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Influence of Carbonate-Flysch Contact and Groundwater Dynamics on the Occurrence of Geohazards in Istria, Croatia

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Abstract: This research focuses on the analysis of soil-water interaction at the carbonate-flysch contact on the Istrian peninsula in Croatia. As a result of the interaction of surface and groundwater and the position of flysch and carbonate rocks in the geotechnical profile, two problems occur in the study area: numerous instabilities and the occasionally high turbidity of drinking water. As an example, the St. Ivan spring was considered. The paper presents a complex mechanism of groundwater circulation in geological structures at carbonate-flysch contacts, differences in runoff through karst aquifers and flysch rocks during heavy rainfall under current and predicted (climate change) conditions, and the mentioned geohazards as a result of extreme precipitation. The analyses carried out showed the decisive influence of the existing geological structure on the dynamics of infiltration and precipitation runoff, as well as the risks of pronounced spring water turbidity and instability events. The main drivers of these geohazards are continuous long-term precipitation for landslides and intense daily precipitation for turbidity. Possible consequences of climate change are the increase in precipitation intensity, amount and higher variation, which subsequently brings risks such as the increase in maximum runoff, i.e., the expected more frequent occurrence of high turbidity and the more frequent occurrence of higher cumulative precipitation triggering instabilities in the area.

Keywords: flysch; karst; groundwater dynamics; turbidity; landslides; climate change; Istria

Citation: Dugonjić Jovančević, S.; Rubinić, J.; Ružić, I.; Radišić, M. Influence of Carbonate-Flysch Contact and Groundwater Dynamics on the Occurrence of Geohazards in Istria, Croatia. *Land* **2021**, *10*, 441. https://doi.org/10.3390/land10050441

Academic Editors: Domenico Calcaterra, Diego Di Martire, Luigi Guerriero and Roberto Tomás

Received: 15 March 2021
Accepted: 18 April 2021
Published: 21 April 2021

1. Introduction

According to its geological and geomorphological structure, the peninsula of Istria is divided into three different units: White, Red and Gray Istria. White Istria, named after the white color of the limestone, includes the area of the Ćićarija massif in the northeast and the Učka massif in the east, and is characterized by the alternation of carbonate and siliciclastic rocks from the Cretaceous and Palaeogene periods. The study area is located around St. Ivan (Figure 1), at the contact of White and central Gray Istria (named after the gray color of the bare soil in the flysch marls). It is an area of complex geological structure, developed surface and groundwater morphology and complex groundwater flow systems.

The aim of this paper is to show how these different geological structures, especially at their contact points, cause very different manifestations of geohazards with precipitation of different durations as their triggers. Both current climatic conditions and potential climate change impacts are considered in the analysis. Frequent landslide phenomena have occurred in flysch rocks, mostly triggered by longer continuous precipitation under current climatic conditions. There is a need to understand how climate change affects these geohydrological hazards, so the occurrence of landslides under climate change conditions in the study area [1] and worldwide [2–5] is increasingly discussed. Gariano and Guzzetti have shown the increasing number of articles on landslide-climate studies published in scientific journals and their geographical distribution [6]. The occurrence of increased turbidity in karst water sources fed by the flysch parts of the basin, associated with changes in the precipitation regime due to the effects of climate change, has been analyzed in several papers [7–10]. Mentioned geohydrological hazards manifest in the form of instabilities at sites of increased groundwater recharge in the carbonate-flysch contact zones, and the occurrence of extreme water turbidity at karst springs, located mainly at the contact of carbonate structures and eroded flysch rock mass around the study area. Their catchments and runoff dynamics are characterized by carbonate-flysch contact, where surface waters enter the aquifers through abysses, and introduce suspended solids into the hydrologic system.

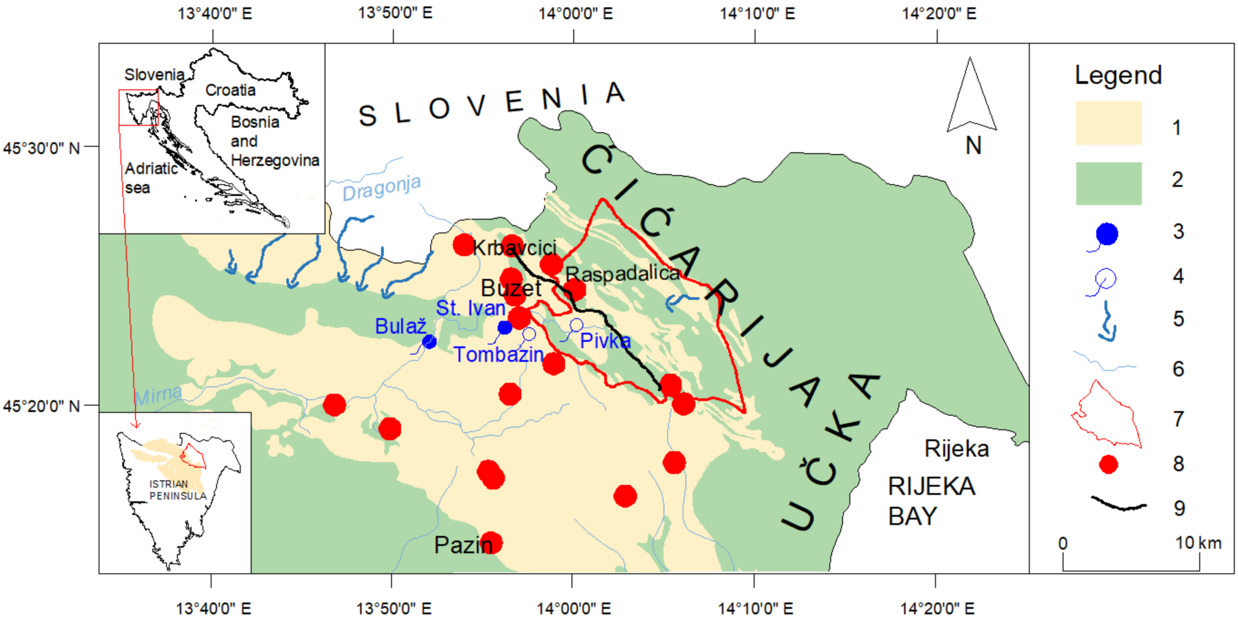

Figure 1. Hydrogeological map of the study area: 1-Paleogene flysch, 2-Cretaceous limestone, 3-permanent karst spring, 4-occasional karst spring, 5-abyss, 6-surface flow, 7-study area, 8-documented landslide, 9-railway line Divača—Pula.

