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A Hydrological and Hydrochemical Study of the Gudiyalchay River: Understanding Groundwater–River Interactions

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Abstract: The Gudiyalchay River plays a crucial role in the environment and human activities of the Guba area in north-eastern Azerbaijan, supporting agriculture and the local water supply. Despite its significance, the river has received little scientific attention. The groundwater beneath the Gudiyalchay riverbeds, a vital source of drinking water and the second primary source of river recharge after snowmelt, remains insufficiently studied, with most monitoring data being outdated. With climate change intensifying, such research is critical to mitigating potential water risks. In this work, all available geological, hydrogeological, climatic, and hydrochemical data were collected to characterize the study area and analyze the seasonal fluctuations in river flow and total dissolved solid (TDS) values, with a focus on the interactions between the river and groundwater at the Khinaliq, Giriz, and Kupchal flow stations. The analysis shows that both river and groundwater TDS values are within acceptable drinking water limits, but continuous data collection is important to confirm this. Flow rate analysis and a literature review revealed that variations in flow rate are linked to seasonal changes, with the flow rate near the Giriz station indicating potential groundwater influence. Based on the literature review and analysis, a simplified hydrogeological diagram is created to provide a clearer understanding of the interactions between the river and groundwater systems.

Keywords: water resources; groundwater–river interactions; recharge; total dissolved solids

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1. Introduction

Water availability has become a major challenge across the world due to industrial and agricultural expansion, urban development, population growth, rising tourism, and climate change. Ensuring sufficient water supply amid growing populations and economic development is a critical global issue of the 21st century [1].

Azerbaijan faces several challenges including water scarcity in arid and semi-arid regions, pollution from various sources, and the impacts of climate change. As a result of climate change, water resources have diminished over recent decades, and further declines are predicted in the future [2,3]. Alongside this, the increasing population, economic development, and expansion of irrigated agricultural areas have accelerated the demand for water at a remarkable rate [4].

Surface water constitutes most of Azerbaijan's water resources, leading to a greater research focus. Groundwater research began in 1962, but major studies ended in the 1980s. The total potential groundwater reserves calculated then were 9 billion m^3, with 4 billion m^3 extractable [5]. Until the 1980s, annual groundwater production ranged from 2.5 to 2.9 billion m^3, dropping to 1.3 to 1.5 billion m^3 post-1980s. Recently, production has risen to 3.0 to 3.5 billion m^3 [6]. Many groundwater wells are unregistered, and unlicensed drilling disrupts the hydrodynamic and hydrochemical balance [6].

The total water reserves of Azerbaijan have been calculated by determining the total rainfall after evaporation and adding the surface water entering the borders. According to Rustamov S.H. and M. Gashgay [7], in 1989, the annual precipitation in Azerbaijan was 37 billion m^3, with 26.7 billion m^3 evaporating, 6 billion m^3 contributing to surface water, and 4.3 billion m^3 contributing to groundwater. Other researchers found similar results, estimating total reserves between 28 and 32.3 billion m^3 in 1988, 2002, etc. [3,7,8]. However, these calculations did not consider dams, groundwater reserves, and lakes. Ələkbərov A.B. and İmanov F.A. [2] further improved calculations of total reserves, which included lakes, dams, and rivers, estimating the total at 55.6 billion m^3. Rivers form the principal part of the water systems of Azerbaijan. There are 8359 rivers of various lengths within Azerbaijan. Of them, only 24 rivers are over 100 km long [8]. The country's rivers are divided into three groups [9]: the Kura basin rivers, the Araz basin rivers, and rivers flowing directly into the Caspian Sea.

The Gudiyalchay River, one of the rivers flowing directly into the Caspian Sea, is a necessary component of the region's natural environment and human activities. The river plays a crucial role in supporting agriculture and providing local water supplies through its diversion into the Samur–Absheron Canal [9]. The groundwater under the Gudiyalchay riverbeds is used for drinking water supply though there is limited information available about these reserves.

Previous research shows river water quality is compromised by salinization and pollution from agricultural runoff, industrial discharges, and poor waste management [8]. In the Khachmaz region, 1.4 million m^3 of industrial waste and over 100,000 m^3 of domestic waste are discharged each year [9]. According to the Geographical Society of Azerbaijan from 1991 to 2022, the water content in local rivers has decreased by 5.0% to 21.2% compared to the period from 1961 to 1990 [10].

The variability of water flow in rivers due to seasonal changes and the increasing demand for water for agricultural, industrial, and domestic uses further complicate water management in the country [11]. To address these challenges, Azerbaijan has developed water infrastructure, adopted conservation practices, and enhanced water quality through improved wastewater treatment and pollution control [5]. To enhance the drinking water supply for the city of Guba and its surrounding villages, a water treatment plant with a capacity of 14,000 m^3/day (162 L/s) was constructed along the Gudiyalchay River. The treated water is distributed to the city and surrounding villages through the 6.6 km long pipeline [12]. A hydropower station was constructed near Guba City on the Gudiyalchay River for energy production. This facility aims to provide renewable energy to the surrounding area, contributing to the region's energy supply and reducing dependence on non-renewable energy sources.

However, despite recent developments, the river and its riverbed water continue to experience inadequate attention and monitoring. There are no continuous measurement stations along the river to collect data on various hydrological parameters. Additionally, although groundwater plays a crucial role in the recharge of the river, these reservoirs have not been sufficiently researched. Hydrological monitoring of Azerbaijani rivers began in 1912 and continued through the Soviet era, focusing primarily on larger rivers. Several projects initiated during this time (1940, 1946, 1970, and 1975) were left incomplete for unknown reasons, leaving most of the available data from the Soviet Union [13]. Currently, the hydrological network managed by the National Hydrometeorology Department does not fully meet the requirements of modern research and monitoring.

Several simple and integrated methods exist to explore groundwater–surface water interactions. Tracing the hydrochemical changes in groundwater is critical for understanding the role of the surface–groundwater connection in hydrogeochemical evolution [14]. Groundwater's primary ions like Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, $SO4^{2-}$, and $HCO_3{}^-$ are predominantly shaped by interactions between water and rock, which record the geochemical signatures of various aquifers and reveal hydrogeochemical dynamics from mixing processes [15]. Human activities, including agriculture and waste disposal, further influence groundwater chemistry, with nitrates often emerging as a significant pollutant. Consequently, monitoring hydrochemical shifts in groundwater is essential to understanding the interactions between surface water and groundwater in geochemical evolution.

Stable isotope analysis of water (δ_{18}O and δ_2H), which is primarily influenced by meteorological factors, conserves distinct signatures through water cycles, allowing it to trace the origins and pathways of groundwater and identify recharge sources [16]. When used alongside chemical analysis, recent studies of δ_{18}O and δ_2H have significantly enhanced the understanding of how surface water interacts with groundwater within stream aquifer systems [14].

Among several approaches, the most appropriate method is often the construction of hydrological models that simulate the generation and flow of surface water and groundwater and their interactions [17]. For analyzing groundwater–river interactions and groundwater flow, several models are available: the integrated SWAT-MODFLOW approach combines the SWAT (Soil and Water Assessment Tool) and MODFLOW models. The SWAT estimates recharge rate and evapotranspiration across hydrological response units [18], while MODFLOW simulates groundwater flow and interactions between rivers and aquifers [19–22]. Together, these models provide comprehensive insights into both surface and subsurface hydrological processes, essential for effective water resource management. The choice of model depends on the data available, such as the spatial and temporal resolution, hydrological characteristics, and specific interaction processes being studied.

This article examines seasonal river flow fluctuations using flow rate and hydrochemical data collected irregularly between 1950 and 2016, focusing on the relationship between river flow and groundwater. By analyzing these samples, this study aims to identify patterns and variations in the river's hydrology, with an emphasis on understanding the role of groundwater in river recharge. This article aims to provide approximations about the possible areas where groundwater might contribute significantly to the river's flow. Additionally, the research includes an analysis of total dissolved solids (TDSs) which is particularly important for evaluating the suitability of water for drinking purposes, as well as indicating variability in recharge sources.

2. Study Area

2.1. Gudiyalchay River

Originating from the northern slopes of Tufandag Mountain at an elevation of around 3000 m, the Gudiyalchay River traverses the Guba and Khachmaz districts before ultimately discharging into the Caspian Sea (Figures 1 and 2) [8]. The Gudiyalchay River has the largest annual flow volume among the rivers in the region [8]. The lower reaches of the river are extensively utilized for irrigation.

The river is distinguished by its robust water volume, fed by a mix of sources: the primary component of its flow is derived from snowmelt, constituting 50%, with groundwater contributing 32% and rainfall accounting for 18%. This snowmelt leads to significant flooding in the river from April to July, during which 60–75% of the annual flow is observed. The average annual discharge is 6.85 m^3/s. The seasonal distribution of the annual flow is as follows: 26% in spring, 41% in summer, 21% in autumn, and 12% in winter. The river's average annual suspended sediment load is 21.9 kg per second [9].

