicated, and the essentially deeper groundwater levels (up to few km) have to be taken into account. As to determination of soil structure in groundwater areas for abovementioned depths, the data are not enough, and we need to analyze a deeper crust structure in respect of a water capacity budget.

In fact, a global unit is based on the unique superdeep well drilled in Kola (USSR/Russia) up to 12, 262 m (1990). In a well-developed crack tress-like system, they observed a granitic layer with high porosity saturated by mineralized groundwater under the temperature of more than 2000°C and pressure of about 1000 atm.

The picture is not typical for the Earth's crust of continental type due to the earlier and standard presentations because the basaltic layer, being a much more strong rock, was not even reached [28].

Our goal is to develop a reasonable rainfall-runoff model for the prediction (if only qualitatively) of dynamic processes in ungauged river basin to discuss some approach to realize the assessment of water balance and forecast catastrophic floods. The model realism is based on the groundwater principal impact in some specific cases on the water events on the Earth's surface. Such key factor, introduced in the model and using a specific knowledge of the river basin, may explain the water balance in the cases when it is still uncertain [29, 30]. Now many researchers have already recognized that the assessment of the water budget should be based on realistic corrections of precipitations, temperature, potential evaporation, and a hydrologic area state in order to form the runoff balance [31]. The validation of our approach is tested on some past flood events discussed below.

The basic idea is that groundwater participates in a cycle process within the catchment, when discharge and recharge of the water balance in different areas occur, and a restoration process in time of water budget as a whole is caused by these factors. But the problem is not a question of moisture recycling only. The precipitation rainfall uncertainty has many sources, both spatial and temporal, and even under a detailed control, a grid spacing of surface water exhibits a great difference. It cannot result in a reasonable pattern for the surface water distribution and representation for rain gauges network (especially for different landscape discretizations and seasons) [24].

Moreover, a correct flood map for surface water flood events cannot be designed without the groundwater spatiotemporal state analysis being necessary for return periods, especially for early warning of hypothetical surface water flood scenario, in particular, to estimate the threshold for debris flows [5, 32, 33].

In addition, for a different structured model plane split of the solid state with porosity (balls, capillary tubes) associated in different geometrical structures and distributed periodically and/or randomly and anisotropically in general, the Darcy law for water flow does not work [34]. The problem becomes more complicated for a high speed of infiltration and for non-Newtonian liquid, especially in stony soil under complex topology of the boundaries and nonlinear process of infiltration. In fact, even for turbulent flow in open channels, many problems in hydraulics picture still exist [35]. But in reality for the texture of rock, we have a crack-net system with a macro-openness (up to tens of mm) and micro-openness (up to 100 μm) of cracks overlapping with a pore structure and some macrodepression zones. The system is, in principle, dynamic under some impacts of both intrinsic and external processes.

Thus, to estimate numerically the permeability and water discharge through natural rocks and/or a layer of soil in such complicated stochastic system, the condition of nonstationary dynamic flow is a practically unsolved problem, even when we know the pressure distribution (by concrete piezometric data located in different areas) in spatially decomposed sections of the system with the integrated length of the cracks being up to a few tens of meters in different stratums. Note that even under the simple Darcy law approximation, the increase of a channel diameter from 1 mm to 2 mm being a routine process, but the water discharge grows dramatically—in the value of approximately one order [36]. Some estimations of pressures in the water channels and different regimes of flow are presented in Appendix A.1 (both by direct calculation and computer simulation technique).

But necessary and preliminary stages to study the groundwater-surface water interaction are connected with the mapping procedure and recognition of dynamic processes in the system based on a big data collection over many (about hundred for each regional area) monitoring and groundwater level time series and also their analysis (e.g., by a cluster analysis technique) [37, 38].

Therefore, it is necessary to fulfill the comparison of measured and theoretical data, based on the advantages of both methods of calculated hydrodynamics for liquid flows (in system with complicated topology) and subsurface mechanics of porous and fractures media (for transient flow of non-Newtonian highly viscous fluids in porous media). This procedure seems not to be realized, especially while taking into account the timing of the water table response [39, 40].

In fact, the existing problems in the field under a traditional groundwater hydrology approach resulting in a fundamental knowledge gap between the modern/stochastic groundwater theory and its application to real events are being discussed in recent published monograph [5] (see also [36]).

It is important that the groundwater lying in the Earth's crust is directly subject to any impact occurring in the crust. In its turn groundwater being an elastic and incompressible medium reacts to these impacts in different ways, including passing them to surface water. The following processes in the Earth's crust are considered: from microseismic and local seismic shocks of various magnitudes to global movement of the tectonic plates. The Earth's crust (and/or its particular parts) is not considered as stable and immutable today—in this case we cannot speak about stable behavior of the groundwater.

Thus, to study the subject, we need some new ideas and concepts. In this respect a possible influence of tectonic stresses on the occurrence of catastrophic floods by the mechanism of modification of the 3D crack-net (as a transit system for groundwater) may be discussed based on this natural transport ways in the conditions of functioning of the river catchment basin [4, 41–43].

As a result, a new map of pressures arises in the underground hydrosphere, and consequently groundwater masses burst out through extra open water transport channels due to fracturing of rocks, with a short discharge time (like mudflow) and/or a smooth long flow that was not previously available in stationary operating conditions of the mountain river basin.

The key point of the proposed approach is the identification of the conditions of earthquake influence on the river basin functioning. The possible role of the preceding seismic activity for some certain disastrous floods of 2013–2017 is analyzed in [10, 11]. These issues have not been paid enough attention to so far. However, taking them into account may help forecast disastrous floods accurately and promptly considering the combination of many factors.

That is why the geological structure of the Earth's crust in dynamics (where groundwater is located) is also an important element of the river basin system or at least one of the key factors significantly influencing the river basin functioning. Unlike precipitation it is almost not considered when analyzing the reasons of the flood emergence.

Several floods, which took place in 2012–2015, are under our consideration and probably could be associated with corresponding seismic processes in the Earth's crust. In the practical aspect, a proposed hypothesis can be useful while defining potentially dangerous areas for catastrophic water events taking into account the interference of the state of the underground hydrosphere and the tectonic structure of the rheological section of bowels for the Earth on concrete territories.

4. Analysis for 2015 disastrous flood in Louisiana, USA. Figures and tables

4.1 Used methods

The disastrous flood took place in the state of Louisiana, the USA, in the period of June 7–20, 2015. It affected four parishes of the state: Caddo Parish, Bossier

Parish, Natchitoches Parish, and Rapides Parish. The flood-generating river was the Red River of the South with a catchment area of 169,890 km^2 including some areas of Texas, Oklahoma, and Arkansas states of the USA.

The simplest model for water balance estimation inevitably includes such main elements as precipitation, evaporation, soil permeability, calculated water mass, and observed water mass [5, 36].

While the goal of exact estimation with the defined precision is not set in this study, some aspects are purposefully simplified. For example, accumulated water mass on a certain day is calculated simply:

$$V_i = \sum_n V_{in}, \qquad (1)$$

$$V_{in} = V_{i-1,n} + (P_{in} - e_{in} - p_n) \cdot S_n, \qquad (2)$$

where V_i is the volume of the accumulated water mass in the whole catchment area on day i, V_{in} is the volume of the accumulated water mass in region n on day i, P_{in} is the precipitation intensity in a region n on day i, e_{in} is the evaporation rate in region n on day i, p_n is the soil permeability of a region n, and S_n is the area of a region n. In this case the region means a specific part of the river catchment area with similar weather conditions. Region-to-region transfer of water mass is neglected; hence there is no index (n $\pm$ 1) in the formulae (1), (2).

Certain temporal and spatial simplification parameters of the used arguments as well as the sources of data are given in **Table 1**.

In addition, there are some significant remarks. Firstly, the evaporation rate does not include transpiration because of its negligible role in the process of evapotranspiration. Put directly, evaporation is meant as Class A pan evaporation. Secondly, we do not use Darcy's law describing the process of percolation. We suppose that the tabular values of permeability of different soil types are quite enough for our consideration. So, soil permeability of the specific region is calculated using the formula:

$$p_n = \sum_j k_j p_j, \qquad (3)$$

where k_j is the approximate percentage of soil type j in the total area of the region, and p_j is the minimal tabular value of permeability of soil type j. Soil permeability in the context of the present work is measured not in m$_2$, as is fixed in

Argument	Temporal simplification	Spatial simplification	Source
Evaporation rate, e_{in}	Monthly average data	USA states: evaporation at a certain region is defined as one at a Class A pan station nearest to the center of a region	USA states: US Department of Commerce, Springfield, the USA [44]
Soil permeability, p_n	No temporal dependence	Different soil types of the region surface are distinguished; resulting soil permeability of a region is calculated as weighted average	Soil types: FAO/UNESCO [45]; soil permeability, tabular values [46]
The area of region, S_n	No temporal dependence	—	Google Maps service [47]

Table 1.
Sources and simplification parameters of data.

Darcy's law, but in mm/day that means how much water daily permeates through the one square unit of the surface.

Thus, we have calculated water mass that potentially could be observed during the floods. And the last thing, we need to compare the calculations and real observations. Obviously, the most exact data would be a really measured volume of water mass, but the problem is that there is no such data. We used the following approximate approach to estimate a really observed water mass [48].

In the case of the Louisiana flood, being under our consideration, a more complex and precise approach is used. We take the information about the Red River levels at Shreveport, Coushatta, Grand Ecore, and Alexandria (the most affected cities of the Louisiana state) [49] and combine this data with the topographic map of Louisiana provided by TopoZone service [50]. Then we multiply the area and the depth with the remark that we do not take the whole flooded area but that part of it that accords to one of the four selected cities. After all we sum four calculated values to get the resulting volume of observed water mass. This approach allows us to get a quite exact value.

4.2 The results

In the case of the Louisiana flood, the flood-generating river was the Red River of the South. All initial data presented below were taken from [47–50] and organized in a convenient way by corresponding data processing. The whole basin has been divided into seven regions (see examples in **Figure 1**). In **Table 2** some parameters of the distinguished regions are presented.

As it is been mentioned above, the approach of calculating observed water mass in the case of the Louisiana flood is a little bit more complex than a usual one, and in **Table 3** the parameters of calculation are presented for a better understanding of the used approach. The final total result is the value: $11.0 \cdot 10^9$ m^3.