Figure 1 shows the distribution of flysch rock mass in relation to carbonate structures in central and northern Istria, as well as the location of the main springs and documented landslides in the study area. It can be seen that not only important water springs are found at the carbonate-flysch contact, but also a large number of instabilities, indicating a very pronounced influence of the geological contact on their formation. Marked landslides present only a few documented instabilities, while many more are found in the non-urbanized areas where landslides pose less risk and therefore go unnoticed. Landslide susceptibility and hazard in this area has been discussed in previous analyses [11–15]. Since frequent instabilities cause severe damage in this area, the assessment of landslide susceptibility and hazard is of general interest and is the focus of several ongoing research projects. Instabilities are mainly caused by geological conditions, geomorphological and physical slope processes, but also by specific groundwater dynamics. The main trigger of landslides in the study area is the infiltration of precipitation and the rise of the groundwater table due to large amounts of precipitation over a long period of time, usually in late winter or spring [12,14].

The water at and below the surface slowly dissolves and erodes flysch and carbonate rock mass. A particular relief in the carbonate rock mass, created by strong tectonic processes, causes strong subsidence and groundwater movement. Characteristic of karst areas is the reduced surface runoff and the predominant subsurface flow. On the other hand, the infiltration into the flysch rock mass is generally slow due to relatively low permeability, the surface runoff coefficient is high, and the material is usually affected by long-term infiltration and antecedent rainfall [16–18]. Potential environmental problems associated with these characteristics and the spatial and temporal distribution of precipitation at the carbonate-flysch contact include groundwater contamination (which spreads rapidly in karst rock) and rock mass instabilities.

In groundwater dynamics, it is necessary to distinguish periods of high and low water. During high water, groundwater flows rapidly and is oriented towards the upper zone interspersed with discontinuities, which allows rapid displacement of pollutants. During low water, hydraulic seepage of water stored in less permeable deposits occurs towards the fault zones, through which the channels connected to the spring are supplied [19]. A dense surface water network has developed on the flysch parts of the basin, which is very often interrupted in contact with carbonate structures, where abysses are formed. These are locations of concentrated surface water inflow and recharge of the karst aquifer.

The paper analyses both problems arising from the geological structure of the St. Ivan area, which conditions the so-called binary aquifer recharge with sometimes even multiple combinations of surface and groundwater discharge. The paper considers the phase of water transition through the subsurface and the duality of the flow regime (through the limestone to the flysch and through the flysch to the karst springs) in relation to the existing structures and the associated geohazards. Due to climate change, an exacerbation of the current conditions and the aforementioned geohazards is expected and discussed.

1.1. Hydrogeological Characteristics of the Study Area

Istria is a peninsula where the Mediterranean climate on the coast changes to a temperate continental climate in the central part. The influence of relief is best seen on the hilly Ćićarija, where, due to the higher altitude, temperatures are lower and precipitation higher, and climatological conditions approach the mountain and boreal climate [20].

Analysis of average monthly precipitation shows that autumn periods are characterized by the highest rainfall, with November being the rainiest month of the year (average precipitation 163.2 mm in 50 years). These prolonged periods of precipitation during the autumn months are crucial for triggering instabilities, with frequent multi-day precipitation as a result of cyclic activities associated with to the so-called Genoese cyclones. The analysis of daily, monthly and annual precipitation has shown that the occurrence of three-month (70–100 days) heavy rainfall events is critical for triggering landslides [12]. The dynamics of groundwater flow are influenced by local hydrogeological and climatic conditions characterized by significant annual precipitation (over 2000 mm on average, Figure 2) and frequent short-term precipitation, with daily amounts of up to 200 mm (Croatian Meteorological and Hydrological Service in 2011).

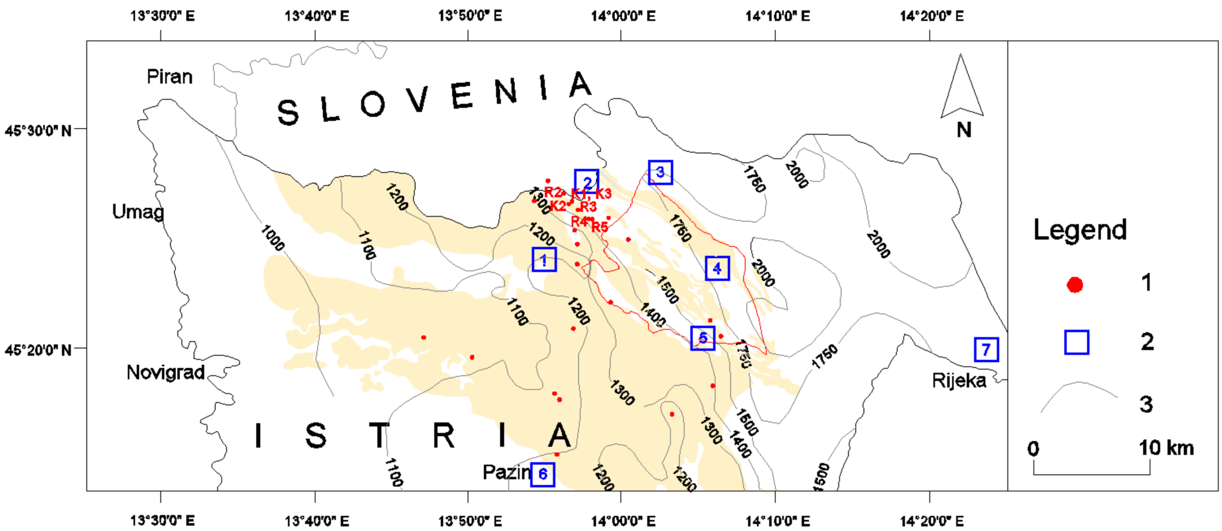

Figure 2. Annual precipitation amounts in the central and northern part of the Istrian Peninsula (according to data from Croatian Meteorological and Hydrological Service in 2011): 1-documented landslide, 2-rain gauge (RG), 3-izohyet.