The river's basin, covering 799 square kilometers, is further enriched by main tributaries like Dogguzul and Agchay in its upper reaches [23]. Agcay, with a length of 24 km and a catchment area of 154 km^2, has a high potential to contribute significant water volume to the Gudiyalchay River. Dokuzul, measuring 12 km in length with a 26 km^2 catchment area, has a moderate potential to contribute to the river's flow [23].

2.2. Geology

The geological history of Azerbaijan covers from the very old Precambrian era to modern-day rock formations [25] (Figure 3). Most of the rock formations age to the Mesozoic and Cenozoic eras, known for their folded and faulted structures and sedimentfilled basins [26]. Among these, there are also ancient layers from the Paleozoic era and the oldest metamorphic rocks dating back to the Precambrian period [27].

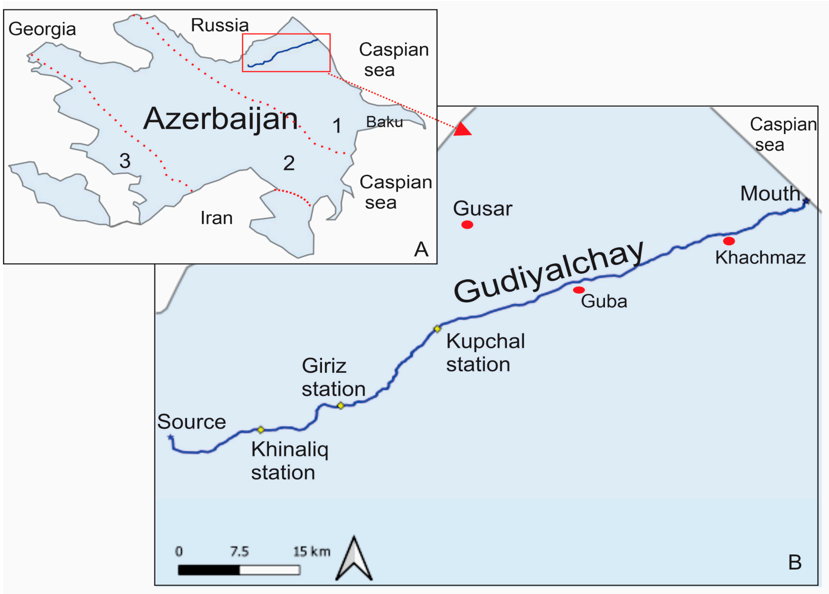

Figure 1. (**A**) Location of Gudiyalchay River and the hydrogeological zones: (1) the Greater Caucasian hydrogeological zone, (2) the Kura depression hydrogeological zone, (3) the Lesser Caucasian hydrogeological zone, and (**B**) the location of stations over the Gudiyalchay River.

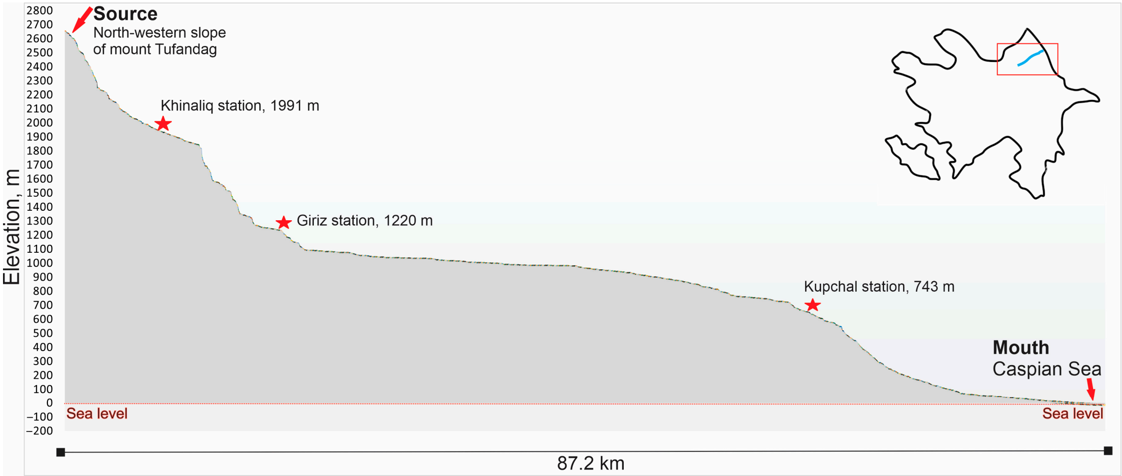

Figure 2. The elevation profile of the river. Elevation data were derived from Landsat/Copernicus aerial imagery [24]. The river length from Khinaliq to Giriz is 12.7 km, and from Giriz to Kupchal is 17.8 km. The main length of the river is 108 km.

Azerbaijan's landscape is shaped by large fold structures called mega-anticlinoria in the Greater and Lesser Caucasus Mountains, as well as the Kura depression area [26] (Figure 3). The Greater Caucasus in Azerbaijan features large folds, known as anticlines, that end in curves near the Caspian Sea coast [27,28]. The Azerbaijani part of the Greater Caucasus Mountains, extending along the northern part of Azerbaijan, exhibits a diverse geological composition reflective of the complex tectonic processes that have shaped the region over millions of years. The main rock types in this area include the following [29]:

- Sedimentary Rocks: These rocks form much of the mountainous terrain. Sandstone, shale, and conglomerates are also present, deposited in environments from deep marine settings to river deltas and floodplains.

- Metamorphic Rocks: Due to intense tectonic activity and the collision between the Arabian and Eurasian plates, original sedimentary and igneous rocks have transformed into metamorphic rocks. In the Azerbaijani part of the Greater Caucasus, schist, slate, and marble are common examples.
- Igneous Rocks: The region contains both intrusive igneous rocks like granite and diorite and extrusive rocks like basalt. These indicate volcanic activity and magma intrusion during mountain-building processes.
- Volcanic Rocks: Evidence of past volcanic activity includes volcanic rocks such as tuffs and volcanic breccias, remnants of eruptions that shaped the landscape.

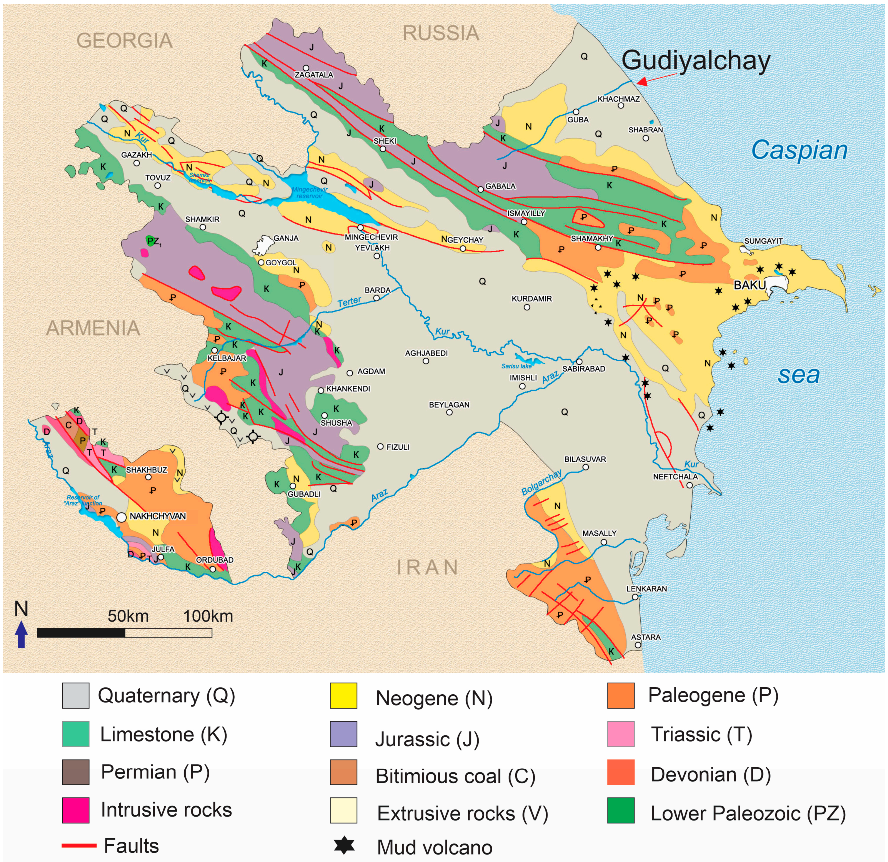

Figure 3. Geological map of Azerbaijan, highlighting geological formations, faults, and mud volcanos [30].

The Gudiyalchay River descends the north-eastern gradients of the Greater Caucasus Mountains in Azerbaijan traversing varied terrains including the striking Kyizilkaya plateau. The river passes through diverse landscapes, with the upper reaches characterized by steep inclines and rocky areas that contribute to significant surface runoff and erosion. Eventually, the Gudiyalchay River flows into the Caspian Sea through the Samur–Devechi lowland.

2.3. Hydrogeology

The hydrogeological zones in Azerbaijan are divided into three main zones based on the geological setting: the Greater Caucasian hydrogeological zone, the Kura depression hydrogeological zone, and the Lesser Caucasian hydrogeological zone [31] (Figure 1A).

