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Use of Holistic Environmental Flow Assessment for the Alijanchay River, Azerbaijan

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Abstract: Holistic environmental flow assessment includes evaluation of chemical, biological, hydrological, and morphological changes predicted from disrupting a river flow regime. Using available water chemistry together with biological and hydrological surveys, we report and assess environmental flows of the Alijanchay River, an important tributary of the Kura River, at four monitoring stations located in Azerbaijan. The river's natural flow regime has changed significantly due to the irrigation activities in the middle and lower reaches and further development is planned through construction of new reservoirs. Our methodology is based on the results of morphological, hydrological, and hydrobiological observations and analysis of the physical and chemical parameters of the river. Environmental flow was evaluated by six hydrological methods proposed in the literature, and a comparative analysis shows that its value has increased from 13.6 to 27.1% of the annual flow volume, consistent with increased pressure on this important surface water supply. Water Quality Indices (WQI) further show seasonal changes of water quality in this important water supply, impacting sustainable uses for drinking and agriculture. Parameters most affected by seasonal changes are turbidity, suspended solids, and dissolved oxygen. Further degradation of environmental flows of this important watershed in Azerbaijan are likely from the planned development. A more comprehensive holistic ecological flow can help support a sustainable plan for use of Alijanchay River basin water reserves, and, if resources are provided for other basins, can support development elsewhere.

Keywords: environmental flow; holistic methodology; water quality; hydrobiological indicators

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1. Introduction

Inefficient use of water resources adversely affects the ecological status of rivers, disrupting the metabolism of aquatic organims and the exchange of energy in river ecosystems. Economic activity in the river basin primarily affects the abiotic properties of its ecosystem, changing its water, thermal, radiation regime, flow rate, and channel processes. Changes in the hydrological regime of the river are ultimately reflected in the biotic properties of the ecosystem and long-term sustainability for beneficial uses [1]. Water bodies such as rivers, in addition to providing socio-economic and water management benefits, have ecological, geospheric, landscape, recreational, aesthetic, and cultural functions [2]. Water use in rivers can be managed in such a way that the water remaining in the channel continues to support ecological processes occurring in the river and can ensure the survival and development of hydrobionts (aquatic organisms).

The concept of environmental flow has historically developed as a response to the degradation of aquatic ecosystems caused by the overuse of water. Despite the variety of terms and numerous research methods, in almost all cases, the environmental flow is considered as part of the river flow that is left in the river ecosystem [3]. The ultimate goal of ensuring environmental flow is to improve and maintain the ecological conditions of a river (increase its "ecological status") according to the terminology of the European Union Water Framework Directive [4] by reducing the negative ecological effects of flow regime alteration.

Since 1940, numerous methods have been proposed to estimate environmental flow, and these methods are divided into four main groups: hydrological, hydraulic, habitat simulation methods, and holistic methods [5]. Two additional groups are also distinguished: combined methods and multivariate regression analyses. Combined methods incorporate hydrological, habitat-water discharge relationships, and holistic elements [6]. It should be noted that each of the proposed methods has its own negative and positive aspects. The main problem is that it is difficult and often impossible to obtain all of the necessary information about the hydroecological characteristics of the river basin during the calculations. Hydrological methods are more widely used in international practice due to their simplicity (only hydrological data are required) and low cost (field studies are not needed).

In the countries of the European Union, including the Mediterranean countries included in this Union, hydrological methods based on the use of minimal water discharges or other characteristics of the river flow regime have been abandoned to assess environmental flow. Unified methods are encouraged, but widespread application of these methods has been delayed [6]. However, new hydrological methods are also being developed and show promise for improved management of rivers. For example, for the Agri River, whose basin is in the south of Italy, the methodology is based on indicators of hydrologic alteration and the index of hydrological regime alteration. The Hydrologic Engineering Center-Hydrological Modeling System (HEC-HMS) was applied, mean monthly water discharge was calculated, and observed daily precipitation data were used to more comprehensively evaluate flow regime. The value corresponding to the 20% (the discharge 80% exceedance probability) of the mean monthly flow for each month was accepted as the quantity of environmental flow [7]. A new hydraulic method was recently proposed to determine the environmental flow of rivers strongly affected by anthropogenic factors. Three main hydraulic parameters were selected (wet-season baseflow magnitude, dry-season baseflow magnitude, and spring recession start magnitude), and their lower and upper limits were determined [8].