Figure 2 shows the result of applying the formula for calculating accumulated water mass (see Section 4.1) to given parameters. The legend is the same as in **Figure 1**.

In order to emphasize the important role of groundwater in the flood event, for illustration purposes, we will take the limiting case when the permeability of the soil dramatically decreases (1000 times). In practice, it really can fall dozens of times
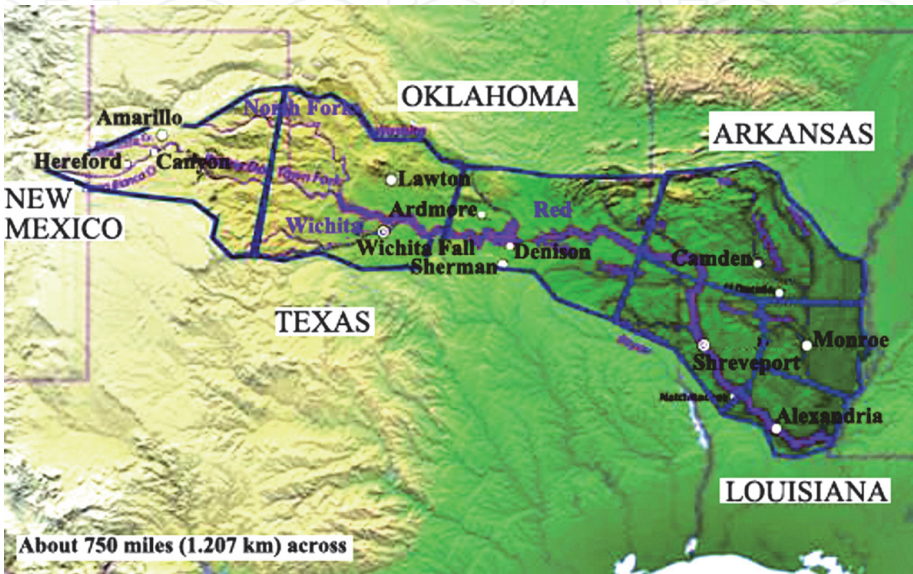

Figure 1.
The distinguished regions of the Red River basin.

Region name	Area, 10^3 km^2	Evaporation rate, mm/day for 2 months	Prevailing soils	Estimated soil permeability, mm/day
Amarillo	24.4	May: 6.7; June: 8.0	Kastanozems, luvisols	800.2
Lawton	34.4	May: 8.2; June: 10.5	Kastanozems, luvisols, cambisols	900.1
Sherman	33.3	May: 5.9; June: 8.7	Acrisols, cambisols, phaeozems, luvisols	1450.1
Camden	35.5	May: 5.0; June: 5.7	Kastanozems, acrisols, gleysols	0.1
Shreveport	16.8	May: 5.6; June: 6.3	Acrisols, phaeozems, planosols, gleysols	3000.1
Monroe	13.1	May: 5.6; June: 6.3	Acrisols, gleysols, luvisols	0.7
Alexandria	12.5	May: 4.8; June: 5.2	Acrisols, gleysols, phaeozems, luvisols	500.2

Total: $11.0 \cdot 10^9$ m^3.

Table 2.
The parameters of the Red River basin regions.

Affected city	Flood stage, m	Red River level on 11.06.2015, m	Estimated observed water mass, 10^9 m^3
Shreveport	9.1	11.2	2.9
Coushatta	9.4	11.8	3.3
Grand Ecore	10.1	12.6	3.6
Alexandria	9.8	10.6	1.2

Table 3.
The Louisiana flood observed water mass calculation.

over several hours due to saturation process, i.e., we assume that all rainfall goes to runoff of the river.

Even having the low estimates of the evaporation process (from web resource [51]), we obtain that the maximum level of water during the flood should have been on June 15, 2015, and should have been in the order of $5 \cdot 10^9$ m^3. The observed peak corresponds to the flooding $11 \cdot 10^9$ m^3. Moreover, if we take into account the presence of surface runoff only (web resource [52]), our estimates in the framework of a simple hydrodynamic model (based, first, on actual terrain and, second, the coverage of the surface by precipitation area) lead to the duration of the floods for a few hours, which is not a real event occurred. Thus, the presence of an additional (except precipitation) source of water masses appear to be real, and groundwater might play a more dominant role.

4.3 Correlation of groundwater level and surface water for catastrophic floods

We now introduce the monitoring data on the well artesian level during the flood time in two sectors of the Red River in Arizona in respect of timing of groundwater recharge and discharge and their impact on the flood event.

Precipitation data by months were obtained at https://water.weather.gov/precip/.

Downloading maps with precipitation was carried out from the same source: https://water.weather.gov/precip/download.php.

(a)

(b)
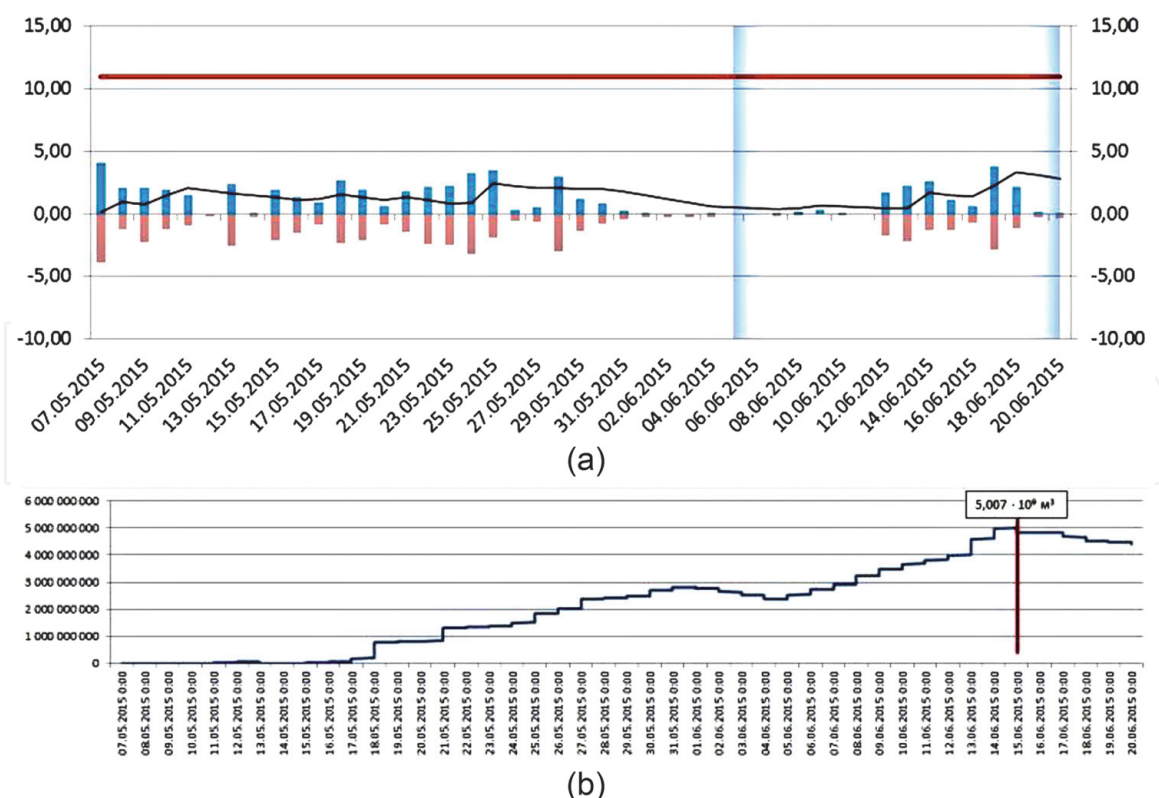
Figure 2.
Water balance of the Louisiana flood (Shreveport city): (a) over days; (b) more detailed dependence (over days).

At the same time, the official conditions for the use of this information data are justified on the specified site as follows.

The precipitation data are quality-controlled, multi-sensor (radar and rain gauge) precipitation estimates obtained from the National Weather Service (NWS) River Forecast Centers (RFCs) and mosaicked by the National Centers for Environmental Prediction (NCEP). The original data from NCEP is in Gridded Binary or General Regularly distributed Information in Binary form (GRIB) format (files pre-March 22, 2017, are in XMRG format) and projected in the Hydrologic Rainfall Analysis Project (HRAP) grid coordinate system, a polar stereographic projection true at 60°N/105°W.

Use the form above to download these files. To automate or download multiple datasets, you can download a program called wget. Due to increased web security, the anonymous FTP server is no longer available but can be still used by https:// water.weather.gov/precip/archive/.

First (**Figure 3**), we show the upper part of a river drainage system (near Shrevport city) [53].

Second (**Figure 4**), we display the lower part of a river with the greatest water-bearing capacity and the smallest inclinations of water surface (near Alexandria city) being the area of the most intensive collection of atmospheric and surface waters on the Earth's surface for the replenishment of groundwater [54].

The dependences in these two cases demonstrate a sufficiently different behavior.