The Greater Caucasian hydrogeological zone is further divided into several basins based on their porosity and layer types. Figure 4 presents a simplified map of the hydrogeological basins in the north-western Azerbaijan [32]:

- Greater Caucasian fractured-porous basin;

- Samur–Gusarchay porous water basin.

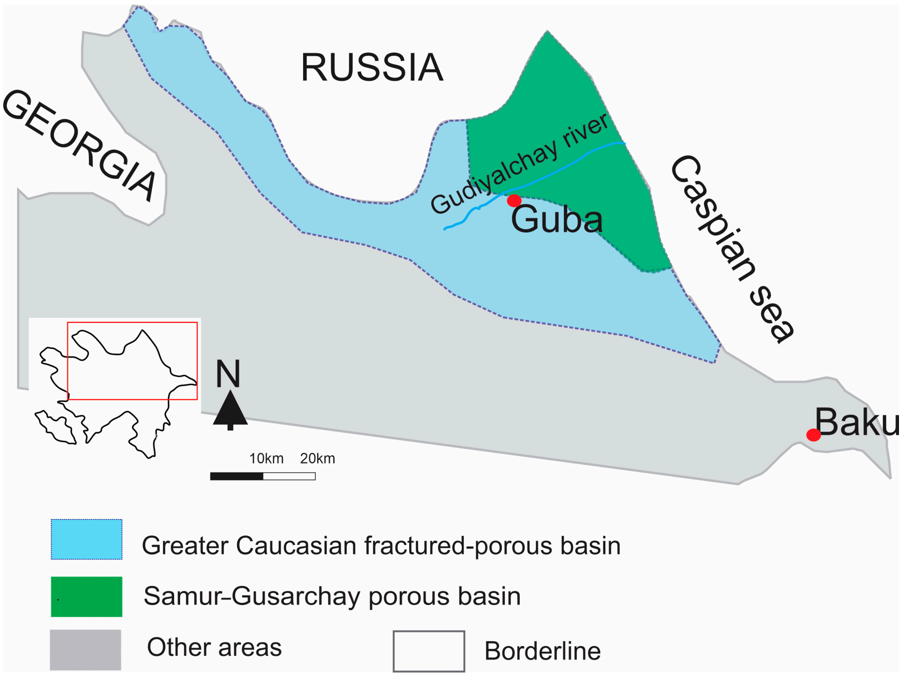

Figure 4. Simplified hydrological basins within the Greater Caucasus hydrogeological zone [13].

The Samur–Gusarchay basin is one of the most significant groundwater sources in Azerbaijan, particularly noted for its high productivity (Figure 4). This basin supplies a substantial portion of the water for Baku and other regions, making it vital for the country's water infrastructure. Groundwater in this basin is primarily fresh, with low salinity. The hydrogeological conditions in the Samur–Gusarchay basin are favorable due to the convergence of alluvial cones and intensive precipitation recharge, ensuring a steady supply of high-quality groundwater [33].

The Greater Caucasian hydrological basin is composed of Quaternary–Jurassic formations. These areas are characterized by rocky terrain, thick weathering zones, valleys, and intermountain depressions formed by alluvial and fluvioglacial sediments (Figure 4). Groundwater primarily occurs in weathered and tectonically disrupted zones and naturally discharges through springs at foothills with flow rates of 5–10 L/s [13]. Groundwater resources in the Greater Caucasus play a crucial role in supplying water to various areas, including the economically important Samur–Gusarchay basin [34,35].

A significant portion of the Greater Caucasus Mountain areas in Azerbaijan is covered with dense forests, and the groundwater in this region remains poorly researched [35,36]. Imanov F.A. and Ələkbərov A.B. [13] report on well data from the wells drilled during the Soviet era in the Greater Caucasus region, although specific locations of these wells are not provided. The depths of the wells ranged from 50 to 250 m, revealing both confined and unconfined aquifers. Unconfined aquifers have groundwater depths ranging from 0.5–1 m to 57 m, with well yields between 1 and 5.5 L per second. Confined aquifers exhibit well yields from 1 to 10 L per second, with piezometric head levels rising between 0.8 and 8 m below ground level.

Alluvial aquifers in the Greater Caucasus region are composed of unconsolidated materials like clay, silt, sand, and gravel deposited by rivers [37]. These aquifers facilitate the natural discharge of groundwater through both small and large springs, with flow rates ranging from 1 to 25 L/s and TDS values between 100 and 250 mg/L. Riverbed aquifers show higher flow rates, particularly in spring, reaching up to 30 L/s with TDS values up to 1000 mg/L [37,38].

Research has indicated significant limestone formations with high porosity and numerous karstic dolines, which might influence the chemical parameters of groundwater and river water [33]. These geomorphological features are formed by the dissolution of soluble carbonate rocks, leading to subsurface voids and surface depressions [1]. The aquifers in karstic limestone formations have high-discharge springs (60–100 L/s) [33]. In these aquifers, TDS values range from 2000 to 4000 mg/L. However, information regarding the depth and specific locations of these aquifers is lacking. The primary recharge sources for these aquifers include snowmelt, rainfall, and river flow, varying with elevation. In mountainous zones, groundwater recharge is mainly derived from atmospheric precipitation, permanent snow, and snowmelt [13]. In the foothill plains, recharge sources include atmospheric precipitation, river waters, and underground flow from mountainous zones. At the head parts of rivers' alluvial fans, water is primarily unconfined, absorbing atmospheric deposits and surface water. As water moves downward due to the hydraulic gradient, these unconfined units may become confined in certain areas [10].

Currently, Azerbaijan's mountainous regions lack a comprehensive groundwater monitoring network. Unfortunately, groundwater in the area is poorly understood, with limited information about aquifers publicly available, and much of the existing research is based on old data.

2.4. Climate

Azerbaijan features a diverse climate types across its different regions. The mountainous regions typically see cooler temperatures and more rainfall compared to the drier conditions of the central plains and the Caspian Sea coastline [36]. Rainfall in Azerbaijan varies throughout the year, peaking from April to June and again in October, with the highest precipitation typically occurring in May and June in the north and west [39]. On the slopes of the Greater Caucasus Mountains, precipitation generally increases with elevation up to a specific threshold. At altitudes ranging from 3700 to 4000 m, annual precipitation varies between 1200 and 900 mm. Beyond these elevations, precipitation levels begin to decline [13]. Usually, annual rainfall decreases to 400 mm in the foothills.

The Guba region experiences dry winters and rainy springs. Between 1991 and 2005, the average annual rainfall is 700–900 mm [39] (Figure 5).

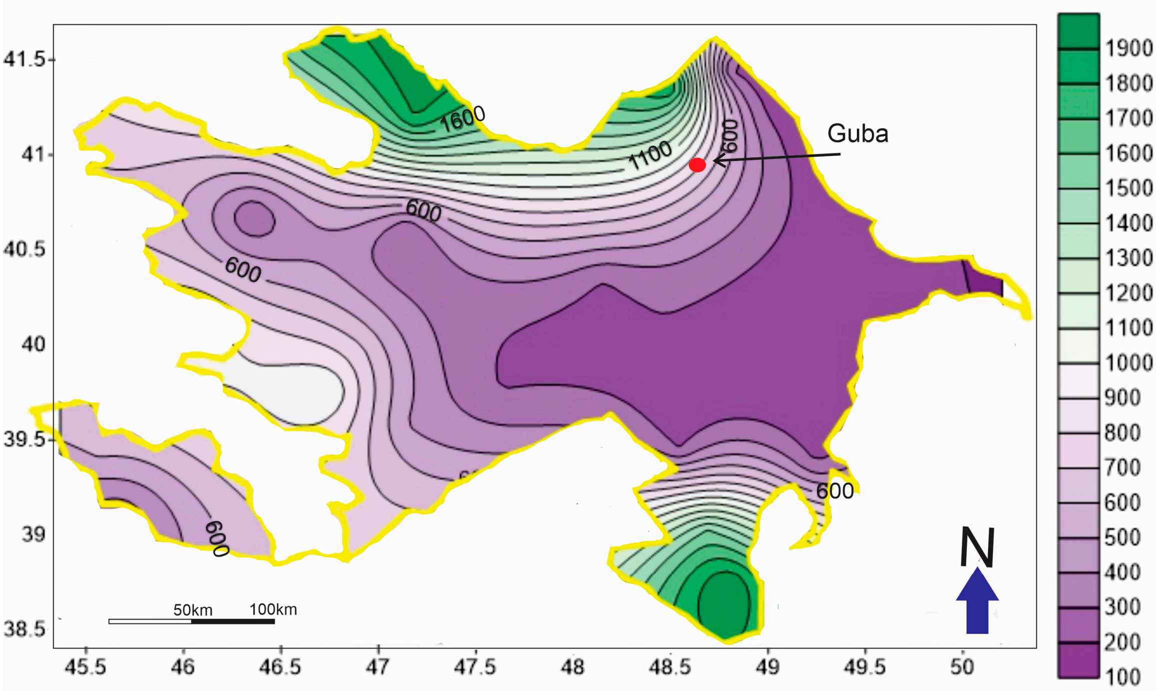

Figure 5. Average annual rainfall between 1992 and 2022 [39].