On the surface of the Istrian peninsula there are rocks from the Jurassic, Cretaceous and Paleogene periods, as well as formations from the Quaternary period, which have the characteristics of engineering soil [20,21]. The geological boundary between flysch and carbonate rocks is the major reverse fault, which also mainly follows the railway line Divača—Pula. The kinematic model is defined as the relationship between rigid limestone and relatively plastic flysch during deformation. Studies have shown that alveolar limestone and flysch deposits in the contact area are more tectonically damaged, which affects their physical and mechanical properties.

The flysch sediments of central Istria are part of a large flysch basin extending from Gorizia in Italy to Albania [22,23], formed at the end of the Paleogene, characterized by successive alteration of fine-grained sedimentary rocks such as shale, siltite, marl and sandstone, and may also contain breccias, conglomerates and limestone. Typical karst morphological forms have developed at the carbonate–flysch contact, including blind valleys and abysms where surface flows dip into subsurface structures. On the other hand, there are large karst springs, which are of great importance for water supply. The Rižana, St. Ivan and Bulaž springs are transboundary karst springs of exceptional importance for the supply of the Slovenian and Croatian part of Istria [20].

According to the hydrogeological properties, the carbonate rock mass varies from high to low permeability. Flysch rock is mostly impermeable, and its position makes it a hydrogeological barrier that interrupts or directs groundwater flow. Runoff processes in such environments can be divided into phases of surface runoff and infiltration (concentrated or diffuse), subsurface runoff and surface water discharge. Due to the geological structure, numerous tectonic movements and faults, some streams have surface runoff until they reach the mouth of the sea, but the majority sink into the karst and drain underground [20]. Thus, the flysch is mostly impermeable, but due to the structures of the Ćićarija massif, fissure systems have developed in the contact zones as concentrated sinkhole zones, through which the water from the flysch parts of the basin quickly penetrates into the karst bedrock.

1.2. Hydrology of Water Resources in the Analyzed Area

Precipitation patterns combined with the hydrogeological characteristics of the terrain have influenced the occurrence and the surface and groundwater discharge in the study area (Figure 1). The lowest discharge base is the St. Ivan karst spring, which is one of the regional pumping stations in the Istrian water supply system. The average annual flow of the spring in the period 1986–2019 is 0.853 m^3/s, of which on average about 0.244 m^3/s is used for water supply. The potential catchment area of this spring, which is fed from the Ćićarija cover structures, is about 60 km^2 [24], but it was expanded to 103 km^2 due to the overlap with some other, more distant springs when defining the sanitary protection zones of drinking water sources.

The minimum capacity of the St. Ivan spring is approximately 0.120 m^3/s and the maximum only about 2.2 m^3/s, which is due to the hydraulically limited leakage capacity. In its hydrological system some other occasional springs operate, the most important ones being Tombazin spring, about 1.1 km away, and Pivka spring, 5.3 km away, which are activated in situations when groundwater inflows in the St. Ivan basin exceed the leakage capacities of the main spring, when the occasional springs located at higher elevations are activated. The St. Ivan spring is relieved by these springs. Leakage occurs first at the lower Tombazin spring (where flows last longer, on the order of several months per year) and then when groundwater inflows are significant, and at the Pivka spring, where flows last a few tens of days per year.

The complex feeding of these springs is partly by direct infiltration and partly by poljas in the basin, where a network of surface water streams is formed in flysch deposits, ending in abysses (Lanišće, Prapoće). Due to the direct contact of surface water streams and the underground karst aquifer of the St. Ivan spring, as well as the developed network of underground fissures, the fluctuations of discharges after precipitation are extremely rapid (the spring reacts a few hours after precipitation). The occurrence of sudden turbidity with extremely high values follows such events.

Such rapid responses to changes in hydrological conditions have a dominant influence on the dynamics of changes in the quality of karst springs, i.e., they increase the risk of their rapid pollution [25–29]. Underground fissure systems and speleological objects (caves, pits, ravines, abysses and springs) are the most hydrologically active parts of karst aquifers, providing the most dynamic water exchange from the surface to the subsurface [20]. This is especially true for conditions in the St. Ivan spring catchment area, which is characterized by significant precipitation as well as pronounced contact between flysch zones and the subsurface karst aquifer.

1.3. Landslides in the Study Area

The main factors influencing the occurrence of landslides are geological structure (lithological composition, weathering degree), geomorphological processes, slope orientation, material properties (layer thickness, permeability, porosity), and hydrological and anthropogenic conditions acting on the slope. The types of occurrence identified in the study area are mainly landslides [30,31], while other types of instabilities are rare and include debris flows and rock falls [12,32]. Instabilities are mainly rotational and translational landslides in which the material parameters vary greatly [13]. The geological cross-section usually consists of two characteristic layers: colluvium and/or residual soil, which form the superficial deposits, and the flysch bedrock of different degrees of weathering [12,13,32,33]. In most cases, the slip surface is formed at the contact between the bedrock and the cover layer, which may vary between the residual soil and the completely weathered flysch rock. Landslides in Istria are usually caused by heavy rainfall and human activities, while earthquakes and snowmelt are not considered frequent triggers.