The concept traditionally accepted by people is that the water table intersects the surface of the Earth (in accordance, as an example, with **Figure 3**). This contradicts the concept we discussed, which is based on the possible local exit area of the groundwater. In fact, a temporary accumulation of groundwater in the zone of aeration is formed due to the percolation of rainwaters (**Figure 4**). The effect can probably occur above the normal/stable water table, which is separated from the surface by an impermeable rock, but with a well-developed system of cracks.
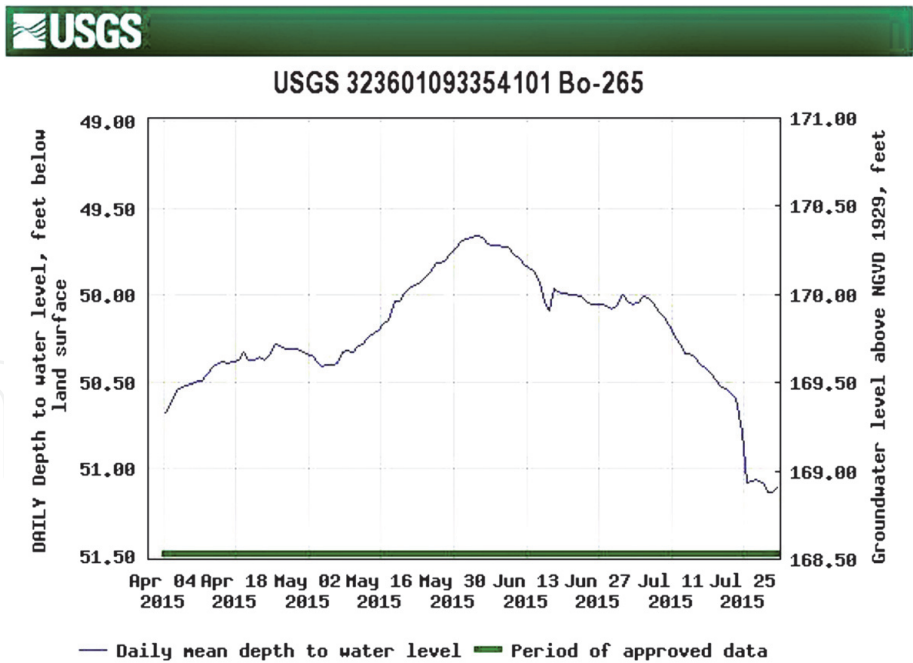
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Figure 3.
Daily depth to water level and groundwater level for upper part of river drainage system.
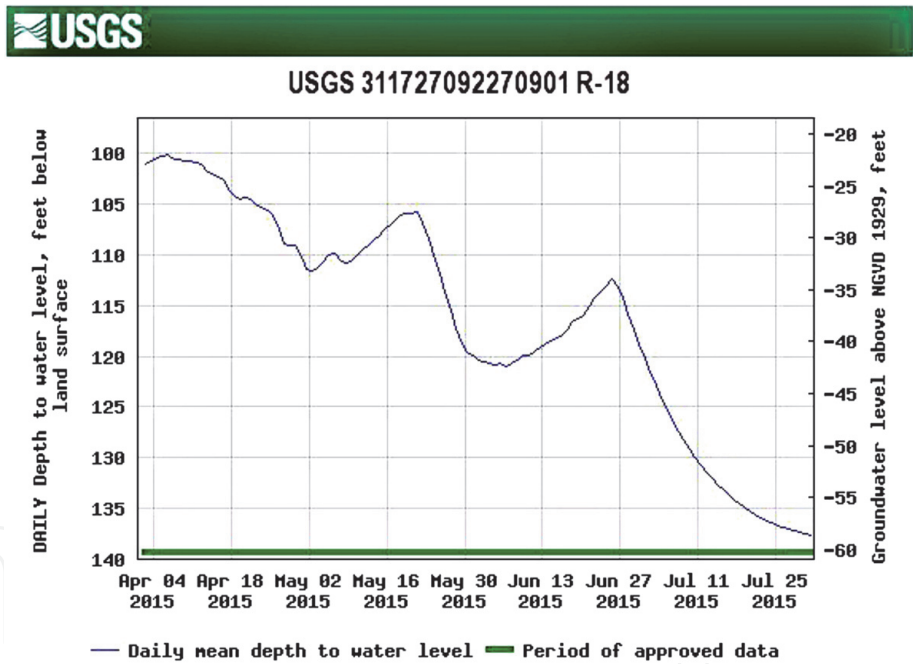

Figure 4.
*The same as in **Figure 3** but for a lower part of a river.*

The coupling of groundwater and flood event is evident very well from **Figures 3** and **4**. In fact, we can see a correlation between the level of water in artesian wells and the flood period development in Louisiana, Shrevport city, over the days: maximal water levels both in Red River on June 9, 2015, and in well practically coincide (**Figure 3**). A principal fact is that the well water level is increased from the middle of May 2015. In the same time period, the well water level near Alexandria city (being lower on the Red River bed than that with Shreveport city) decreases (**Figure 4**).

The last nonobvious correlation fact ("anticorrelation effect") may be explained by the pressure aspect: backwater due to the rise of surface water mass in the stream

channel near Alexandria city accompanied by the decrease of the ground horizon level in a lower sector of the channel (see Appendix A.1).

Then, in both cases the artesian well level decreases and goes to the equilibrium state when the flood event is over, and the self-throwing out process has stopped.

The misbalance of the calculated and observed water masses is quite large for the considered cases. In the case of Louisiana flood, the difference is about $7 \cdot 10^9$ m^3, and a relative difference becomes $\approx 60\%$. Thus, while we predict the potential area of flooding relying solely on the precipitation intensity, there is a high risk of underestimation of the possible outcome. And, if no other water source except groundwater is available, we have to more carefully estimate the role of groundwater in the flood development.

Also note that the prevailing soil type in the most affected regions of the Louisiana state is gleysols. This soil type is characterized by the close interconnection with groundwater [55]. That means that groundwater aquifers are very close to the surface in those regions. We suggest it should really be of importance, and this fact is not worth underestimating while we see such a great relative difference between calculation and observation.

The given analysis of water balance on the example of the 2015 Louisiana disastrous flood does not pretend to the exhaustiveness. The only aim was to show the possible discrepancy between potentially accumulated and observed water masses. The idea is not to downplay the role of precipitation in the flood emergence and development, but to consider the whole system of river basin in the close interconnection of its parts, where groundwater is an important part as precipitation, especially while we consider disastrous floods. Obviously, we also have to take into account the processes of evaporation in different seasons [56].

5. The mechanism of the 3D riverbed formation

In a number of previously published works [57–63], a mechanism was proposed for the formation and functioning of the mountain river bed and the catchment basin. The fundamental position of this concept is that river channel cracks are laid in the rock as a result of relaxation of accumulating stresses and begin their development, namely, from the water intake (mouth) to the source but not in the opposite way. The mechanism of forming the channel branching (formation of future tributaries) occurs in accordance with the laws of mechanics for the rock destruction. At the end of the channel, i.e., the cracks, a stress zone forms, where rock destruction processes intensify, and a round-shaped drainage funnel is formed (the source zone of the river).

The crack, formed in the rock, extends not only along the surface but can reach great depths (hundreds and more meters). Thus, groundwaters are pulled together here (under the influence of capillary forces in a stable state) and can rise to the surface under the influence of the pressure map developed by different reasons. The processes are "basic and permanent" in a functioning river but occur with variable intensities due to external factors. The surface runoff, because of precipitation, represents another unstable component of the water balance and depends mainly on the climatic/season conditions. If a channel crack core is not deep and has not reached a groundwater source, it can still develop in the anhydrous regime of the "dry channel" and/or during the action of a temporary surface runoff. Thus, the first conclusion can be made: it is not enough to consider rivers from the point of view of only surface hydrological objects, where only a surface runoff and seepage occur. It should be presented as a river basin functioning as a 3D dynamic object under impact on many factors, including geological states/seismic processes.

In fact, the river channels are deep formations through which a coupling of surface water with groundwater is carried out. Thereby, on the one hand, the process of global crack formation relieves internal pressure, and, on the other hands, the water cycle is carried out due to the emerging structure of cracks.

We present the details of a possible crack topology in Appendix 2.

6. Nonlinear hydrodynamics approach and modeling

Now we shortly focus on the mathematical modeling of catastrophic water flows on the land surface in the frame of the concepts of nonlinear hydrodynamics of the wave process development with the formation of solitons (within the different classes of solutions for the Korteweg-deVries (KdV) equation) [35]. According to the soliton ideology, there is a competition between two phenomena, the first, in time t, i.e., dispersion (decay of the process), and, the second, due to nonlinearity (amplification of the process). The key parameter for the problem is coefficient $k(t)$, where $k(t) \sim ?(t)^{\text{disp}}/?(t)^{\text{nonl}}$ is a ratio of characteristic values for two competing processes: dispersion (?) and nonlinear interaction (?). The mechanism of such processes should be considered separately, and the amplification can be introduced by not only a heavy rain but also by a groundwater exit.

Different classes of the KdV equation and well-known solutions in modeling have been under our study. But as to the natural water event we are going from the inverse problem: to find the class of solution being associated with the items of observable phenomena on the land surface.

In principle, different regimes can occur and should be under analysis in respect to the detailed states of the water systems:

- Soliton (particle-like) self-organization solutions

- An inverse scattering solution and spectral representation

- Many-body exact N-soliton collective solution

- A vortex motion

- Many dimensional problems

- Perturbation theory approach (reaction on any perturbation)

- High nonlinearity and self-trapping and instability regimes

- Overturn regime

- A solitary long stationary wave

- Nonlinear periodic wave envelopes with shelf track

The regimes, marked by bold type above, are principal for catastrophic floods in observable real events [64].

As an example, let us consider two regimes of the surface wave propagation (amplitude u) with velocity v for the groundwater recharge behavior, depending on the channel depth λ: $\lambda \sim h(x)$ as a function of traveling coordinate x (cf. [4, 5]).

1. Fast (flash−/jump-like) enhancement variation. And therefore, a multiple-soliton process occurs vs. traveling coordinate x when we have two magnitudes for sharp variation of (t):

$$\lambda(t) = \begin{cases} \lambda_1, & t < 0 \\ \lambda_2, & t > 0 \end{cases} \quad \lambda_2 > \lambda_1 > 0 \text{ which is shown in } \mathbf{Figure\ 5}.$$

2. Slow increasing variation for $\lambda(t) \sim$ smooth transition from $\lambda 1$ to $\lambda 2$ ($0 < \lambda 1 < \lambda(t) < \lambda 2$): see **Figure 6**.