Snow cover in Azerbaijan is unevenly distributed, varying significantly between lowland and mountainous regions. In the foothills of the Greater Caucasus, the average snow thickness is about 10 cm, increasing to 20–50 cm in mid-mountain areas, and exceeding 70 cm at higher elevations. In the Lesser Caucasus foothills, snow cover averages 10–15 cm, with 20–30 cm in mid-mountain areas and up to 40–50 cm in the highlands [39]. The Guba region experiences significant snowfall during the winter months, characteristic of its mountainous terrain. Snowfall begins in December with an average of 11 cm and increases through January and February, peaking at 30 cm in February. By March, snowfall decreases to around 22 cm and further reduces to 8 cm in April. The region typically sees snowfall on 6 to 8 days per month during the peak winter months, contributing to a total winter snowfall of approximately 108 to 116 cm.

In the Guba region, during the winter months (December, January, and February), the average temperatures are quite low, with January being the coldest month. In January, the average high is 5 °C and the low is −3 °C, while December and February are slightly warmer, with highs of 6 °C and 4 °C and lows of −1 °C and −2 °C, respectively. The spring months (March, April, and May) experience moderate warming with temperatures ranging from 9 °C to 21 °C, while the fall months (September, October, and November) see a cooling trend with temperatures between 10 °C and 23 °C. Summer, encompassing June, July, and August, is markedly warmer. July is the warmest month, with an average high of 29 °C and a low of 19 °C, followed closely by August (28 °C/18 °C) and June (26 °C/16 °C). Across the entire year, the average maximum temperature peaks in July at 29 °C, while the average minimum temperature drops to its lowest in January at −3 °C. This seasonal variation highlights the distinct cold winters and warm summers typical of a temperate climate [39].

In the higher elevations of the Greater Caucasus, precipitation is higher than evaporation but, in the lowland, evaporation sometimes exceeds the mean annual rainfall several times, which prevents runoff formation and causes intensive evaporation of surface water and groundwater.

3. Data and Methods

3.1. Data

Precipitation and temperature data were obtained from the Meteorological Service of Azerbaijan.

The Gudiyalchay River has three main flow measurement stations: Khinaliq, Giriz, and Kupchal (Figure 1). Flow measurements at these stations were conducted irregularly from 1950 to 2016, and the data were provided by the Ministry of Ecology and Natural Resources of Azerbaijan. For analysis, average monthly flow values were calculated using monthly samples taken over multiple years, where available.

Chemical analyses provided by the Ministry of Ecology and Natural Resources of Azerbaijan include values for calcium (Ca), magnesium (Mg), sodium plus potassium (Na+K), bicarbonate (HCO_3), sulfate (SO4), chloride (Cl), and total dissolved solids (TDSs) from the Khinaliq, Giriz, and Kupchal stations covering the period from 1950 to 2016.

Moreover, single samples provided data on TDS values in 2014, 2016, and 2022 from the monitoring well in the riverbed near Kupchal station.

3.2. Methods

The geographic information system software QGIS 3.16 was utilized to map the location of the study area, including the specific sites of the flow stations and hydrogeological basins, as shown in Figures 1 and 4. The elevation data were extracted from Landsat 8 aerial imagery and mapped using Golden Software SURFER 13 to create a topographical profile of the study area (Figure 2).

To analyze rainfall distribution (Figure 5), rain data were interpolated using the kriging method in Surfer 13. The average data for chemical analyses were calculated from all available water samples to ensure comprehensive representation. The monthly average flow rate was derived from samples collected irregularly between 1950 and 2016, using the arithmetic mean. In the absence of samples for certain years, the average of the preceding and following data was calculated and used.

4. Results

4.1. Flow Rate Analysis

Khinaliq station, situated at a higher elevation (Figure 2: 1991 m), demonstrates lower flow rates during the winter and early spring months (January to March) with values ranging from 1 to 1.8 m^3/s (Figure 6). These values are indicative of minimal snowmelt contribution during these colder months. As temperatures rise in April, snowmelt increases, leading to a gradual rise in flow rates, peaking in June (6 m^3/s). The significant increase in flow rate during the summer months (June to August) highlights the primary role of snowmelt in river recharge at this station. Flow rates decrease in the autumn months (September to November) as snow reserves deplete and temperatures fall, stabilizing around 3.1 to 4 m^3/s (Figure 6).

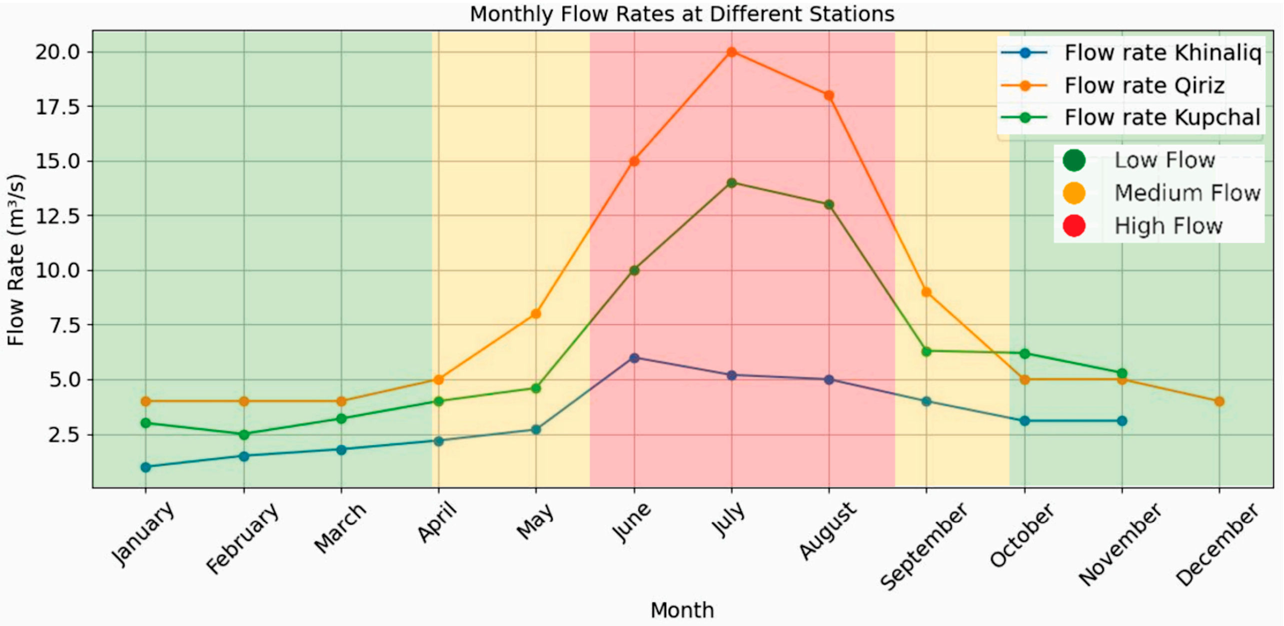

Figure 6. Average monthly flow rate values at Khinaliq, Giriz, and Kupchal stations (1950–2016). Samples were collected during various periods between 1950 and 2016. The average monthly values were calculated from the available data.

At Giriz station (Figure 2: 1220 m high), the flow rates start relatively higher even in the winter months compared to Khinaliq, ranging from 4 m^3/s from January to March (Figure 6). This higher base flow suggests an additional source of recharge, likely groundwater, which supplements the flow during periods of minimal snowmelt. The flow rates increase significantly in April (5 m^3/s) and peak in July (20 m^3/s). The steep increase from May (8 m^3/s) to June (15 m^3/s) indicates rapid snowmelt at mid-elevations. The gradual decrease from August to November aligns with the diminishing snowmelt and stabilization of possible groundwater inflow (Figure 6).

Kupchal station, located at a lower elevation (Figure 2: 743 m elevation), shows distinct seasonal variations with notable peaks in flow during the summer months, similar to Giriz (Figure 6). However, the flow rates at Kupchal in the winter and spring months (January to March) are lower compared to Giriz, ranging from 2.5 to 3.2 m^3/s. This suggests a potential reduction in groundwater influence or increased extraction of water for various purposes. Flow rates peak in July (14 m^3/s), reflecting the cumulative snowmelt and potential groundwater recharge (Figure 6).

Flow Rate Variations with Elevation Change

As the river flows from higher to lower elevations, starting from Khinaliq to Kupchal, several hydrological processes occur. Snowmelt is the primary recharge source across all elevations, with peak flow rates observed from April to July. Groundwater acts as a secondary but significant recharge source, particularly at Giriz station, where the elevation decreases more sharply, facilitating groundwater movement from higher to lower elevations.

Khinaliq Station (1991 m elevation): Flow rates are low in winter (1–1.8 m^3/s), increasing significantly in spring and summer due to snowmelt, and peaking at 6 m^3/s in June. Minimal groundwater influence is suggested by low winter flow rates, indicating the primary recharge source is snowmelt and rainfall.