From the slope stability point of view, precipitation has a multiple influence. The first and most important is the initiation of landslides; the second, but no less important, is the derivation of weathering processes that affect the material shear strength properties [34,35]. The process of rainfall infiltration through flysch deposits was recently studied by Peranić [16,17]. Due to the low hydraulic permeability of the soil and its retention properties between the slope surface and the phreatic line, longer infiltration periods are required to trigger landslides in the study area. Failure generally occurs due to the molding of the water table, which produces an increase in positive pore water pressure, leading to a decrease in effective stress and eventually reducing the shear strength of the soil along the potential slip surface [17].

Around the Divača–Pula railway line (Figure 1), northeast of the town of Buzet (Raspadalica), numerous instabilities have occurred for decades (remediation designs 1992–1999). Landslides have also been recorded further south, around the village of Krbavčići and other locations near the flyschkarst contact, using stereoscopic interpretation of aerial photogrammetric images [14]. The first major mass movements on slopes in the village of Krbavčići, near Buzet were recorded in 1961. The multiple retrogressive translational landslide in this area was reactivated in January 1979 [33] after a long rainy period on a slope with an average inclination of 15–20%. The driven landslide mass (59,000 m^3) crossed the road and buried the vineyards located on the slopes southwest of the road. The landslide was stabilized and the road was built over the landslide body by constructing a viaduct. In the winter of 2003, displacements were noted in the upper part of the slope at the same location. After a period of heavy rainfall, a debris flow with a colluvial cover (35,000 m^3) formed in a trench above the existing viaduct, on a slope with an average inclination of 15–30%. The slumping is caused by an increase in water content in the cover layers, resulting in a fluid, consistent condition. Fine-grained flow is not a typical instability phenomenon in this area, but is geomorphologically predetermined by the presence of deeply incised fossil ravines filled with clayey or weathered rock material. The analysis of the possible reactivation of the Krbavčići landslide was further discussed in Vivoda Prodan and Arbanas [36].

2. Materials and Methods

Considering the dynamics of groundwater flow through the limestone into the flysch and through the flysch into the limestone rock mass, two geohydrological hazards emerge. This two-sided problem is illustrated in Figure 3.

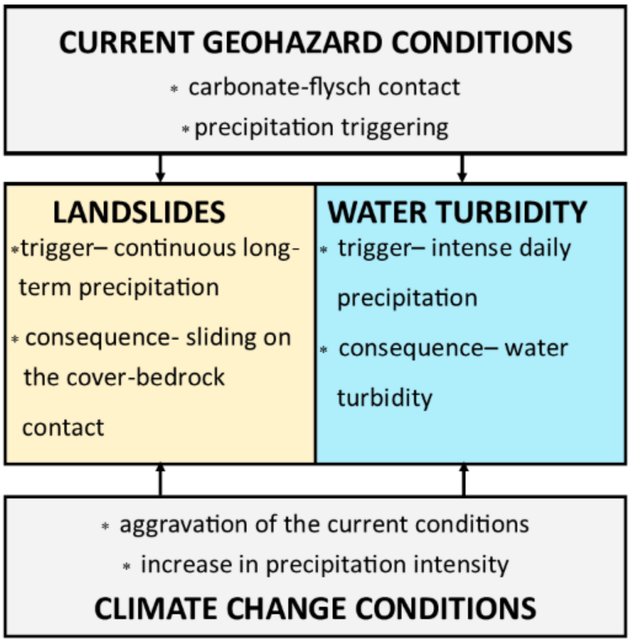

Figure 3. The two-sided geohydrological hazard problem in the study area.

Precipitation data were analysed using data measured at six meteorological stations in the vicinity of the study area in Istria and Rijeka weather station (RG7 in Figure 2, about 40 km from the study area) in the network of the Croatian Meteorological and Hydrological Service. The analysis of short-term heavy precipitation and the assessment of possible changes in its characteristics due to climate change impacts was carried out within the RAINMAN project (https://www.interreg-central.eu/Content.Node/RAINMAN.html, accessed on 3 March 2021). This analysis is a part of the Draft Strategy for Adaptation to Climate Change in the Republic of Croatia for the period until 2040 with an outlook to 2070 [37] using the results of the regional climate model RegCM4 [38]. The spatial domain of integration covered a larger European area (EURO-CORDEX domain), using boundary conditions from four global climate models along with the aforementioned regional model RegCM4: the model of the French meteorological service Cm5 (http://www.umr-cnrm.fr/spip.php?article126&lang=en, accessed on 3 March 2021), the model of the Dutch consortium EC-Earth (https://www.ec-earth.org/index.php/about, accessed on 3 March 2021), the model of the German Max-Planck Institute MPI-ESM (http://www.mpimet.mpg.de/en/science/models/mpi-esm/, accessed on 3 March 2021) and the model of the British Meteorological Service (Met Office) HadGEM2 (http://www.metoffice.gov.uk/research/modelling-systems/unified-model/climate-models/hadgem2, accessed on 3 March 2021). Climate change in the future, and thus the characteristics of the precipitation regime of short-term heavy rainfall (duration 3, 6, 12, 18 and 24 h) are modelled in line with the IPCC RCP4.5 scenario, according to which a moderate increase in greenhouse gases is expected by the end of 21st century [37].

Hydrologic conditions at the spring sites were monitored by automatic loggers for continuous monitoring of water level (accuracy ± 1 cm), and by flow calculations based on the results of flow measurements (accuracy ± 5%). The standards HZN ISO 4373: 2008 for monitoring the level, and HRN ISO 1088: 2007 for determining the flow were applied. Water turbidity was monitored using an automatic recorder with the expression of turbidity by a Nephelometric Turbidity Unit (NTU), applying the HRN ISO 7027: 2001 standard.