This general approach and practical verification were applied to some catastrophic water events including the conditions for a solitary destructive wave
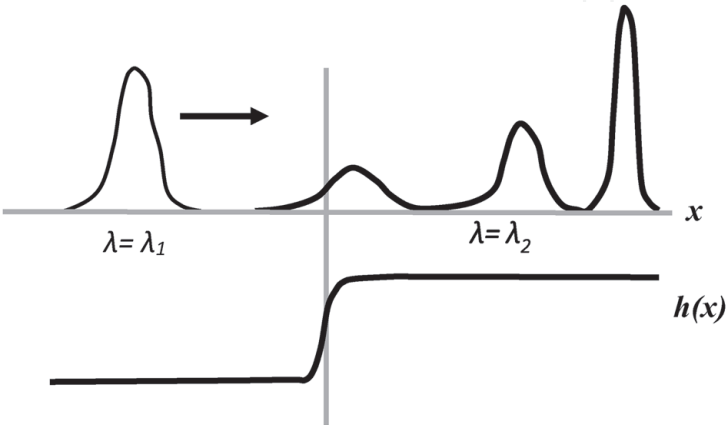
Figure 5.
The jump mechanism (trigger-like) for the recharge enhancement of the water body by flash groundwater process for the space variation of the channel depth λ.
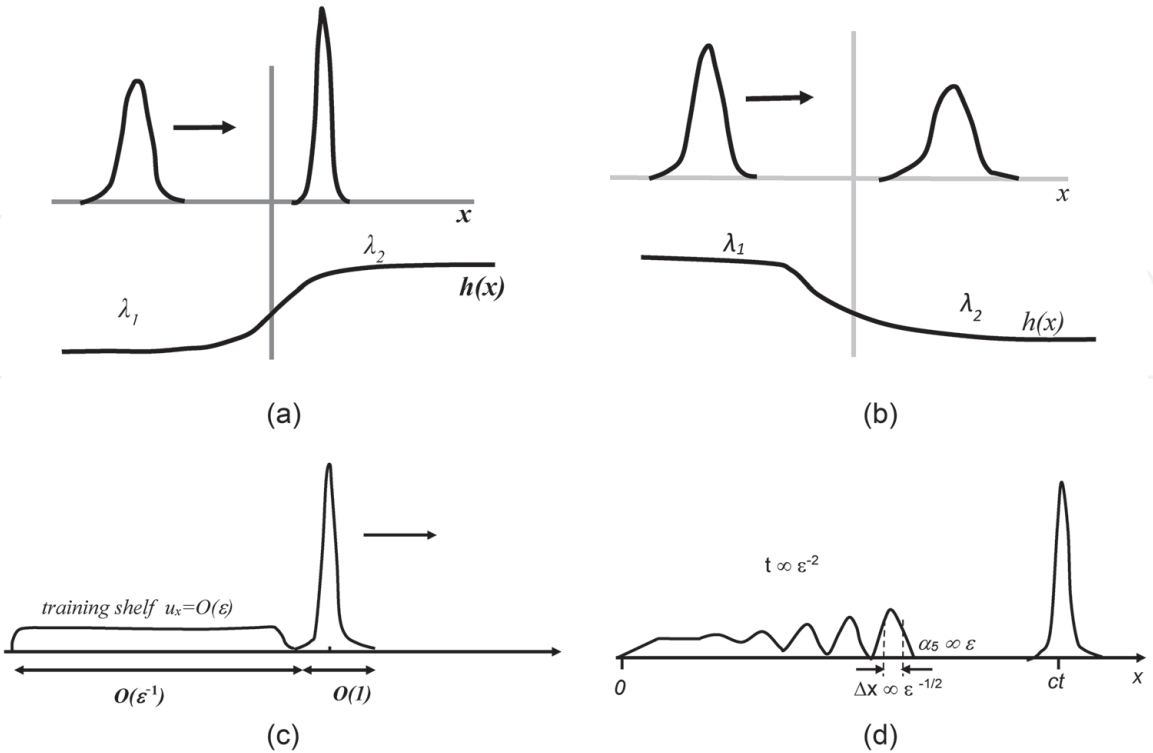
Figure 6.
Flash process modeling for a sudden water discharge (the debris/flood event): (a) - under the depth decreasing ($\lambda_2 < \lambda_1$); (b) - under the depth increasing ($\lambda_2 > \lambda_1$). The amplitude of soliton is increased and decreased, accordingly, vs. x; (c) more detailed analysis results in the shelftype dependence; (d) when the dissipation takes place (i.e., bottom friction), the decreasing of the wave amplitude u occurs (u ∼ 1/h).

propagation, e.g., for Colorado flood (USA, September 2013) and Krymsk city (Krasnodar region, Russia) fast event (July 6–7, 2012) which occurred over the land surface under the trigger mechanism (see Appendix A.1.2.).

7. Impact of tectonic stresses in the Earth's crust on the dynamics of groundwater basin functioning

We discussed above the status of groundwater in terms of its possible role in the catastrophic water events on the Earth's surface. But now let us consider a simple concept of tectonics for the complex mutually influencing processes in heterogeneous environment with different phase states in bowels of the Earth. In the case, topography is a reflection of the tectonic and geodynamic processes that act to uplift the Earth's surface and the erosional processes that work to return it to base level. Numerous studies have shown that topography is a sensitive recorder of tectonic signals [8].

7.1 The proposed approach

From the practical point of view, the monitoring of dynamics in the development of hydrostatic/hydrodynamic pressures in underground aquifers in comparison with the database before and after the events (e.g., by measurements in some network artesian wells) is an important factor in assessing the acceptable risk for the territories under these events. Its combination with the monitoring of seismic activity will allow making a more detailed analysis of these interactions for a natural disaster forecasting in both fundamental aspect and in the aspect of applying modern information technology (e.g., GIS technology).

The artesian well water state as the precursors of earthquakes of different natures have been widely discussed for many years, and a comprehensive research for earthquake prediction has been carried out [4, 33, 36, 61]. But the interconnection of tectonic stresses in the Earth's crust, in the aspect of dynamics of the groundwater basin functioning, is practically out of consideration.

These nonstationary and nonlinear groundwater transport processes under the earthquakes impact (resulting in the great hydrostatic/hydrodynamic pressure enhancement in hydrosphere) are rapidly developing phenomena. The influence of the Bernoulli effect, i.e., a sharp drop in pressure (water hammer) in a high-speed liquid flow in the expanding cavity, explains the strange fact (at first glance), when a great local pressure (from the very beginning in the deep underground layers) does not always result in the bowels of the Earth to the expected strong (in the including height) water emissions on the Earth's surface (see Appendix A.1 and Appendix A.2).

The proposed concept of the tectonic regime for the territories is based on several factors: layering crustal layer of the Earth, its lateral heterogeneity, and internal mobility of the 3D deep rock masses. Such violation of monolithic rocks and their fragmentation granularity are associated with the environment (both on the micro- and macroscale), i.e., with the presence of free space between the discrete solid particles [5]. The stability of such systems is provided, including void fill with water from its own underground sources, and due to the infiltration of surface water. Typical maximum depth for these two mechanisms could be estimated by the values of 10–15 km and up to tens to hundreds of meters, respectively [32]. This granularity, which is the result of degradation processes (leading to block-hierarchical structure), is a characteristic parameter even for the set of lithospheric plates [42]. This results in the possible vertical transition between different

breeds of shell lithosphere (vertical accretion), accompanied by a shift of their boundaries, i.e., a "shimmering border." Such geodynamic process, apparently, is important to determine the vertical lift and underground deep water during earthquakes.

If we talk about the inverse problem, i.e., about the impact of groundwater on the modification of the tectonic stress, this process has an independent tectonic significance for the preparation of earthquakes, including the aspect of stress transfer in the underground water basin over long distances due to the weak compressibility of water [33]. Such transfer tension should be considered in conjunction with the effect of heavy rains, which leads to the release of both transport paths of the drainage mechanism and to the increase of the surface water masses (lakes, reservoirs, etc.). Thus, the pressure increase in a single hydraulically connected 3D system of the river basin may occur and result in the groundwater exit to land surface [65, 66]. We analyzed some hypothetic considerations under the concept by the database presented in [67–70].

There are at least two obvious mechanisms explaining how the occurred earthquakes can influence the river basin functioning. The basis of both is the impact of the earthquake seismic waves, which can propagate over huge distances in the Earth's crust (up to several thousands of km). Now we are interested in their influence and possible mechanisms of the topology variation of the existing groundwater transport ways.

On the one hand, some parts of the transport net may suddenly change during the topology restructuring. When the cracks are blocked, there happens a dramatic growth of pressure in the other parts of the net. Herewith the cardinal effect is a water breakout on the surface when water gushes, being a water hammer mechanism of the breakout manifestation. Possibly the flash floods of destructive power are implemented by this mechanism. It is important that after this breakout (which has opened a new channel). The groundwater can flow continuously for a long time defining the long water staying on the surface (until the local groundwater resource is exhausted). Moreover, the crack topology restructuring can cause the connection of the initially unconnected groundwater basins and/or disconnection of the connected ones. Such events may also significantly influence the water balance of the river basin system.

Manifestation of all these changes requires a long time period for different geographical conditions. This defines a temporal lag which may be observed between the considered seismic events and the floods in specific areas. Thus, slowly developing and long-lasting (large-scaled by flooding area) floods are defined in this case by the long process of the groundwater flow through newly opened channels and/or even ancient/dry riverbeds which have been inactive in the aspect of feeding from groundwater basins earlier.

The key part of the concept is determined by the impact of fractured bedrock in the water budget for the river basin as a unified 3D system. The reasons for that are a pressure field variation in a groundwater basin and the modification of the crack-net system itself by different factors. They occur both suddenly and/or smoothly. We consider a possible role of tectonic stresses in the Earth's crust in the groundwater basin functioning in dynamics. The observable phenomenon is a hydrology state variation.

But sometimes questions of the subjects should still be discussed [71]. In fact, the hydrological changes could be caused by inter-basin water transfer and the reservoir development on the hydrological regimes of different/two rivers. Moreover, even when they are neighboring watercourses with similar climate, even topographic and geological characteristics, their hydrological characteristics extremely differ [72].

7.2 Definition of potentially dangerous areas in the aspect of the probability of occurring floods under the influence of seismic factors

Our general consideration (over existing datable) in the concept shows that a more significant impact of the groundwater exit on land surface occurs for the earthquake hypocenter depth ~10 km when the magnitude value is about M5.0 (~10^{12} J), which may be associated with seven points in earthquake epicenter on the land surface.

Further, we carried out some correlation analysis on the subject. The most accurate correlation (+)/anticorrelation (−) (the Pierson coefficient K) can be estimated for two principal parameters: river discharge during the flood and artesian water level in wells in some localized river basin areas. We had $K \gtrsim (-0.97)$ but with some optimal day shift ~10–20 days (for the distance ~200 km) during the Mississippi river catastrophic flood (April to June 2011; maximal level, on May). Thus, we can tell about an anticorrelation event, i.e., it means that the river discharge increase/decrease is due to the decrease/increase of the artesian water level. As to other correlations—between the precipitation level and both the river discharge and the groundwater level during the event—the maximal value of K was less: $K \lesssim +0.7$. Thus, in fact, the groundwater plays a dominant role for the case.