The transition from Khinaliq to Giriz, covering a distance of 12.7 km, (1220 m elevation): Higher base flow in winter (4 m^3/s) compared to Khinaliq, with dramatic increases in summer (15–20 m^3/s). Groundwater typically moves from higher to lower elevations, making areas with significant elevation drops, like near Giriz, likely points of groundwater recharge to the river. For instance, higher winter flow rates at Giriz compared to Khinaliq suggest groundwater contribution since snowmelt is minimal during these months. The sharp increase in flow rates from Khinaliq to Giriz from April to July indicates significant snowmelt contribution, but consistently higher flow rates at Giriz during other months suggest groundwater influence. The influence of groundwater increases when the piezometric level rises, indicating that the aquifer is being fed by water from infiltration, horizontal flow, or recharge occurring further upstream.

The stretch from Giriz to Kupchal, spanning 17.8 km (743 m elevation): Lower winter and spring flow rates (2.5–4 m^3/s) than Giriz, peaking at 14 m^3/s in July but dropping to 13 m^3/s in August. The decrease in flow rate at Kupchal during high extraction periods may indicate reduced groundwater recharge or increased water extraction for agricultural use.

The Gudiyalchay River originates at an elevation of around 3000 m, following a meandering path as it descends to the Khinaliq station at 1991 m and the Giriz station at 1220 m, where it maintains a relatively narrow channel. As the river descends to lower elevations between 800 and 700 m, the sediment transport creates river bars, as evident in aerial imagery from Landsat/Copernicus [24]. Notably, the flow rate decreases in this region compared to the upper stations, and the river channel widens. Several other possible factors contribute to the reduced flow rate in the lower elevations:

- Evaporation: A wider river surface increases exposure to sunlight and wind, potentially leading to higher rates of evaporation.
- Infiltration: A broader riverbed enhances the interaction between surface water and the surrounding groundwater system. The widened channel may also facilitate more groundwater discharge zones, where river water percolates into the groundwater system.
- Water Extraction: The lower parts of the Gudiyalchay River include agricultural areas, leading to substantial water extraction for irrigation, domestic, and industrial uses, which further impacts the flow. İmanov F.A. and Ələkbərov A.B. [13] note that since 1948, a small arch above the Gudiyalchay–Kupchal station has been diverting an average of 0.30 m^3/s of water per month from the river. The calculations by İmanov F.A. and Ələkbərov A.B. [13] show that the average flow rate at Kupchal station from 1991 to 2010 decreased by 0.58 m^3/s compared to the average flow rate from 1950 to 1990, due to anthropogenic activities.

4.2. Hydrochemical Characteristics

The analysis of average long-term chemical parameters for the river, as shown in Table 1, reveals insights into its water quality and suitability for various uses. Calcium (Ca) levels vary, with concentrations ranging from 38.2 mg/L at Khinaliq to 49.7 mg/L at Kupchal, and an overall average of 45.53 mg/L. In comparison, magnesium (Mg) concentrations have a mean value of 15.27 mg/L. These figures suggest a moderate level of water hardness, which is characteristic of rivers influenced by karstic geology and seasonal snowmelt.

Table 1. Average values of cations and anions (1950–2016) in different stations and maximum threshold values for drinking water standards derived from the World Health Organization [40].

Station	Ca (Cation) mg/L	Mg (Cation) mg/L	Na+K (Cation) mg/L	HCO_3 (Anion) mg/L	SO_4 (Anion) mg/L	Cl (Anion) mg/L	TDS mg/L
Khinaliq	38.2	13.9	15.2	130.2	68.5	3.7	271
Giriz	48.7	13.6	16.5	154.3	74.8	4.2	312
Kupchal	49.7	18.3	19.2	164.4	76.6	4.3	328
Maximum acceptable limit	150	50	200	400	250	250	1000

Sodium and potassium (Na+K) concentrations show an upward trend as the river flows downstream, starting at 15.2 mg/L in Khinaliq and reaching 19.2 mg/L in Kupchal, with an average concentration of 17.00 mg/L. Bicarbonate (HCO_3) levels, crucial for maintaining the water's buffering capacity and overall chemistry, also increase along the river, ranging from 130.2 mg/L to 164.4 mg/L, with a mean value of 149.63 mg/L.

Sulfate (SO_4) and chloride (Cl) levels are relatively low, with averages of 73.30 mg/L and 4.07 mg/L, respectively. The total dissolved solid (TDS) average is 303.67 mg/L, slightly above the ideal taste threshold (<300 mg/L) but well below the maximum allowable limit of 500 mg/L.

Analyzing water samples from Khinaliq, Giriz, and Kupchal reveals increased levels of calcium (Ca), bicarbonate (HCO_3), and total dissolved solids (TDSs) downstream, particularly at Giriz and Kupchal. These higher concentrations suggest groundwater influence, likely from alluvial and karst aquifers. Groundwater typically carries more dissolved solids than surface runoff, supporting the hypothesis of substantial groundwater contributions at lower elevations.

The variations in Ca, Mg, and HCO_3 levels are attributable to different recharge sources. While snowmelt and rainfall contribute to the initial river flow, groundwater rich in these ions joins the river as it progresses, altering its chemistry.

According to the previous literature [4,6,9], the higher TDS values of the Gudiyalchay River can be also attributed to the presence of carbonate rocks, including limestone and dolomite, from the Cretaceous and Jurassic periods in the river's upper catchment area.

Figure 7 illustrates the total dissolved solid (TDS) values from the monitoring well near the riverbed near Kupchal station. The TDS (total dissolved solid) values from the monitoring well in the riverbed near Kupchal station at 743m elevation show notable variations over the years. Overall, the TDS values have fluctuated, but there is a slight upward trend when comparing the initial value in 2014 (321 mg/L) to the most recent value in 2022 (336 mg/L).

The relationship between the flow rates of the river and TDS values from groundwater suggests a possible interaction between the river and groundwater. Higher flow rates during the summer months, due to snowmelt recharging both the groundwater and the river, could lead to increased surface river flow, reducing the TDS concentrations in the groundwater. This explains the lower TDS values observed in the summer of 2014 (231 mg/L) and 2016 (293 mg/L). Conversely, during the winter months, lower flow rates might reduce the dilution effect, resulting in higher TDS concentrations as seen in January 2014 (320 mg/L) and December 2016 (315 mg/L). This pattern, however, is not entirely consistent as the July 2022 TDS value (336 mg/L) is higher despite a high flow rate (13 m^3/s), indicating that other factors, such as changes in land use, water consumption, or environmental conditions, could also be influencing TDS levels (Figure 7). These analyses are based on single samples and do not provide precise information. Continuous data are necessary to analyze TDSs better.

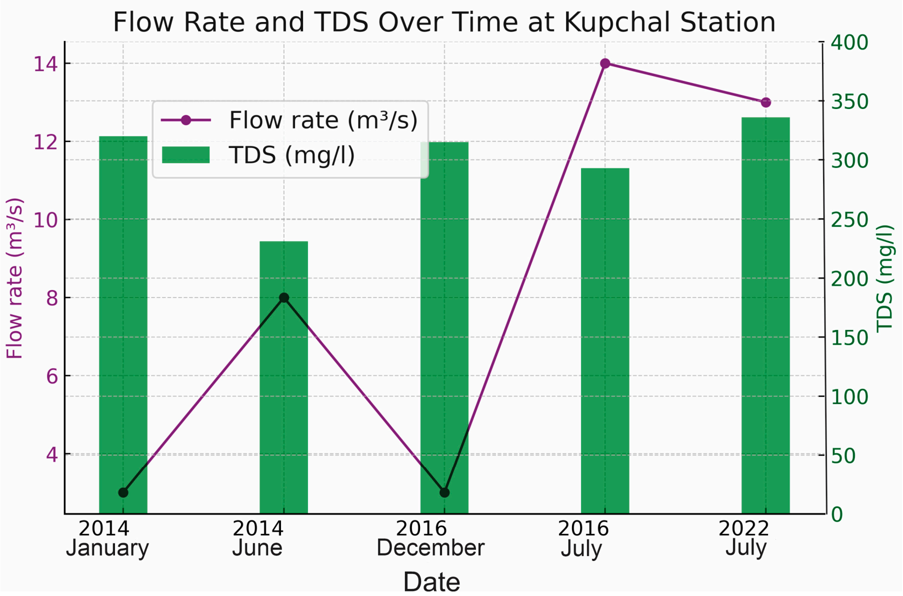

Figure 7. Relationship between TDS values of groundwater (single samples) and average monthly flow rate of river at Kupchal station.

5. Discussion

The Gudiyalchay River, originating in the higher elevations of the Greater Caucasus, is primarily recharged by snowmelt and groundwater, with precipitation playing a secondary role. Despite being a crucial water supply for the region, the river basin and the groundwater beneath its riverbed have not been sufficiently researched. Previous studies provide general information about the area's hydrogeology, mentioning the presence of karst formations and karstic aquifers, yet their precise locations remain unknown. Although the alluvial aquifers exhibit good porosity and the springs demonstrate substantial discharge rates, there is a lack of precise piezometric head data to accurately characterize the groundwater dynamics. Therefore, in this study, we relied on literature reviews and data analysis, which, despite being limited, enabled us to make general hypotheses about the hydrogeology of the area.