The positions of landslides were taken from the existing geotechnical field studies and landslide remediation designs (Faculty of Civil Engineering archives, archives of the Istrian County Roads Office and Civil Engineering Institute of Croatia) and analysed in previous work [12,13,32]. Landslide investigation usually includes geodetic surveys, drilling, geological mapping, geophysical surveys with seismic refraction, geoelectrical tomography techniques and soil/rock laboratory testing. Landslide data containing basic information on location, type, dimensions, time of occurrence, triggering factor, and soil properties, have been collected and presented in several papers [12,32].

Slope stability analyses based on Limit Equilibrium Method (LEM) or Finite Element Method (FEM) formulations are generally used to determine the factor of safety and its reduction due to the rise of the groundwater level and increase in pore water pressures. Based on the collected data, the mechanism of extreme turbidity occurrence and the instability mechanisms influenced by water infiltration are presented.

3. Results

3.1. Mechanism of Extreme Turbidity

In part of the area, precipitation rapidly infiltrates the highly permeable cover and flows vertically into the basic karst aquifer, so that the St. Ivan spring has very pronounced groundwater dynamics at three levels of discharge: at the main St. Ivan spring, the occasional Tombazin spring (located on a slightly higher horizon) and exceptionally at the Pivka spring [24]. Such rapid changes in hydrological and hydraulic conditions in the ground often cause very pronounced groundwater turbidity, reaching close to 2000 NTU [20], and problems in ensuring adequate water quality (Figure 4). Figure 4 shows the relationship between recorded precipitation at the Lanišće station (RG 4 in Figure 2) and extreme turbidity and flow at the St. Ivan hydrological station during the period from 23 June to 26 June 2015. During 23 and 24 May 2015, 24.9 mm of precipitation caused an increase in turbidity at the St. Ivan spring from 3.1 NTU to a maximum of 1812 NTU in only 8 h. To illustrate, the limit for turbidity of drinking water in Croatia is 4 NTU [39], and in order to remove such extreme turbidity, which significantly exceeds the allowed values, the raw water must be treated through a sophisticated purification process. In addition, high water turbidity causes changes in other water quality indicators.

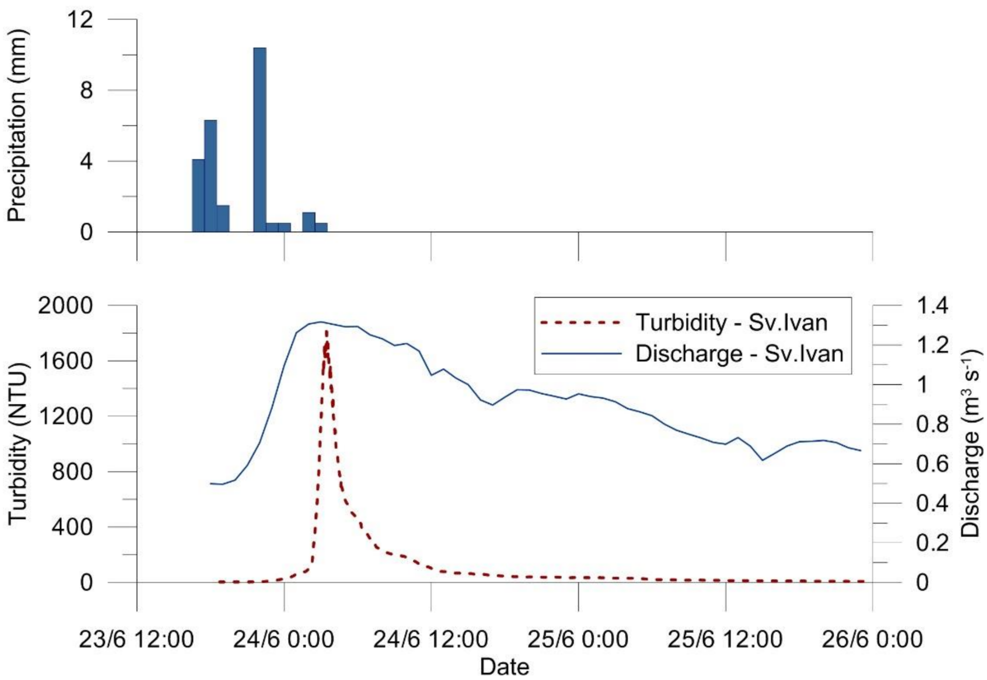

Figure 4. Relationship between the recorded precipitation at the Lanišće station and extreme turbidity and flow at the hydrological station St. Ivan in the period from 23 to 26 June 2015.

Figure 5 shows the mechanism of precipitation sinking from flysch basins into karst aquifers and the extension of its flow, with the following phenomena: (1) entry of fine-grained particles from flysch sediments into the subsurface, increasing turbidity at the water source; (2) activation of previously deposited fine-grained particles into groundwater flows by increased flow and higher flow velocities. Concentrated vertical groundwater flows transport particles of suspended sediment that have been washed from the surface. This primarily relates to more intense precipitation events, activation of erosional processes, and torrents with pronounced production of sediments in flysch parts of the basin and their fluvial transport. Concentrated groundwater recharge causes rapid sediment transport, both from the surface during precipitation events and from previously deposited sediments in karst aquifers activated during high flow velocities. Such situations are manifested in the regime of groundwater discharge at karst springs not only in the form of hydrograms of steeply rising limbs, but also by the occurrence of exceptional water turbidity [20,40].