In addition, the presence of large water objects (on the route of seismic waves) weakens their amplitudes; the availability of the tectonic plates borders results in the reflection and refraction effects for propagating seismic waves. Let us consider in more details the earthquake which occurred in Kansas, USA, in May 2015, which may be recognized as a disastrous flood in Louisiana, USA. For understanding the reasons why the flood occurred exactly in Louisiana, we should pay attention to the geological structure of the Red River basin where the disaster occurred. The thing is the Red River basin is located over the Southern Oklahoma Aulacogen, which, as any geological rift, is a kind of wedge in homogeneous medium. It is well known that at the boundary between homogeneous mediums, Stoneley waves have their maximal amplitudes [36]. Because of this, the location of the Red River basin over the Southern Oklahoma Aulacogen could play a crucial role in the disastrous flood emergence. Local geological structure could amplify the seismic influence of the earthquake occurred in Kansas.

In this case the most important forecasting for the floods is that the procedure helps to solve the problem of flood localization when a group of earthquake epicenters is located in one area. If the position of such group of the earthquake epicenters does not localize in the hazard area by itself, then the analysis of local geological structure allows making some conclusions: more distinct borders of homogeneous rocks cause higher risk of seismic wave amplification, and then the disastrous flood is provoked by them.

Another important aspect of such groundwater resource depletion is connected with the strange factor of increasing the risk of wildfire emergence on the area in the near future. In fact, the flood in California, USA, in February to June 2017 (**Figure 7**), lasted for half a year, and then large wildfires occupied in the state and lasted for two following months [73]. It is possibly connected with the fact that the soil is not really moisturized after the flood because the water goes to the balance recovery of deeper aquifers.

Similar events also took place after the historical flood in the Amur basin (2013) where large wildfires were raging after several months almost over the same area [74].

And the final feature concerning the hydrostatic pressure map in the 3D net of the river basins may be introduced by analogy with the system of communicating vessels (see Appendix A.1.2.). For example, when the flood in the Amur river basin (2013) occurred, the neighboring surface river basins of the Amur and the Lena
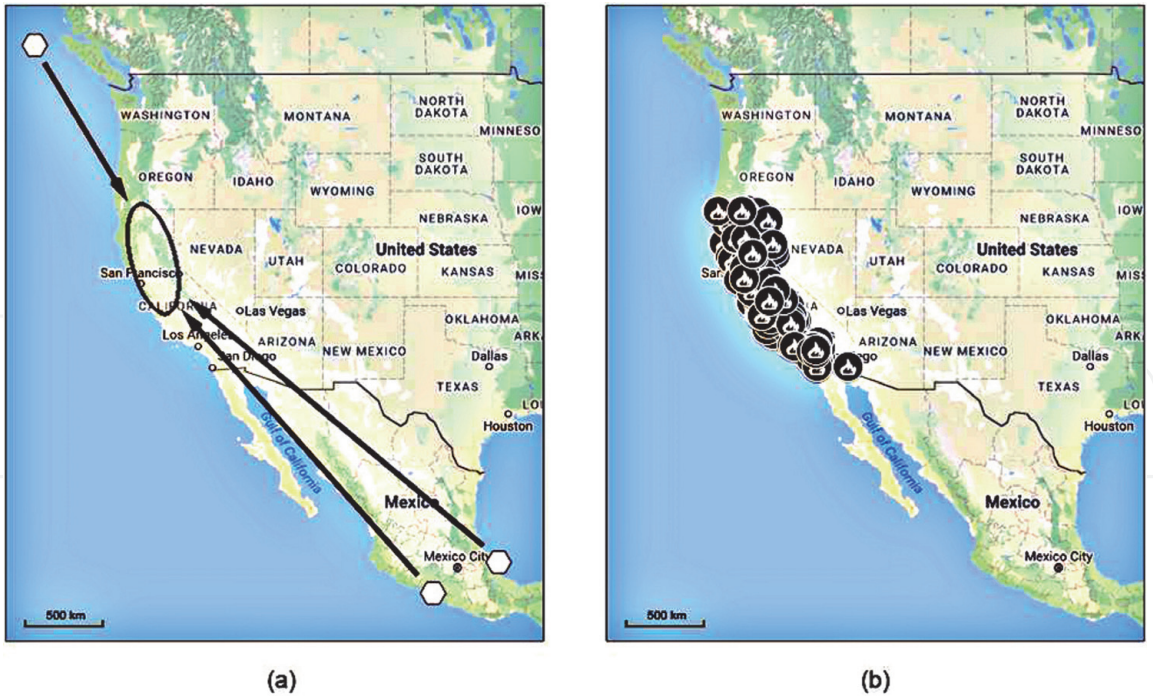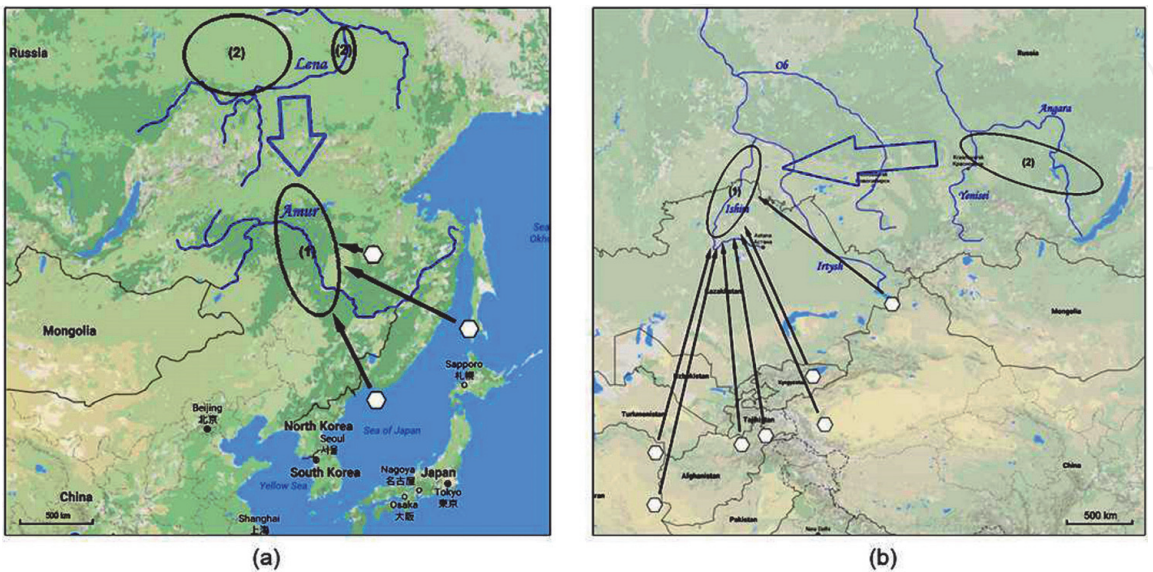
Figure 7.
The disastrous flood and wildfires in California, USA: (a) white hexagons, earthquakes epicenters; black oval, flooding area; and (b) wildfire seats.

rivers can be considered as connected because of the possible common underground basin (**Figure 8**). The phenomena are the regular events in some time period (our analysis shows, approximately in 5–7 years; for the abovementioned case, it happens in 2019 again).

In fact, simultaneously with the disastrous Amur flood, the water level in the Lena river dropped below the navigable level. That is why the connection of underground basins for different (great) rivers may be global in geological scales.

Thus, for the future forecast, the definition of potentially dangerous areas should be presented by the following procedure in the frame of the concept—all data for the analysis made have been taken from [67–70].

Figure 8.
Presumably connected river basins (a long-distance impact): (a) the Amur and the Lena rivers and (b) the Ob and the Yenisei rivers. White hexagons, earthquakes epicenters; black ovals (1), flooding areas; black oval (2), areas of wildfire propagation.

Step 1. Marking the epicenters of strong earthquakes (e.g., with the magnitude over M 5) on the geographical map with the designated boundaries of lithospheric plates.
Step 2. Schematic depiction of the fronts of the seismic waves propagating from the earthquake epicenters.
Step 3. Defining potentially dangerous areas.
Step 4. Monitoring the flood occurrence in potentially dangerous areas in comparison with the state of groundwater/artesian wells.

8. Conclusion

The chapter suggests an original approach to explain and predict the process of a flood and/or mudflow (debris) formation and spreading out over the river beds in mountain conditions. The phenomenon is under the flash increase of water masses involved (being strongly above the precipitation intensity budget) due to the groundwater impact. The 3D crack-net in the frame of the unified rivershed in a mountain massif is a natural transportation system (varied by some dynamic stress factors) for the groundwater in accordance with the hydrostatic/hydrodynamic pressure redistribution due to different reasons (e.g., earthquakes). The process has a nonlinear wave character with obvious signs of self-organization, and it can be described within the soliton model of nonlinear hydrodynamics. The approach can result in a more reasonable forecast and early warning for the natural water hazard/disaster taking into account the groundwater flow contribution over the land surface as a dominant factor under some conditions.

Acknowledgements

Appendix

The materials given in the Appendices are our original calculations, including the picture of the pressure map in underground and surface objects for computer analysis.

A.1 Numerical estimations for hydrostatic/hydrodynamic pressures in groundwater channels

As a rule we consider the stable regime of the river basin functioning in practice. The system describing its dynamics has many parameters, two of which are mostly important for us here: the precipitation intensity and the volume of the surface runoff fed by groundwater. Evidently the stable regime is characterized by the insignificant variations of these parameters that do not cause the unstable regimes of the whole system.

The classical laws of hydraulics were considered, as an example, in [75] concerning the features that allow their application to subsurface flow in general and,

particularly, to karst hydrology. Whether the movement of groundwater in karst can be defined as flow through individual channels or whether it can be considered as a continuous medium with saturated holes in a solid matrix is pondered over.

However, the volume of the surface runoff fed by groundwater is not constant—it is a complex function, depending on both the pressure distribution in the system of the groundwater transport ways (defined by the 3D topology of cracks) and the state of surface water. The intense precipitation during the disastrous floods can not only directly increase the volume of the surface runoff but can contribute to the creation of the low pressure area at high speed of water flow (due to the Bernoulli principle) [36]. This defines the kind of groundwater attractor initiating its flowing.

The distribution of hydraulic pressures in the system of groundwater transport ways is not constant and depends on many factors: topological (the quantity of cracks and their geometry, the channel size, the border roughness, the branching at the exit on the surface) and geohydrodynamical (the pressure formation, the water sedimentation, the Earth's crust local deformations, tectonic processes). Herewith, even the insignificant change of numerical characteristics of some of these factors can cause the disastrous consequences for the groundwater exit on the surface.