Approximately 165 articles published on altered flow regimes in watersheds from several different continents were analyzed in 2010 [9], and an attempt was made to reveal regularities between the number of in-channel and riparian responses to flow regime alteration. Discharge magnitude, frequency, duration, etc., were used as the quantitative indicators of the flow change, and macroinvertebrates, fish, and coastal plants were used as ecological indicators. According to authors, in 152 (92%) of these studies, it was concluded that changes in anthropogenic origin of the flow reduce ecological indicators and increase ecological risks, reducing beneficial uses of the water. Consistent with holistic environmental flow, they recommend a thorough analysis of data related to natural and anthropogenic regime periods to expand the understanding of the impact of anthropogenic changes in river flow on river organisms [9].

In the 1990s, a hydrological method for determining the environmental flow of Azerbaijan rivers was developed and subsequently improved [10–12]. Habitat modeling and integrated (holistic) methods are considered more objective, as these methods require hydrobiological monitoring data in addition to hydrological and hydrochemical data. Unfortunately, such monitoring has only been carried out sporadically since holistic methods were developed. Since the 1990s, most researchers apply a holistic approach to environmental flow assessment (EFA). In this holistic approach, the water resources of a river basin should be managed in such a way that environmental flow volume, water use, water quality, and energy production are satisfied simultaneously. Three important points should be considered in an EFA methodology based on this approach:

1. When determining environmental flow, not only hydrological or hydraulic criteria, but also the needs of the hydrobionts and plants of rivers are considered.
2. The environmental flow should ensure the protection of not only single species of flora or fauna, but the entire river community as a whole.
3. Environmental flow is not only certain values of minimum water flows. Its quantity is determined by a number of river flow components (water discharge, their frequency and duration, and rate of change). The seasonal river flow forms the natural habitats and enables rivers to function properly.

Most countries of the European Union have reflected in legislative documents the provision of an appropriate volume of ecological river flow, taking into account the needs of ecosystems at the national and regional levels [13]. According to Article 90 (Environmental Water Release) of Chapter XIV (Protection of Water Bodies) of the Water Code of the Republic of Azerbaijan, "In order to maintain water bodies in a state in accordance with the relevant environmental requirements, water is released from reservoirs (ecological water release) and the volume of water withdrawal without recovery is determined" [14].

At present, there is no approved normative document defining assessment of environmental flow and calculation of the amount of environmental flows from water bodies in the Republic of Azerbaijan. Projects implemented by the State Water Resources Agency of Azerbaijan still use the simple hydrological method recommended for application throughout the USSR [15]. To more efficiently use water resources in Azerbaijan, there are plans to build new reservoirs on ten rivers, including the Alijanchay River. The main goal of the present article is to develop and propose a holistic method for assessing the environmental flow of the Alijanchay River, on which the construction of one of these reservoirs is planned. It is hoped that the benefits of using a more modern evaluation of environmental flow will be used for more sustainable development of the increasingly scarce surface water resources in Azerbaijan and other countries.

2. Study Site

The Alijanchay River is an important northern tributary of the Kura River, the largest river of the Caucasus, and one of the five main rivers of the Shirvan region of Azerbaijan (Figure 1). This tributary source area is at an altitude of 3500 m, and its confluence with the Kura River occurs at an altitude of 13 m above sea level. Its length is 97 km, and the area of its basin is 1010 km^2. Part of the river basin is in a mountainous area, and the rest is in the plain. Only sedimentary rocks are spread across the basin, including Mesozoic limestones, dolomites, and siltstones, with alluvial sands and clays. The river formed in two alluvial fans downstream [16]. The average annual air temperature is 13 °C, the average long-term annual precipitation is 1130 mm, and the annual potential evaporation is 917 mm. In the Alijanchay River basin, the annual precipitation increases from 230 mm to 1480 mm with increasing elevation [17]. Several natural landscape zones have formed in the Alijanchay basin: from lowland semi-deserts to sub-nival and nival landscapes. Mountain forests are located between a 600 and 2200 m altitude (149 km^2) [18].

At the Gayabashı hydrological station, which is located very close to the dam of the reservoir designed on the river, the average multi-year water discharge was 5.52 m^{3}s^{-1}, the maximum water discharge was 146 m^{3}s^{-1}, and the smallest water discharge was 0.12 m^{3}s^{-1}. The share of groundwater baseflow, rain, and snow water in the annual flow of the river is 43%, 36%, and 21%, respectively [19,20].