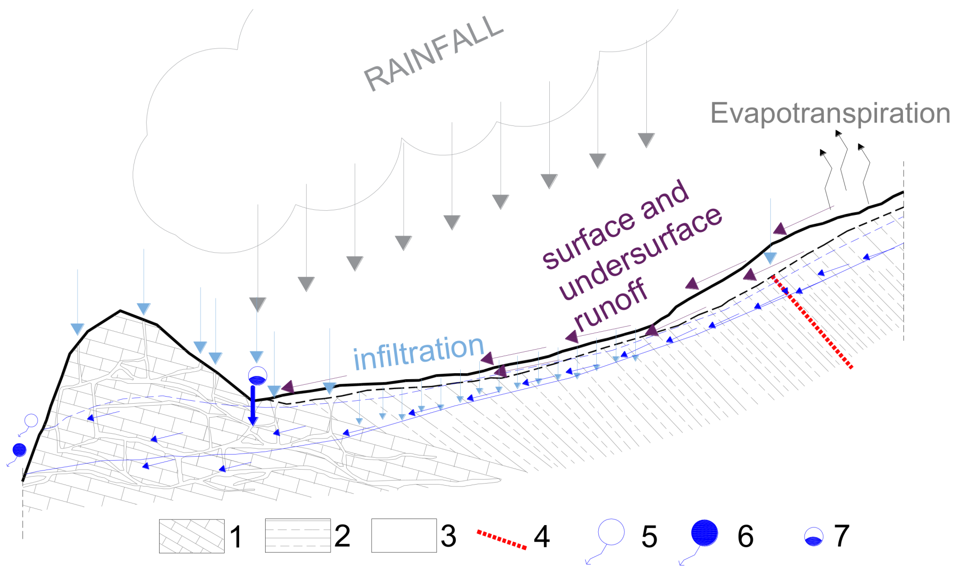

Figure 5. The mechanism of water subsidence from flysch into underground structures and the formation of extreme turbidity: 1 karst; 2 flysch; 3 cover; 4 reverse fault; 5 occasional source; 6 permanent source; 7 abyss.

3.2. Instability Mechanisms Affected by Water Infiltration

Due to the relatively low permeability of the cover material, the infiltration of the surface water in flysch sediments is relatively low and the surface runoff coefficient is high. However, contact with carbonate structures results in deeper and more intense infiltration of rainfall into the soil and triggering of the marginally stable slopes. Precipitation over the carbonate rocks quickly infiltrates in the subsurface and along the contact with the impermeable flysch bedrock (Figure 6). Due to the good permeability of the limestone and the relative impermeability of the flysch deposits, which have the function of a hydrological barrier, groundwater can be registered down to a depth of 20 m after heavy and prolonged precipitation. Sandstone layers in the geological profile can act as drainage paths and reduce the negative impact of water. The stability analysis showed that, due to the slope geometry and the location of the flysch-karst contact, the limit equilibrium state easily changes to the unstable state. The main trigger of all instabilities is saturation, which leads to a decrease in the factor of safety. When the water table rises, the flow of water through the cover derives the hydrodynamic forces, leading to an increase in pore pressure and subsequently a decrease in shear strength and sliding. Heavy and short rainfall, on the other hand, has an erosive effect and does not usually influence the sliding event [12,41]. However, it can influence the small, shallow landslides.

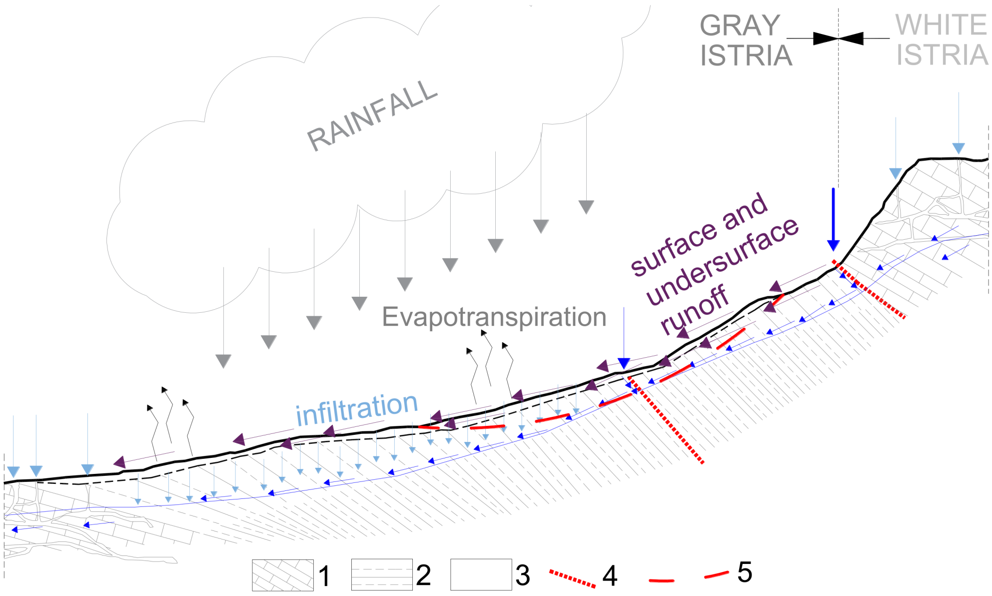

Figure 6. Mechanism of karst water infiltration into the subsoil and landslides at contacts with flysch bedrock: 1 karst; 2 flysch; 3 cover; 4 reverse fault; 5 typical sliding surface.

The mechanism described is supported by numerous documented landslide phenomena throughout the study area and in the vicinity of the carbonate-flysch contacts (Figure 1). As described in previous work [12,32], landslides generally occur at the contact of the cover formed of coarse-grained limestone fragments derived from higher-lying carbonate rocks and fine-grained, powdery clay mixtures derived from weathering of the flysch rocks (Figure 6).