In fact for the simplest case of a laminar flow in a smooth bordered channel, the total water discharge Q through number of N thin cracks is described by the following relations [9]:

$$Q = \sum_{i=1}^{N} Q_i; Q_i = \frac{m}{12\mu}(r_i)^3 I, \tag{A1}$$

where m is the volume weight of water, μ is the viscosity index, r_i is the radius of the ith crack, Q_i is the local discharge, and I is the pressure gradient defined by the ratio of the difference between hydrostatic pressures on a definite part to the length of this part.

Thus, when a crack discloses two times (the routine process for $r_i \sim 1$ mm), the water discharge grows by almost an order. At the same time, the increase of the pressure during the crack contraction is even more significant $\sim 1/r_i^4$, which causes the increase of the water breakout possibility. All these factors are even subject to the microseismic influence and not necessarily to the serious tectonic processes.

On the other hand, intense precipitation can also influence the bedrock fracturing and directly change the hydraulic pressure distribution in the 3D system of the river basin.

Therefore the analysis of the water events should be complex in every case.

A.1.1 Numerical assessment of groundwater involvement

Let us consider how pressure arises in a wellbore. We will consider the case when water comes from an artesian well on the surface by itself. The main parameter is the discharge of the well, i.e., the cubic meters of liquid per a time unit come out of the hole (Q). Flow rate Q and pressure P_1 at the exit of water from a vertical well (easily measured/observed values) determine both the dynamic pressure P_d in the underground (horizontal) channel and also an integral pressure P_2 at the outlet pipe of the water drive horizon, being the parameters under analysis (**Figure A.1**). The above parameters can be connected by the relations given below:

For the dynamic pressure in a vertical borehole:

$$P_1 = \frac{\rho v^2}{2} \tag{A2}$$

where v is the speed of water flow and ρ is the density of the liquid.

For the flow rate in a vertical borehole:

$$Q = \pi R^2 \cdot v \qquad (A3)$$

where R is the radius of vertical borehole.

Thus, the relationship with P_1 and Q is given by:

$$P_1 = \frac{\rho Q^2}{2\pi^2 R^4}. \qquad (A4)$$

When water leaves aquifers for the Earth's surface, the pressure is lost due to the actual process of water lifting from the depth horizon (**Figure A.1**) and due to atmospheric pressure, i.e., we have:

$$\begin{cases} P_1 = \rho g h - P_{atm} \\ P_2 = P_d \end{cases} \qquad (A5)$$

where h is the borehole depth and P_1 is the water pressure at the outlet on the surface, P_2 can be considered equal to P_d, and P_{atm} is the atmospheric pressure (which, in the case of our interest, is usually small compared to P_2).

With (A4), (A5) for pressure P_d in the aquifer, we finally have:

$$P_d = P_{atm} + \frac{\rho Q^2}{2\pi^2 R^4} + \rho g h \qquad (A6)$$

Thus, relying on the parameters of a borehole, we can measure the pressure in the aquifer. The model is an approximation because it does not take into account many factors, i.e., friction, topology of the borehole, compressibility of the liquid/fluid, and the possibility of turbulent motion. However, it can explain the mechanism and trend/tendency in general and can be used for calculating the order of magnitude of the desired pressure.
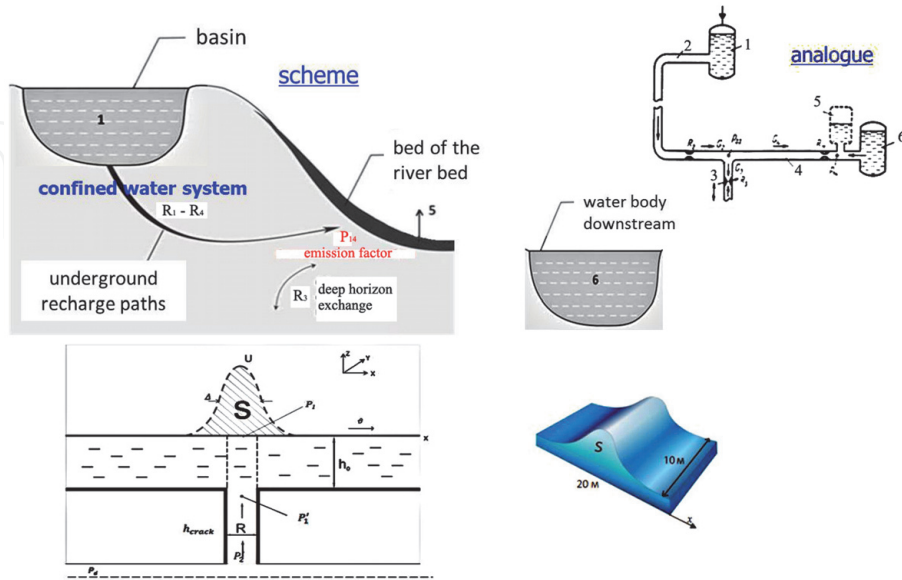
Figure A.1.
Model of the fluid system and the conditions of influence of deep (underground/ground) water on the formation of surface water flows: Simple hydrodynamic (1) and hydraulic (2) equivalent schemes for potentially dangerous areas; (3) shows the key parameters for calculation procedure to have a water exit (as a soliton object (S)) on the land surface. The existence of the water reservoirs/lakes both above and below the localization of the groundwater exit on the surface can change the pressure map in underground water layers.

To calculate the pressure, we can use the data typical to a borehole (see, e.g., [58]): the information of this type horizon lies at the depths of 150–300 m; the mode of a well is a spouting; well productivity at a full self-flowing reaches 480 m^3 day^{-1}; R = 0.54 m; h = 150 m (in the area of localization/well perforation); Q = 0.0056 m^3 s^{-1}.

From Eq. (A5) we have:

$$P_d = P_{atm} + 0.06 \text{ Pa} + 14.7 \cdot 10^5 \text{Pa} \approx 16 \text{ atm}, \qquad (A7)$$

where it is assumed that P$_{atm}$ = 1 atm.

It can be seen that the pressure in the underground horizon P$_d$ is big enough, but it is "wasted" during the rise of water from the depth ($\sim \rho gh$). Therefore, a water flow at the exit to the surface is a standard spring in fact.

Thus, for a powerful release of water to the surface in case of a sudden water/debris ejection, there should be the situation when a high-pressure zone (P$_d$>> 16 atm) is formed in the water aquifers. In the next item, we will do the necessary estimations.

A.1.2 Conditions for the release of a water flow in the river channel

As indicated above, the pressure in subterranean horizon is calculated on the basis of its observable flow rate on the surface. Now we define the average flow rate, which is necessary for the formation of the surface emission in the form of a solitary wave of the given amplitude corresponding to the observations of the events under a certain catastrophic phenomenon, i.e., we determine the required amount of water pressure in aquifers for this phenomenon being manifested on the Earth's surface

Let us assume a riverbed as a channel with high walls along the z-axis (so that the resulting wave object has a constant shape across the width—y-axis—of the channel). Then, knowing the bandwidth, one can calculate the amount of the water mass at a predetermined amplitude *u(x,t)*. Indeed, the ratio will be based on $u(x,t) = A \left[\text{sech} \left(\frac{x-vt}{\Delta} \right) \right]^2$, i.e., we use the description of a wave process in time t and distance x in the form of a soliton solution of the Korteweg-deVries equation as a flash process modeling, where A is the initial wave amplitude (underground blowout on surface, for example, in our model), $v = \frac{4}{3}$ is the wave velocity, and $\Delta \sim \frac{1}{\sqrt{v}}$ is the parameter characterizing the effective size of the perturbation (i.e., soliton width) (see [35]). We do not consider the relationship between water balance and the KdV equation. Here the subject of our interest is the question, when a sudden release of water masses for some reason has already occurred and how it will spread along the mountain slope in the future in terms of causing possible damage to the surface. Detailed equations and their solutions are presented [4], but the priority basis of the article is to discuss the modification of the pressure map due to external factors precisely in the underground horizons. Therefore, we give only the necessary standard hydrodynamic formulas [5] to illustrate the key parameters that are required in the comparative calculation of pressures in the underground and surface segments of water basins for the conditions of their emergence to the surface. Taking into account the expected initial (for t = 0) wave height, for example, 7 m (maximum height of such a wave was observed in the case of catastrophic flooding in Krymsk city (Russia) on July 7, 2012), and when the effective size of the perturbation Δ is assumed to be equal to 2.93 m [66], we have: $u(x) = 7\text{ch}^{-2}\left(x\frac{1}{2.93}\right)$.

Summing up we find the area S of the soliton in one section across the river channel: $S = \int\limits_{-\infty}^{+\infty} u(x)dx = 40.9 m^2$.

Assuming that the same soliton existing in each section of the channel (along the y-axis) have the width of 10 m, we have the estimation of the volume of water mass in this model of catastrophic wave, which is about $\sim$409 m^3 for the whole cross section.

Taking the time required for the formation of the wave occurring during the release within 15 s, we have Q = 27 m^{3}s^{-1} for the average flow rate[1]. Soliton formation time of the ejected onto the surface of the water mass is estimated roughly enough, since a small amount of real data is taken into account. But the refinement of time ultimately affects only on the concrete figures of the calculated pressure vs. an observable water flow on the surface. So, the mechanism described in the model is not changed.

Evaluative analysis of groundwater discharge into the river channel can be considered as the first approximation in analogy with the artesian well. In fact, if we consider the simplest case of a crack through which water rises as through a vertical pipe of fixed radius, then the problem becomes analogous to the problem of finding pressure P$_2$ in the horizon of the well (see **Figure A.1**).

But in the case when a spout water going along the crack does not immediately come to the surface but goes to the river bottom first, then a static pressure of the water layer in the river depth should also be taken into account (in addition to P$_{atm}$) to estimate the pressure at the outlet of the system. Then, using the relations (A4) and (A5), we can estimate the amount of a required pressure, first, in the horizon from which water flows (P$_2'$) and, second, under river flow pressure (P$_1'$), when spouting water from aquifers goes to the riverbed.