According to Rustamov S.H. [41], the mountain river basins in Azerbaijan can be divided into three distinct zones: (1) the flow formation zone (high mountain areas, mid-mountain areas, and foothill areas), (2) the transit zone, and (3) the discharge zone. These zones are more clearly defined during low water periods, and they exhibit different climatic and hydrological characteristics, as well as varying interactions between surface and underground water. Applying this classification to our study area results in the following:

1. Flow Formation Zone: This zone is primarily located in the mountainous areas where river catchments originate. Groundwater forms and discharges in this zone, often emerging as springs that feed the rivers. The number and discharge of springs typically increase with elevation up to a certain height.
    - High Mountain Areas (>2500 m)—Source of Gudiyalchay River: These areas have rocky, poorly permeable ground and steep valley slopes, promoting surface runoff. Groundwater formation here uses about 15% of atmospheric precipitation. Springs are rare.
    - Mid-Mountain Areas (1000–2500 m): These are the areas where the Khinaliq and Giriz stations are located. These areas have gentler slopes and widespread sediments, which favor groundwater formation. Most springs are found here, and their flow patterns follow a delayed response to precipitation.
    - Low Mountain and Foothill Areas (500–1000 m)—Areas near the Kupchal Station: These areas transition from denudation to accumulation forms. Rivers flow through wide valleys of alluvial sediments, where collected groundwater feeds

the rivers throughout the year. Precipitation is lower, leading to fewer and smaller springs.

2. Transit Zone—Elevations after the Kupchal Station: In the central parts of river alluvial fans, groundwater flows between different layers. The unconfined water layers, thickest at their source, thin out as they move downward, while confined layers increase in thickness.
3. Discharge Zone: This zone is located in the foothills and plains where the natural flow regime is disrupted. Here, the river's flow decreases as water is absorbed into the ground, forming springs at the edges of alluvial fans. In the summer, groundwater levels drop, causing many springs to dry up.

Based on the analysis of data and a review of the previous literature, a simplified and general hydrogeological diagram has been created to illustrate these concepts (Figure 8). This diagram provides a visual summary of the key findings and classifications relevant to the study area.

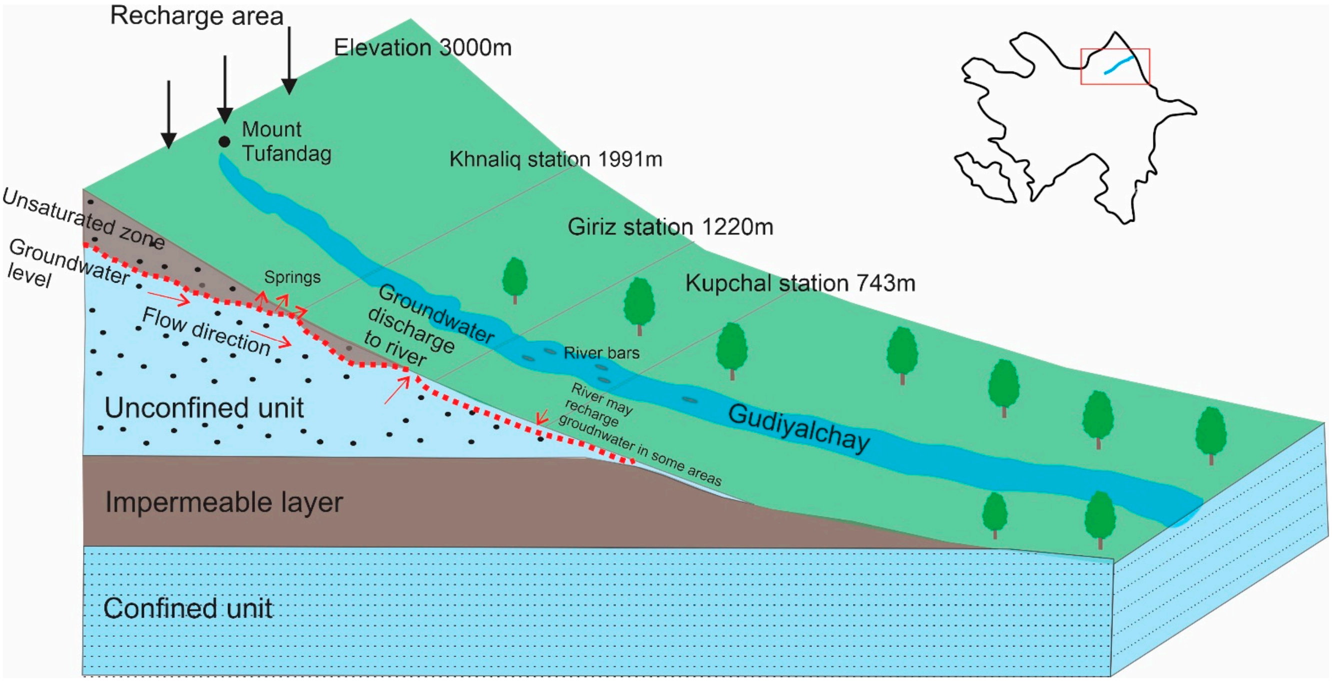

Figure 8. Simplified hydrogeological diagram illustrating groundwater–river interactions in the Gudiyalchay River basin. The depicted thicknesses and colors of the units are approximate.

The hydrogeological diagram illustrates the source of the river from a mountainous area at around 3000 m, where rain and snowmelt contribute to the groundwater recharge (Figure 8: Recharge area). Water infiltrates through the unsaturated zone into the groundwater system below, flowing downhill towards lower elevations. This region features an unconfined unit, a permeable geological formation that allows water to move freely and is depicted above an impermeable layer. Groundwater flow is indicated by a red dotted line, showing movement from higher to lower elevations. Water is mostly unconfined at the headwaters of rivers' alluvial fans (Figure 8: Unconfined unit), absorbing atmospheric deposits and surface water. The depth of groundwater in the unconfined aquifers of the area can reach up to 57 m below the ground surface [13]. Along groundwater flow, springs emerge where groundwater naturally surfaces near Khinaliq and Giriz, contributing to the river flow (Figure 8: Springs). In the foothill plains, the recharge sources include atmospheric precipitation, river waters, and underground flow from mountainous zones (Figure 8: Flow direction). Additionally, river bars, which are accumulations of sand or sediment, can influence the interaction between the river and the groundwater. In some areas, the river itself may recharge the groundwater, especially during high flow or flooding periods. Below the unconfined unit, an impermeable layer creates a barrier that results in a confined groundwater unit, where the water is under pressure. As the water moves downward following the hydraulic gradient, these unconfined units may become confined in certain areas [41]. The well data from the Soviet era, as reported by Imanov F.A. and Ələkbərov A.B. [13], indicate that the depth of groundwater from the ground level in confined aquifers ranges from 0.5 to 8 m in the wells in this area, although the exact locations of these wells are not specified.

Regarding the water quality for drinking purposes, the observed TDS (total dissolved solid) values are within acceptable limits. The World Health Organization (WHO) [40] recommends a TDS level of less than 1000 mg/L for drinking water. The values recorded at the groundwater near the Kupchal station range from 230 mg/L to 336 mg/L, which are well within this guideline. However, previous research [33] mentions TDS values exceeding 2000 mg/L in karstic aquifers of the Greater Caucasus, which exceed drinking water standards. The exact locations and depths of these aquifers are unfortunately unknown. To better analyze the chemical parameters of the groundwater in this area, continuous data collection is crucial.

Despite the scarcity of data, this research has enabled us to propose a simplified hydrogeological diagram. This initial diagram can serve as a foundation, which can be refined with additional geological and hydrogeological data.

To contextualize the findings of our study on the Gudiyalchay River, it is essential to compare our results with those of other well-studied mountainous river systems. One of the most relevant comparisons can be made with rivers such as Incline Creek, Third Creek, and Galena Creek in the Sierra Nevada in the United States [42], which share similar hydrological characteristics with the Gudiyalchay River. The rivers in the Sierra Nevada offer a relevant comparison to the Gudiyalchay River due to their similar hydrological regimes, primarily driven by snowmelt and groundwater recharge. Extensive studies on these rivers have shown clear seasonal variations, where snowmelt significantly increases streamflow during spring and early summer, while groundwater contributions maintain base flow during the late summer and fall. This seasonal pattern is mirrored in the Gudiyalchay River, where snowmelt is a key driver of summer flow rates, and groundwater sustains the river during low-flow periods, particularly at the Giriz station.

The Sierra Nevada study, utilizing the GSFLOW model, demonstrates that earlier snowmelt causes the peak groundwater discharge to occur earlier in the year, resulting in decreased groundwater contributions during the summer [42]. While our study of the Gudiyalchay lacks the detailed modeling applied in the Sierra Nevada, the observed trends in groundwater sustaining base flow during low-flow periods suggest similar dynamics. The identification of unconfined aquifers contributing to river recharge in the mid-mountain areas of the Gudiyalchay aligns with the rapid recharge observed in the Sierra Nevada rivers, particularly near stream channels.