3.3. Influence of Climate Change on Changes in Precipitation Regime

The dynamics of the geohazard occurrence will intensify under conditions of increasingly present manifestations of climate change. Indeed, climate change and possible environmental changes may exacerbate existing geohazards. Possible consequences of climate change are particularly present in the Mediterranean region [42]. Figure 7 shows the expected changes, i.e., the increase in short-term heavy precipitation over a 100-year return period relative to the duration of precipitation. The figure shows the relationship between the mean value of the four models described in the methodology (Cm5, EC-Earth, MPI-EMS, HadGEM2) and the calculated maximum values of short-term heavy precipitation in the future (envelope of the calculated maximum values of the four models) relative to the short-term heavy precipitation defined from a historical data set of a 100-year return period. The results of the performed modelling of 3-, 6-, 12-, 18- and 24-h short-term heavy precipitation for the 100-year return period (2017–2070), in relation to the historical period 1971–2016 at the Rijeka weather station, were used for the aforementioned reductions.

The expected changes are more pronounced for shorter durations than for longer ones. The changes, i.e., the increase in maximum 24-h precipitation, are expected to range from 5% of the average expected change in the results of the four models, to about 10%, as estimated on the basis of their maximum expected values. For shorter durations, the expected changes are even more pronounced, ranging between 15% and almost 30% for three-hour precipitation. The expected larger variations in the occurrence of multi-day precipitation in the future [37] may cause a more frequent occurrence of more intense precipitation periods. No significant change is expected for the mean annual totals and their intra-annual distribution. The influence of climate change on the precipitation regime in the studied area is expected for longer precipitation periods: (i) in the form of the reduction of the total annual amounts by the end of this century, (ii) on the periodic occurrences of intense daily and cumulative monthly precipitation amounts, depending on the climate scenarios and models used, up to 30–35% [43].

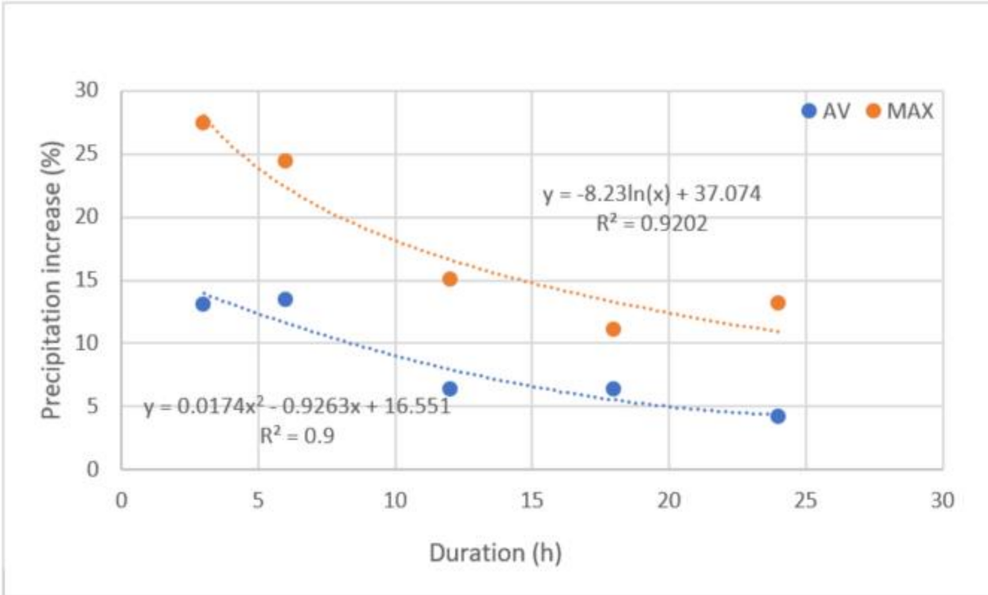

Figure 7. The change (%) in the probability of maximum 3-, 6-, 12-, 18-, and 24-h short-term heavy precipitation occurrence for the 100-year return period 2017–2070 with the respect to the historical period 1971–2016 as an average and as an envelope of the maximum calculated values of the analysed models (Cm5, EC-Earth, MPI-EMS, HadGEM2).

The expected increase in the precipitation intensity of different durations due to climate change impacts, expressed as the mean of different climate models/scenarios (AV), and as their maximum, show that more pronounced changes are expected for shorter precipitation durations. This will, of course, not directly change the dynamics of their infiltration through flysch deposits due to the limited permeability of the fresh rock mass, but will increase surface runoff. The volume and velocity of surface water will increase, and with it the potential for erosion, and consequently the production and transport of turbidity particles to the abyssal zones. This will increase the input of suspended solids into the subsurface, leading to an increase in turbidity, i.e., NTU. On the other hand, according to the given climate projections, precipitation of longer duration (24 h and longer), is expected to change in the order of 5–10%. Such expected differences are not so pronounced, but they may still contribute to increase in landslide instability at longer time intervals, when they would be repeated.

4. Discussion and Conclusions

The analyses carried out showed the decisive influence of the carbonate-flysch contact on the dynamics of infiltration and water flow, as well as the risks of extreme situations and possible geohazards. In the studied catchment area of the St. Ivan Spring these geohazards are present as the occurrence of pronounced spring water turbidity, as well as the expressed landslide hazard [11,13–15]. The demonstrated processes represent not only everyday problems, but also increased costs for landslide remediation and the need for integrated geohazard management. This problem can be viewed through the prism of existing conditions, but also the conditions of potential climate change.

The problems caused by intense rainfall related to runoff became more evident with urban development and water supply improvements in these areas. It is expected that further urbanization and demand for drinking-water will extend the negative impacts of the above geohazards in the studied area and beyond in similar locations. Geological, geomorphological, speleological and hydrological analyses are necessary to obtain detailed information on the potential vulnerability of karst aquifers, and to minimize them. Knowledge of existing characteristics and monitoring of changes in natural parameters such as temperature, electrical conductivity, microorganisms, etc., are required to mitigate existing water hazards.