For this model, we have [29]:

$$P_1 = P_d - \rho g h_{\text{crack}} - \rho g h_{river} - P_{atm} \qquad (A8)$$
$$P_d = P_2'$$

Thus:

$$P_2' = \frac{\rho Q^2}{2\pi^2 R^4} + \rho g h_{\text{crack}} + \rho g h_{river} + P_{atm} \qquad (A9)$$

where flow rate Q = 27 m^{3}s^{-1} has been estimated above in accordance with the observable water flash in the Krymsk city event [66].

When h$_{river} \equiv$ h$_0$ = 5 m, R = 0.54 m, and for two values for the definition of aquifer depth (crack) h$_{\text{crack}}$ = 12 m (groundwater) and h$_{\text{crack}}$ = 150 m (deep horizon/artesian of groundwater), we have the values P$_2'$ = 64 and 79 atm for the depths h$_{\text{crack}}$ = 12 and 150 m, respectively (P$_{atm}$ taken as 1 atm).

Although these estimates are quite rough, because they contain many assumptions and idealizations, they allow to establish the procedure of estimating the required pressure in the aquifer for the expected/observable volume of water/debris flow with the chosen parameters. As can be seen from the results in a given ejection time, the visible difference between the values of pressure required to release from small and large depths is quite big.

In case when the release from groundwater horizon takes place over a shorter period of time, the depth of water will play a minor role in evaluating the pressure. It should be also taken into account that the flow resistance is always available (for various reasons, including "the debris" contribution) in the channel output. So, the output pressure P$_1$ should be smaller (as well as Q). Another principal factor for the correction of the numbers is determined by nonstationary process of the water discharge when the initial value of pressure in a closed reservoir (P$_2'$ in our case) is rapidly decreased due to exit to free space on the surface ("hydraulic shock") [5, 35, 36, 62].

However, the approach results in a reasonable model for a nonlinear trigger process of catastrophic water event with some principal aspects, e.g., development

in time of the catastrophic water traveling front over the surface. We carried out some computer simulation for the process. The picture gives a reasonable result for a solitary destructive wave propagation during the catastrophic event under real conditions of the event described in [66].

Thus, the trigger mechanism (scenario 1) of a catastrophic event (occurred in the designated conditions) is realized at the values $P_{flash} \geq P_d' \sim 65$ atm or 79 atm.

As to spreading flood in terms of smooth replenishment of groundwater (scenario 2), for already formed high water (after its release and/or due to the accumulation of water masses from other sources such as rainwater into the channel/river bed), the dynamics of its development can also be determined by additional recharge of groundwater (as localized in certain areas and/or spatially distributed as the water mass on the riverbed).

Finally, even if the flood was originally formed in the localized area for other reasons (because of the intensive/heavy rains), the presence on the flow way over riverbed sectors, the water masses from various sources, including groundwater, can greatly enhance the event. Apparently, this scenario can be considered in the analogy with a long-term catastrophic flooding, e.g., in the basin of the Amur River (August to September 2013, Russia/China) [40].

A.1.3 The water flow diagram modeling in a channel

In the system of fractal cracks (connected with the main channel for groundwater), the formation of extreme flow is possible, i.e., a devastating case is caused by instantaneous flash mechanism. The development of such process is related to two factors

First, within the main channel of propagation of the groundwater, a motion is turbulent. In accordance with the theory of Kolmogorov [35], we assume that such a turbulence is isotropic. The fact means that both velocity and pressure fields in the water flow have pulsations related to the nonlinear energy transfer between the vortices. This approach allows us to determine both the maximum possible size of the vortices defined by characteristic/fractal dimensions of the underground channel and, another factor, the minimum size of vortices due to the process of dissipation. Energy transfer in the eddies formed near a border is a complex nonlinear process, which we described by using a modernized Prandtl semi-empirical model.

Second, the mechanism of groundwater propagation in the system of cracks extending from the main underground channel is described in the frames of the fractal geometry methods [62]. The approach allows determining the degree of similarity in the crack system, i.e., the ratio of mean diameters and lengths of cracks/faults for each step of decomposition. The fact results in the integrated quantitative characteristics of 3D network, as a whole, by fractal dimension. The formation of fractal cracks (in the coupling of fragment length and the number of fragments) ensures an optimal traveling network for propagating water, but changes in external conditions can lead to the formation of hydroblow with the extreme water flow formation on the surface, i.e., a flash event arises.

The proposed approach allows carrying out the modeling in different spatial scales, to determine the features of hydrodynamic processes for generating an extreme water flow, when it is going out on the land surface, and results in the catastrophic water phenomenon.

A computer simulation of the water transit in different types of the crack model has been carried out. We used a simple formula in the frame of the Prandtl model [24] for a turbulent flow to calculate a velocity u distribution:

$$\frac{v}{v_{max}} = [(r - y)/r]^{0.84\sqrt{\lambda}} \tag{A10}$$

where λ = 64/Re is the hydraulic friction coefficient depending on the Reynolds number Re, r is the cross section, and y is the cross-section coordinate (y = 0 in the center of a channel); and for a maximal velocity u_{max}:

$$v_{max} = P_1 - \frac{P_2}{4\eta L} r^2 \qquad (A11)$$

where $P_1 - P_2 \equiv \Delta P$ is a pressure difference, η is dynamic viscosity, and L is crack fragment length.

Calculation for the water flow velocity profile in the central part of a channel and the stream function is presented in **Figures A.2** and **A.3**, consequently.

But we have to take into account both the specific landscape of the territory and the precipitation regime. In [72] they present the characteristics of 17 intermittent karst lakes of Upper Pivka. During the extended precipitation in November 2000, when the amount of precipitation was more than three times the average, all the lakes were flooded for the first time in several decades. Also several additional small karst depressions were flooded, where overflowing had never been recorded before. By combining the field observations with the interpretation of aerial photographs of the water level, the extent of the lakes and the volumes of containing water were calculated.

In [71] a special attention is paid to studying the relation between the waters of the Krčić River basin and the waters surfacing in the three Krka River sources.
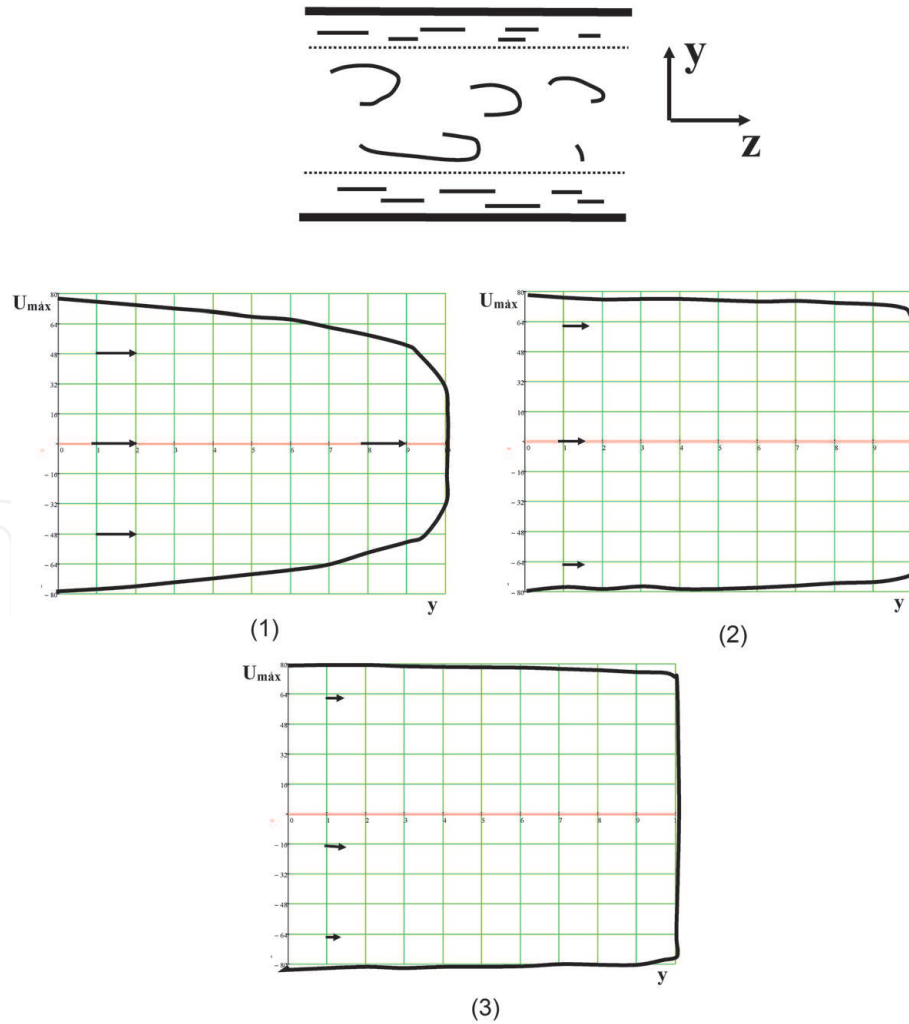
Figure A.2.
Water flow velocity profile V (y) in the central part of the fluid movement channel. Flow diagram (on the top) and the dependence of the function V (y), for the different Reynolds numbers (Re) being the parameters for turbulence: (1) Re = 300; (2) Re = 2300; (3) Re = 3000.
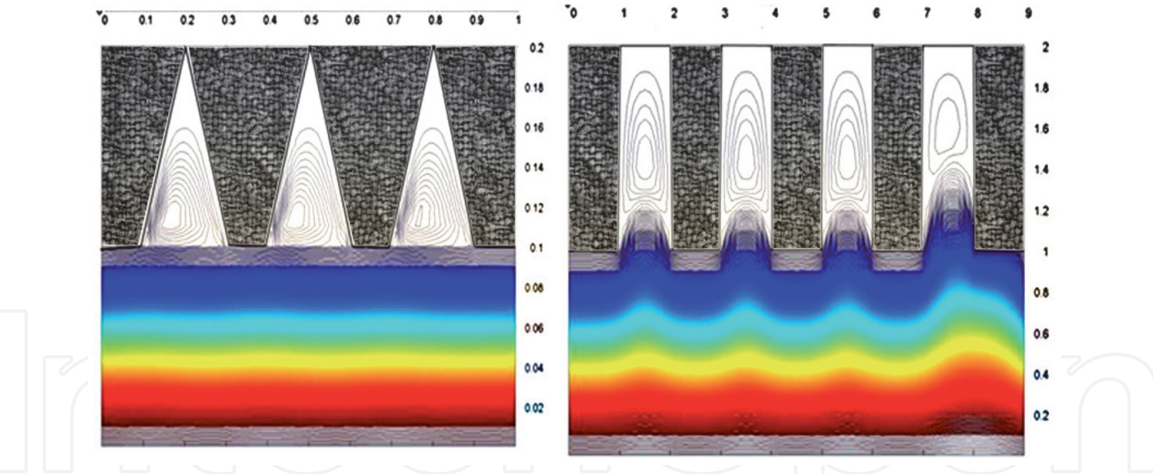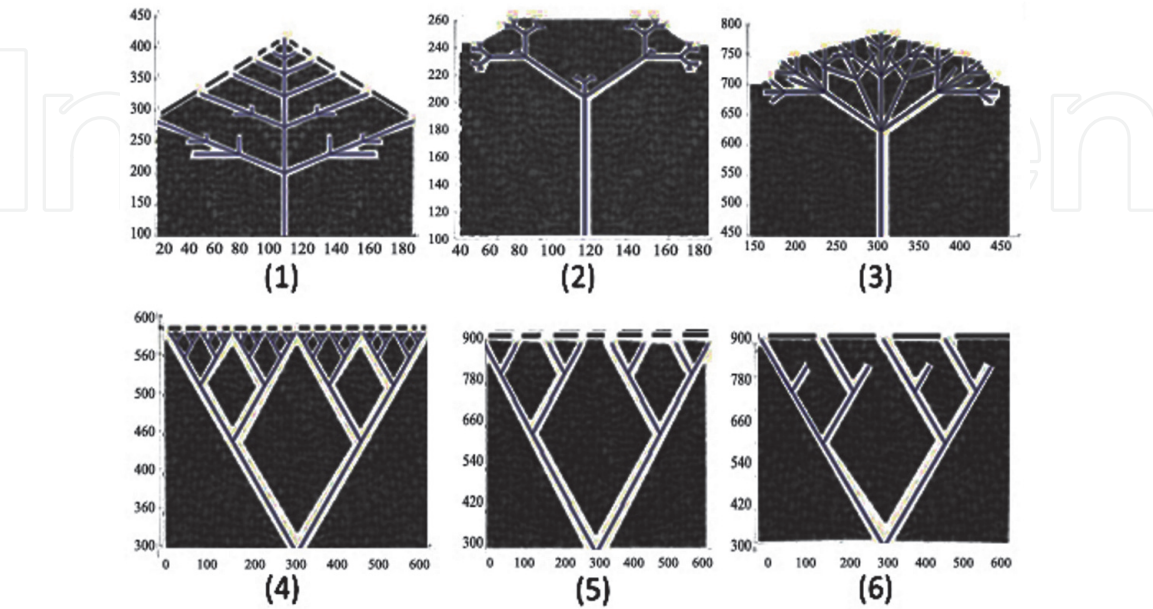
Figure A.3.
The fluid flow function Ψ values for Re = 1000 with different types of depressions/roughness on the top edge of the tube for passing water: (1) border zones with four rectangular recesses zones; (2) border zones with three triangular recesses. The roughness of the configuration may be presented as a crackness model.