Various economic activities are carried out in the Alicanchay basin, including irrigated and rainfed cropland, as well as livestock farming (cattle and sheep). The water provides drinking water supplies for several villages (Jayirli, Salamabad, Khaldan, etc.), and the river is used for receiving discharge of treated sewage. Irrigation facilities include a small reservoir with several canals. A complex of waste water treatment facilities have been built, and a new reservoir for irrigation is under contruction. Currently, the irrigated areas in the river basin are 3483 ha (wheat, potato, and orchards).

Figure 1. Geographical position of the Alijanchay basin.

Water losses are very high (40–50%) because the irrigation canals are not sealed or concreted [21]. After the construction of the new water reservoir with an operational capacity of 100 million m^3 on the river, it is planned to provide irrigation water to 42,000 hectares of land in the river basin and surrounding areas, and to build modern irrigation systems to reduce water losses. Currently, water intakes are carried out from downstream of the river throughout the year. In the villages located here, the drinking water supply of the population is provided through modular water treatment facilities. Average monthly water withdrawal for municipal use is approximately 360 m^3/day [22]. The water source of these facilities is the canals drawn from the Alijanchay. Not only is water taken from the river, but a small amount of treated waste water is also discharged into the river. Thus, in 2014, a complex of waste water treatment facilities was built in the territory of Oguz region, where the Alijanchay flows. Treated water from this facility (3600 m^3/day) is discharged to the Alijanchay. Economic activities affect not only the quantity of the river's flow, but also the quality of the river's waters, the habitants living there, and the ecological status of the river as a whole.

3. Materials and Methods

Information about the water regime and characteristic water discharges of the Alijanchay is based on the observation data of the National Hydrometeorological Service at stationary hydrological stations [23]. Four hydrological stations operated on the river in different years (Figure 1). The first observations were made at the Khaldan station in just two years (1931, 1932). Starting from 1935, Khanabad station was opened and operated until 1957 with some interruptions. Khalkhal station, opened in 1948, was closed in 1957. The data of the Khalkhal station, located in the upper part of the Alijanchay basin, allows us to obtain an idea of the regime characteristics of the river in its natural conditions. The Khaldan and Khanabad stations were later closed due to their location downstream, in the part where the natural regime of the river was disturbed due to the influence of anthropogenic factors. Gayabashi was opened in 1958, but this hydrological station was discontinued in 2013. The main flow characteristics of the Alijanchay River are provided in Table 1.

Table 1. Drainage areas and discharge recorded at the Alijanchay monitoring stations.

Measurement Station	Catchment Area, km^2	Observation Period	Water Discharges, m^{3}s^{-1}		
			Long Term Annual Value	Max Value	Lowest Value
Alijanchay—Khalkhal	66.7	1948, 1950–1957	1.45	9.70	0.26
Alijanchay—Gayabashi	708	1959–1973, 1975–2013	5.52	146	0.12
Alijanchay—Khanabad	1160	1935, 1938–1944, 1948–1957	3.81	62.0	0.26
Alijanchay—Khaldan	1200	1931–1932	2.00	11.2	0.21

Currently, the “Montana” method proposed by Tennant in 1975 is used to quantify the ecological flow in more than 25 European countries [3]. The application of this method is performed using calculations in the following order:

1. Calculations are made for the water management year. The water regime of the river is divided into two equal periods. The first period covers April–September, and the second period covers October–March.
2. Average perennial water discharge is calculated for each calendar month.
3. For each period (April–September and October–March), the multi-year average water discharge is determined separately.
4. For each period, 10, 20, 30, and 40% of multi-year average water discharges are calculated separately.

The values of 10, 20, 30, and 40% of the multi-year average water discharges are compared with the observed water discharges in the corresponding periods of the year, and the ecological condition of the river is evaluated.

The “7Q10” method is used by the U.S. Fish and Wildlife Service and in Massachusetts, Canada (option 7Q20), and Great Britain (option 7Q1), [5]. According to this method, a probability distribution curve of minimum water discharge for 7 days is established, and from this curve, the water discharge with return period in 10 years (supply P = 90%) is determined. The 7Q10 discharge is considered equivalent to an environmental flow.

Estimating environmental flow using a Q95% method, an average duration curve of daily water discharges is established, and the discharge 95% exceedance probability is determined from this curve. Q95% is taken as the quantity of ecological flow [22].

According to Fashevski method, for the annual ecological flow from reservoirs on rivers with an average long-term annual water discharge up to 1 m^3/s the value of the monthly minimum water discharge with 95% exceedance probability and for rivers with an average long-term annual water discharge more than 1 m^3/s the 75% of the monthly minimum water discharge with 95% exceedance probability are taken as the environmental flow. Distribution of annual ecological flow value (volume) by months is determined according to the corresponding distribution of natural annual river flow [15].