Moreover, both regions are characterized by topography and geological constraints that influence groundwater recharge and discharge dynamics. In the Sierra Nevada, steep terrain and shallow, permeable aquifers overlying impermeable bedrock result in rapid drainage and significant stream–aquifer interactions. Similarly, the Gudiyalchay River transitions from high, rocky mountain areas with low permeability to lower regions where alluvial sediments facilitate greater groundwater interaction with the river. These shared features between the Gudiyalchay and Sierra Nevada rivers provide strong support for the hydrogeological patterns observed in our study.

Moving from North America to South Africa, the Nuwejaars River offers another valuable point of comparison, particularly regarding groundwater–surface water interactions influenced by topography [43]. Both the Gudiyalchay and Nuwejaars rivers demonstrate a transition in groundwater contribution along their courses—from significant input in the uplands to reduced influence in the lowlands due to geological constraints like confining layers. The simplified hydrogeological model we developed for the Gudiyalchay River accurately captures this transition (Figure 8), reflecting similar dynamics observed in the Nuwejaars River.

In summary, these comparisons with well-documented river systems underscore the relevance and accuracy of the hydrogeological insights gained from our study of the Gudiyalchay River. Despite the limitations in data availability, the observed trends and the simplified hydrogeological model we developed align with findings from other mountainous rivers, validating our approach. These comparisons not only confirm the general patterns of groundwater recharge and river flow dynamics in the Gudiyalchay River but also enhance our understanding of its unique characteristics, providing a solid foundation for future research.

Regular monitoring is crucial for understanding the groundwater–river interactions and managing the water quality of the Gudiyalchay River, ensuring its suitability for drinking and agricultural purposes. One of the primary challenges in studying groundwater–surface water interactions is the lack of a detailed mechanistic understanding of the processes involved. Despite advancements, the reactive interface between surface water and the subsurface requires more experimental and model-based evidence to understand the controls and magnitude of the processes involved fully [19,44].

The absence of continuous monitoring data limits a comprehensive understanding of the Gudiyalchay River's dynamics, as mentioned in numerous studies [2,3,6,8,9,13,33,35,37].

Establishing such stations would provide valuable data to inform water management practices, ensure sustainable use of the river's resources, and protect its ecological health. Since dynamic and static rivers have different connections to groundwater, spatial and temporal measurements are necessary to capture variations and interactions between surface and groundwater systems [45].

Currently, no effective flow models exist in Azerbaijan to simulate different scenarios. With regard to its relevance for environmental and water management and protection, the impact of groundwater–surface water interactions is still not fully understood and is often underestimated, which is not only due to a lack of awareness but also a lack of knowledge and experience regarding appropriate measurement and analysis approaches [45]. Therefore, the implementation of high-quality data and integrated methods is essential [46]. Groundwater flow models are invaluable tools for hydrogeologists, enabling quantitative analysis and improved understanding of groundwater flow systems and related issues [20–22]. Groundwater–surface water interaction models are crucial for understanding and managing water resources, predicting the impacts of environmental changes, and informing sustainable water management practices [17,45,47,48].

In flood-prone regions, it is crucial to develop a new hydrological network based on automated observation systems. Historical flow data from Giriz and Kupchal stations occasionally show peaks above 35 m^3/s, potentially influenced by flooding. The period from May to June is particularly flood-prone due to the combined effects of snowmelt and groundwater recharge. During these months, melting snow significantly increases the river's water volume, and heavy rain can exacerbate the situation, causing floods. Observation points on mountain rivers, subject to flooding and high flows, should be designed to study characteristics such as flood arrival times, average water levels, and annual flow distribution at various elevations, including high altitudes, medium mountains, and foothill areas [49,50]. Aerial imagery and GIS-based analysis are increasingly crucial in modern science, particularly for flood risk assessment, as demonstrated in several research studies [51–53].

These recommendations aim to improve the understanding and management of the Gudiyalchay River and its associated groundwater systems, ensuring sustainable and informed use of water resources in the region.

6. Conclusions

This study highlights the significant seasonal variations in Gudiyalchay River flow across the three stations, with increased flow during the summer months due to snowmelt and decreased flow during the winter months, influenced by reduced precipitation and snowmelt. Groundwater plays a crucial role in sustaining the river's flow during these low-flow periods, especially at the Giriz station, where substantial groundwater recharge is evident even during drier months. In contrast, Kupchal station exhibits lower flow rates, likely due to factors such as water extraction, channel widening, higher evaporation rates, and reduced precipitation.

The observed inverse correlation between TDS levels at Kupchal and river flow rates underscores the impact of snowmelt recharge on water quality, which is a critical consideration for managing the region's water resources. This research not only enhances our understanding of the hydrological dynamics in the region but also provides a foundational hydrogeological model that, while simplified, lays the groundwork for future studies.

Given the limitations due to insufficient data, future research should focus on gathering more comprehensive data to develop a more detailed hydrogeological model. Such advancements will be essential for effective water resource management and planning across the entire river-influenced region.

Author Contributions: Conceptualization: L.M.; methodology: L.M. and S.N.; software: L.M.; resources and formal analysis: M.-K.T. and V.M.; data curation: M.-K.T. and V.M.; writing—original draft preparation: L.M.; writing—review and editing: L.M. and S.N.; supervision, S.N. and V.M. All authors have read and agreed to the published version of the manuscript.

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References

1. Mammadova, L.; Negri, S. Understanding the impacts of overexploitation on the Salento aquifer: A comprehensive review through well data analysis. *Sustain. Futures* **2024**, *7*, 100188. [CrossRef]
2. Ələkbərov, A.B.; Imanov, F.A. Azərbaycanın su ehtiyyatları: Problemlər, Yanaşmalar, Realliqlar. *Water Probl. Sci. Technol.* **2016**, *UOT551.493*, 15–25. (In Azerbaijani)
3. Tahirov, R.; Zeynalova, M. Azərbaycanın su resurlarının mühafizəsi. *J. Metaphys.* **2021**, *4*, 101–109. (In Azerbaijani)
4. Humbatova, S.I.; Hajiyev, N.G.O. Ecological agriculture and land resources in Azerbaijan. *Econ. Soc. Dev. Book Proc.* **2020**, *2*, 242–256.
5. Ministry of Ecology and Natural Resources of Azerbaijan. Su Resursları. Available online: https://eco.gov.az/az/melumat-merkezi/kitabxana (accessed on 15 July 2024).
6. Alakbarov, A.B.; Groundwater of Azerbaijan. Dutch Portal to International Hydrology. Available online: https://www.hydrology.nl/images/docs/ihp/groundwater_governance/Groundwater_of_Azerbaijan.pdf (accessed on 11 July 2024).
7. Рустамов, С.Г.; Кашкай, П.М. Водные Ресурсы Азербайджанской ССР. Academy of Sciences of the AzSSR, Institute of Geography; Baku, Azerbaijan, 1989; 184p.
8. Məmmədov, M. *Azərbaycanın Hidroqrafiyası*, 2nd ed.; Təhsil NPM: Bakı, Azərbaycan, 2012; 254p. (In Azerbaijani)
9. Abduyev, M. *Azərbaycanın dağ Çaylarının Hidrokimyəvi Xarakteristikası Coğrafi Qanunauyğunluqları*; ADPU: Bakı, Azərbaycan, 2021; 363p. (In Azerbaijani)
10. Azerbaijan Coğrafiya Cəmiyyəti. Azərbaycan Çayları. Available online: https://gsaz.az/articles/view/108/ (accessed on 10 July 2024). (In Azerbaijani).
11. Kazimova, S. Azərbaycanda müasir iqlim dəyişmələrinin su ehtiyatlarına təsiri. *Lənkəran Dövlət Univ. Nəşrləri.* **2018**, *1*, 137. (In Azerbaijani)
12. Azersu. Bülleten. Available online: https://azersu.az/img/staticPageFile/1583323317iyul-2013az.pdf (accessed on 20 July 2024).
13. İmanov, F.A.; Ələkbərov, A.B. *Azərbaycanın su Ehtiyyatlarının Müasir Dəyişmələri və Inteqrasiyalı Idarə Edilməsi*; Mütərcim: Bakı, Azerbaijan, 2017; ISBN 978-9952-283327. (In Azerbaijani)
14. Ke, Y.; Song, X.; Yang, L.; Yang, S. River–Spring Connectivity and Hydrogeochemical Processes in a Karst Water System of Northern China: A Case Study of Jinan Spring Catchment. *Water* **2024**, *16*, 829. [CrossRef]