It was determined that the process of water flow of the Krčić waters consists of a controllable surface component and a subsurface flow consisting of a diffuse laminar segment and a concentrated turbulent segment.

Thus, the groundwater contribution can be predicted due to different configurations of topologies of the crack-net system, and comparison of observed measured and forecast flood characteristics on the land surface becomes possible.

A.2 Modeling of the cracknel fractal structure

More complicated/real topology of the groundwater transportation system and flow regimes is connected with a detailed fractal structure. Our geometric models for some channels, in the frames of two cases, i.e., deterministic and "fractal trees," are shown in **Figures A.4** and **A.5**. The results of our calculation show that for

Figure A.4.
Model of extensive channel system in the deterministic approach "fractal tree": (1) zone "the Christmas branch"; (2) the "top" structure; (3) the "Φ-type top" structure; (4) complex the "V-tree"; (5) unloaded the "V-tree"; (6) the "V-tree" single-sided structure.
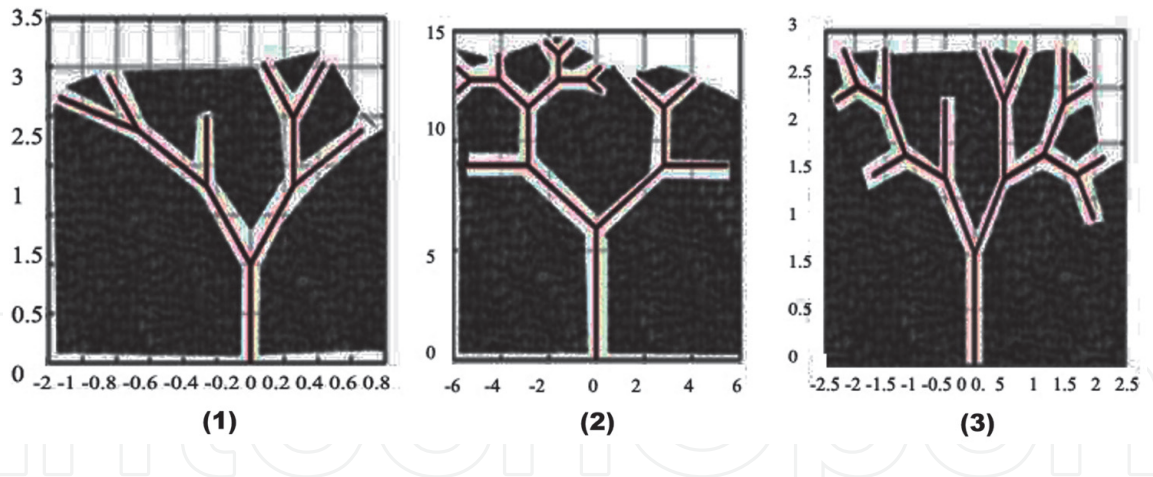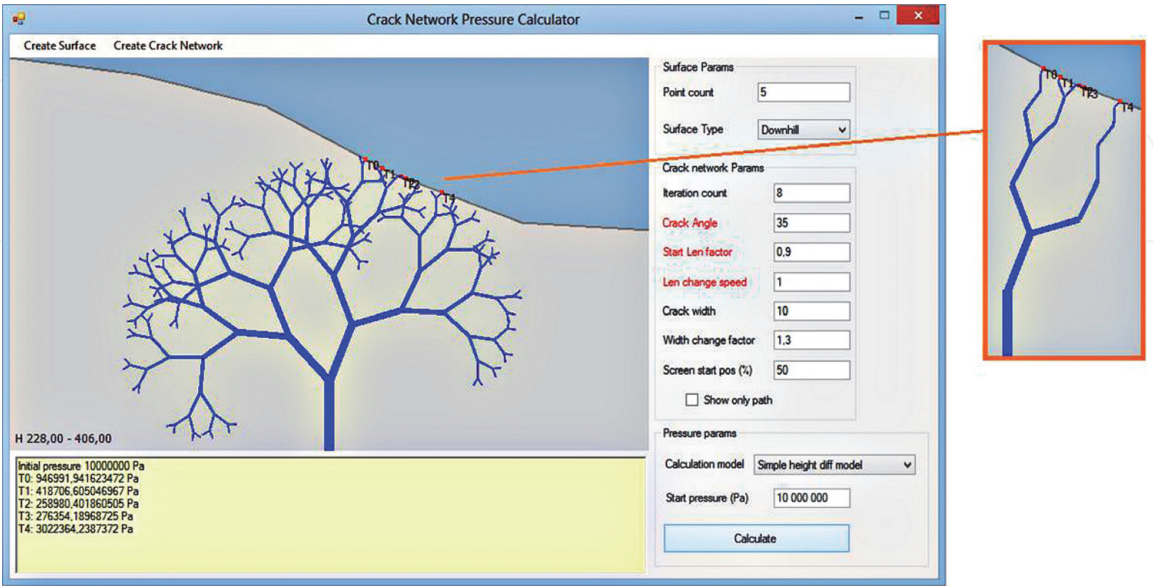
Figure A.5.
The channel model in stochastic approximation of the "fractal tree." various options for topology views/degree of complexity of the system of channels and the corresponding angles of rotation of the elements: (1) the rotation angle of π/10 with 5 iterations by computer simulation (at which the stable configuration is reached); (2) the dominant main channel, rotation angle of π /3 for 5 iterations; (3) the angle of π/3, 10 iterations.

different models of the underground crack-net structure, we have many locations of the groundwater exit.

The construction of various types of "trees" in the simulation system of the channels and their projection on the surface borders with the pressure map (identification water exit points on the surface) are shown in **Figure A.6**. We take into account the calculated dynamic pressures at which the water spouts from the channel system at a suitable pressure in the main channel/trunk system.

The problem should be associated with other hydrodynamic processes. In fact, in [13] they discussed that water infiltration and recharge processes even in karst systems are complex and difficult to measure with conventional hydrological methods [15]. In particular, temporarily saturated groundwater reservoirs hosted in the vadose zone can play a buffering role in water infiltration. This results from the pronounced porosity and permeability contrasts created by local karstification

Figure A.6.
*Interface computer simulation network of fracture rock/transport water system (cf. **Figures A.4** and **A.5**): The result is the calculation of the required pressure in the system trunk (main channel) to enter groundwater through branched/bifurcation channels on the surface (the required pressure value on the basis of the observed/recorded water emissions) taking into account the hydrodynamic pressure in the system (in accordance with the concept of **Figure A.1**).*

processes of carbonate rocks. This study provides detailed images of the sources of drip discharge spots traditionally monitored in caves and aims to support modeling approaches of karst hydrological processes. In addition, in [26] they present potential and actual sources of groundwater contamination on the Kras plateau, which is the recharge area of the Klarici karst water source that provides drinking water for the Kras plateau and Koprsko primorje.

Author details

Tatiana Trifonova[1], Dmitriy Trifonov[2], Dmitry Bukharov[2], Sergei Abrakhin[2], Mileta Arakelian[3] and Sergei Arakelian[2]*

1 Lomonosov Moscow State University, Moscow, Russia

2 Stoletovs Vladimir State University, Vladimir, Russia

3 Yerevan State University, Yerevan, Armenia

*Address all correspondence to: arak@vlsu.ru

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