Locations where instabilities at the carbonate-flysch contact are common are also found in the Rječina Valley, Sušačka Draga and Vinodol Valley. The mentioned locations (Figure 8) are part of a large flysch basin extending from Gorizia in Italy through Trnovski Gvozd–Rječina Valley-Vinodol Valley-NE part of Krk Island, Rab and Pag Islands, then Bukovica-Dabrarsko Polje in Herzegovina, and most of the Adriatic islands. Instabilities in these areas have been discussed in numerous papers [18,44–48]. The central part of the Rječina Valley is active in terms of geodynamic and seismic activities, with daily rockfall events and numerous catastrophic landslides and floods recorded in the last 250 years [45,49]. Benac et al. [18] describe conditions in the Rječina Valley as anisotropic. considering infiltration and groundwater flow to be rapid in debris and slow in cohesive talus material. The subsurface groundwater originating from direct infiltration or karst aquifer on the top (as shown in Figure 6) is accumulating in the clayey to silty weathering zones. Sušačka Draga Valley has a similar geological disposition, where instabilities played a major role during the construction of the Adriatic Highway. Many instability phenomena were also found at the contact between flysch and carbonate complex in the Bakarac Valley between the settlements of Bakarac and Križišće village [50]. Due to the heterogeneous geological structure, complex tectonic relation and hydrological conditions, the Vinodol Valley from Križišće settlement to Novi Vinodolski is characterized by various types of sliding and erosion processes [47] which are a problem especially in populated areas and manifest themselves in the form of deformations in local roads and buildings.

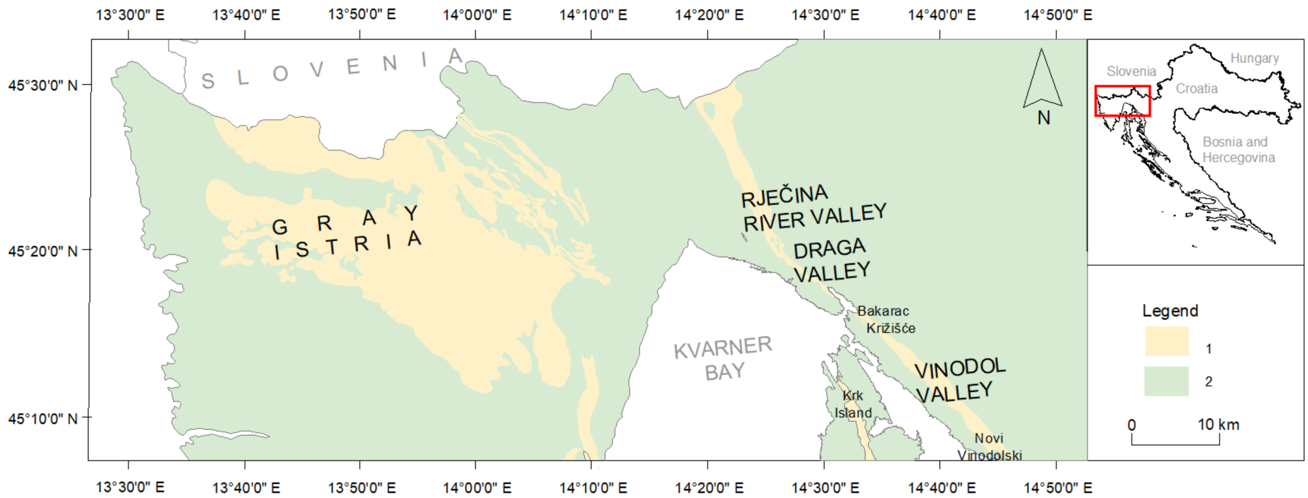

Figure 8. Flysch basin in the area of geomorphological unit around northern Adriatic coast (according to [21]).

Increased landslide activity is an expected effect of climate change. However, there are factors that influence the occurrence of instability more than the extent to which climate change affects the precipitation patterns and slope stability (e.g., uncontrolled human activities that are difficult to assess). It can be concluded that the magnitude of potential change in increasing the number of instabilities remains uncertain, with a low probability of changes in the cumulative multi-month amounts, as the main driver of instability in the study area. Increased short-term precipitation should lead to increased material weathering and slope processes that increase landslide risk. The decrease in the factor of safety with the increase in the degree of flysch weathering was discussed in [36]. From the 2D stability analyses performed, the authors concluded that the fresh flysch rock material had a factor of safety of 1.175, the factor of safety for the slope built in the moderately weathered material decreased slightly to 1.132, and to 1.064 for the completely weathered material.

Several modelling approaches have been evaluated by other authors based on their potential to predict landslide response to climate projections. Based on these analyses, it was concluded that there is a high degree of uncertainty resulting from the margins of error of scenario-driven global climate predictions, and the insufficient spatial resolution of currently available downscaled projections [2]. Gariano and Guzzeti have performed a preliminary global assessment of future landslide impacts, a global map of projected climate change impacts on landslide activity, and recommendations for risk mitigation strategies under a warming climate. The results of their study show the generally expected increase in shallow landslides and debris flows caused by projected climate change. They concluded that the modelling results of landslide-climate studies depend on the emission scenarios, the Global Circulation Models, and the methods used to downscale climate variables, and that the effects of climate change on landslide risk remain difficult to quantify [6].

Author Contributions: Conceptualization, S.D.J. and J.R.; methodology, S.D.J. and J.R.; formal analysis, S.D.J. and J.R.; investigation, S.D.J., J.R., I.R. and M.R.; writing—original draft preparation, S.D.J., J.R. and I.R.; writing—review and editing, S.D.J., J.R., I.R. and M.R.; visualization, S.D.J. and M.R.; supervision, S.D.J. and J.R. All authors have read and agreed to the published version of the manuscript.

Funding: This work has been supported in part by the University of Rijeka under the projects Uniri-tehnic-18-97, Uniri-tehnic-18-298.

Institutional Review Board Statement: Ethical review and approval were waived for this study, because the study does not involve humans or animals.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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