15. Appelo, C.A.J.; Postma, D. *Geochemistry, Groundwater and Pollution*; CRC Press: Boca Raton, FL, USA, 2004.
16. Yapiyev, V.; Rossi, P.M.; Ala-Aho, P.; Marttila, H. Stable Water Isotopes as an Indicator of Surface Water Intrusion in Shallow Aquifer Wells: A Cold Climate Perspective. *Water Resour. Res.* **2023**, *59*, e2022WR033056. [CrossRef]
17. Broecker, T.; Teuber, K.; Gollo, V.S.; Nützmann, G.; Lewandowski, J.; Hinkelmann, R. Integral flow modelling approach for surface water-groundwater interactions along a rippled streambed. *Water* **2019**, *11*, 1517. [CrossRef]
18. Petpongpan, C.; Ekkawatpanit, C.; Bailey, R.T.; Kositgittiwong, D. Improving integrated surface water–groundwater modelling with groundwater extraction for water management. *Hydrol. Sci. J.* **2021**, *66*, 1513–1530. [CrossRef]
19. Banerjee, D.; Ganguly, S. A Review on the Research Advances in Groundwater–Surface Water Interaction with an Overview of the Phenomenon. *Water* **2023**, *15*, 1552. [CrossRef]
20. De Filippis, G.; Foglia, L.; Giudici, M.; Mehl, S.; Margiotta, S.; Negri, S.L. Effects of different boundary conditions on the simulation of groundwater flow in a multi-layered coastal aquifer system (Taranto Gulf, southern Italy). *Hydrogeol. J.* **2017**, *25*, 2123–2138. [CrossRef]
21. De Filippis, G.; Giudici, M.; Margiotta, S.; Mazzone, F.; Negri, S. Numerical modeling of the groundwater flow in the fractured and karst aquifer of the Salento peninsula (Southern Italy). *Acque Sotter.* **2013**, *2*, 17–28. [CrossRef]
22. De Filippis, G.; Giudici, M.; Margiotta, S.; Negri, S. Conceptualization and characterization of a coastal multi-layered aquifer system in the Taranto Gulf (southern Italy). *Environ. Earth Sci.* **2016**, *75*, 685–701. [CrossRef]
23. Abdurrəhmanova, G.C. Qusarçay-Qudiyalçay hövzələrində Landşaft Diferensiasiyasının Çay axınına Təsiri. *Coğrafiya Və Təbii Resur.* **2018**, *1*, 42–48. (In Azerbaijani)
24. Geological Survey (USGS). Landsat 8 OLI/TIRS Collection 2 Level-1. Available online: https://earthexplorer.usgs.gov/ (accessed on 20 July 2024).
25. Həbibov, T. *Azərbaycan Geologiyası*; Azərbaycan Dövlət Pedaqoji Universiteti, Azərbaycan Respublikası Təhsil Nazirliyi: Bakı, Azərbaycan, 2011; 317p. (In Azerbaijani)
26. Азизбеков, Х., Ш. Геология СССР; «Недра» XLVII. Азербайджанская ССР: Москва, Russia, 1972; pp. 1–520. (In Russian)
27. Alizade, A.A. *Geology of Azerbaijan II*; Institute of Geology and Geophysics: Baku, Azerbaijan, 2015.
28. АлиЗаде, А. Геология в Азербайджане; Хозяйственные Минералы; Nafta-Press: Baku, Azerbaijan, 2003; pp. 1–577. (In Russian)
29. Adamia, S.; Zakariadze, G.; Chkhotua, T.; Sadratze, N.; Tsereteli, N.; Chabukiani, A.; Gventsadze, A. Geology of the Caucasus: A Review. *Turk. J. Earth Sci.* **2011**, *20*, 489–544. [CrossRef]
30. Azərbaycanın Geoloji Xəritəsi. Available online: https://azerbaijan.az/geological (accessed on 8 August 2024).
31. Howard, K.; Israfilov, R.; Israfilov, Y.; Griffith, A.; Ismailova, M.; Rashidov, T. Use of groundwater models for managing serious urban water issues in Baku, the capital city of Azerbaijan. In Proceedings of the International Symposium on New Directions in Urban Water Management, Paris, France, 12–14 September 2007; UNESCO: Paris, France.
32. Eyvazova, Y.M. *Böyük Qafqazın Şimal-Şərq Yamacı və Şirvan Çaylarının Ekoloji Axımı*; Namizədlik Dissertasiyasının Avtoreferatı: Bakı, Azerbaijan, 2005; 29p. (In Azerbaijani)
33. Alakbarov, A.B. Groundwater quality status and problems of sustainability in Azerbaijan. In *XXXVIII IAH Congress: Groundwater Quality Sustainability*; University of Silesia Press: Krakow, Poland, 2010; pp. 109–115.
34. Aliyev, F.S.; Askerov, F.S. Sources of groundwater supply to urbanized areas in Azerbaijan: National development of groundwater resources. *NATO Sci. Ser. V Earth Environ. Sci.* **2006**, *74*, 59–77.
35. Alakbarov, A.; Agamirzayev, R.; Alakbarov, P. Geoenvironmental problems in Azerbaijan. *Urban groundwater management and sustainability, NATO Sci. Ser. V Earth Environ. Sci.* **2006**, *74*, 39–58.
36. İmanov, F.; Aliyeva, I.; Nagiyev, S.; Leummens, H. Changes in the annual flow of the Kura River. *Geogr. J. Pol. Geogr. Soc.* **2023**, *94*, 39–52. [CrossRef]
37. Mahmudov, R.N. Azərbaycanın su Resurslar; Bakı, Azərbaycan, 2003; 24p. Available online: https://www.azadliq.org/a/su-resurs-quraqliq/31686642.html (accessed on 24 August 2024). (In Azerbaijani).
38. İsmayılov, V.M. Böyük Qafqaz Çaylarının Rejim Xüsusiyyətlərinin Coğrafi Qanunauyğunluqları. In *Coğrafiya Elmlər Namizədliyi və Alimlik Dərəcəsi Almaq Üçün Təqdim Edilmiş Dissertasiya iş*; AMEA: Baku, Azerbaijan, 2009; 167p. (In Azerbaijani)
39. National Hydrometeorological Service. Yağıntının Miqdarı. Available online: https://meteo.az/index.php?ln=az&pg=226 (accessed on 15 July 2024).
40. World Health Organization. *Guidelines for Drinking-Water Quality*, 4th ed.; World Health Organization: Geneva, Switzerland, 2022.
41. Rüstəmov, S.H. *Azərbaycan SSR-Nin Çayları və Onların Hidroloji Xüsusiyyətləri*; SSR EA Nəşriyyatı: Bakı, Azərbaycan, 1960. (In Azerbaijani)
42. Huntington, J.L.; Niswonger, R.G. Role of surface-water and groundwater interactions on projected summertime streamflow in snow dominated regions: An integrated modeling approach. *Water Resour. Res.* **2012**, *48*, W11524. [CrossRef]
43. Mazvimavi, D.; Clarke, S.; Day, J.; Dube, T.; Kanyerere, T.; Machingura, J.; Malijani, E.; Mkunyana, Y.P.; Swartbooi, E. Understanding of Surface Water-Groundwater Interactions from Headwaters to Lowlands for Catchment Scale Sustainable Water Resources Management. *Water Res. Comm.* **2022**, *22*, 61.
44. U.S. Geological Survey. Part 1: Major Concepts of Ground-Water Hydrology. In *Ground Water and Surface Water: A Single Resource*; USGS: Washington, DC, USA, 1996.
45. Lewandowski, J.; Meinikmann, K.; Krause, S. Advances in groundwater-surface water interactions: Recent advances and interdisciplinary challenges. *Water* **2020**, *12*, 296. [CrossRef]

46. Brunner, P.; Therrien, R.; Renard, P.; Simmons, C.T.; Franssen, H.-J.H. Advances in understanding river-groundwater interactions. *Rev. Geophys.* **2017**, *55*, 818–854. [CrossRef]
47. Kelly, L.; Kalin, R.M.; Bertram, D.; Kanjaye, M.; Nkhata, M.; Sibande, H. Quantification of temporal variations in Base Flow Index using sporadic river data: Application to the Bua Catchment, Malawi. *Water* **2019**, *11*, 901. [CrossRef]
48. Tang, T.; Guo, S.; Tan, L.; Li, T.; Burrows, R.M.; Cai, Q. Temporal effects of groundwater on physical and biotic components of a karst stream. *Water* **2019**, *11*, 1299. [CrossRef]
49. Norwegian Water Resources and Energy Directorate (NVE). River Basin Management Plan 2011—River Basin District Vestlandet. Available online: https://publikasjoner.nve.no/report/2011/report2011_05.pdf. (accessed on 15 August 2024).
50. Engeland, K.; Aano, A.; Steffensen, I.; Støren, E.; Paasche, Ø. New flood frequency estimates for the largest river in Norway based on the combination of short and long time series. *Hydrol. Earth Syst. Sci.* **2020**, *24*, 5595–5611. [CrossRef]
51. Aano, A.; Engeland, K. Integrated GIS Analysis for Flood Risk Assessment in Norwegian Rivers: A Case Study of Sokna River 2024. Available online: https://meetingorganizer.copernicus.org/EGU24/EGU24-19378.html (accessed on 29 August 2024).
52. Alfredsen, K.; Tekle, M.G. Effect of flow ramping on stranding potential related to river morphology—Developing hydraulic indices for peaking severity. *River Res. Appl.* **2023**, *40*, 203–216. [CrossRef]
53. Skrede, T.I.; Tørudstad, V.; Pons, V.; Alfredsen, K.; Muthanna, T.M. From flood paths to floodways, an efficient method to map, identify and evaluate suitable floodways: A case study from Trondheim, Norway. *J. Environ. Manag.* **2023**, *346*, 118672. [CrossRef]