Methodology proposed by F.A. Imanov to calculate the ecological flow of mountain rivers is based on the statistical analysis of the average water discharges for each month. Values of ecological flow calculated by this method correspond to the minimum discharge 93.3–97.5% exceedance probability [10].

The "UNDP/GEF Kura 1 project" method is based on the following principles:

1. At least 15 years of hydrological observation data are required.
2. Information about taking water from the river is taken into account.
3. During the observation period, the average quantity of the series of minimum decadal water discharge is taken as extreme minimum water discharge.
4. Environmental flow is calculated separately for each decade.

According to our proposed "holistic" methodology for assessing the environmental flow of the river, the durations of the survival flow, low flow, and high flow periods, as well as the values of water flow corresponding to these periods, were determined [24]. Survival flow is the critical, extremely low flow recommended during a designated drought period.

Seasonal field studies on the river were reviewed and analyzed for this assessment. Four monitoring points were selected from the source of the river to its mouth during additional field research conducted on the Alijanchay in 2018–2020. Water discharge was measured 12 times in different seasons of the year at each of these points, and monitoring was organized on the physico-chemical parameters and hydrobiological indicators of water. Temperature, pH, dissolved oxygen, electrical conductivity, total dissolved solids (TDS), and turbidity were determined using various instruments (Table 1). Water measurements include chemical oxygen demand (COD), biological oxygen demand (BOD_5), dissolved anions and cations, ammonium ions, and suspended substances. These parameters are the most common pollutants of river waters and widely used by most authors for calculation of WQI [25–28]. The results were compared with drinking water requirements. Water samples were collected using long-term sampling devices according to the ISO 5667-6 standard [29]. The turbidity of each water sample was measured immediately using a HACH 2100Q portable nephelometer device (HACH Company, CA, USA). The measurement range of the device is 0–1000 NTU (nephelometric turbidity units), and the measurement accuracy is ±2%. All methods [30–44] used for analysis are provided in Table 2.

Table 2. Methods and equipment utilized in laboratory analysis.

Parameter	Technique	Equipment	Method
pH	Potentiometric	Sartorius DOCU pH-Meter (Sartorius AG, Goettingen, Germany)	ISO 10523:2008 [34]
Turbidity	Nephelometric	HACH 2100 Q (HACH Company, Loveland, CA, USA)	ISO 7027-1:2016 [39]
Conductivity	Conductometric	HACH HQ 430d flexi (HACH Company, Loveland, CA, USA)	ISO 7888:1985 [40]
TDS	Conductometric	HACH HQ 430d flexi (HACH Company, Loveland, CA, USA)	ISO 7888:1985 [40]
Dissolved Oxygen	Optic electrod	HACH HQ 430d flexi (HACH Company, Loveland, CA, USA)	ISO 17289:2014 [37]
Cations	Optical Emission Spectroscopy	ICP-OES Thermo Scientific 7000 (Thermo Fisher Scıentıfıc, Waltham, MA, USA)	ISO 14911:1998 [35]
Anions	Chromatography	Ion Chromatograph DIONEX ICS 5000 (Thermo Fisher Scıentıfıc, Waltham, MA, USA)	ISO 10304-1:2007 [33]
Ammonium	Photometric	HACH DR 3900 (HACH Company, Loveland, CA, USA)	ASTM D 1426 [29]
Nitrate	Photometric	Agilent Technologies Cary 60 UV-Vis (Agilent Technologies, Santa Clara, CA, USA)	SM 4500 NO_3^- B [43]
Chlorides	Titrimetric	Manual titration	ISO 9297:1989 [41]
Sulphates	Turbidymetric	HACH DR 3900 (HACH Company, Loveland, CA, USA)	ASTM D 516-02 [30]
Phosphate	Photometric	Agilent Technologies Cary 60 UV-Vis (Agilent Technologies, Santa Clara, CA, USA)	ISO 6878:2004 [38]
COD	Open reflux titrimetric	Termoreactor ECO-6	ASTM D1252-06 (2020) [31]
BOD	Monometric	WTW Oxitop, Lovibond (Wills Towers Watson plc, London, UK)	EN 1899-1/1998 [32]
Suspended solids	Gravimetric	Filtration Unit	ISO 11923:1997 [36]

Sampling and identification of benthic organisms from the river was organized by taxonomy, species composition, number, and biomass. Species of organisms were determined using several reference books [45–54].

A water quality index (WQI) was used to evaluate the overall water quality status of the Alijanchay River and to evaluate how important parameters affect intended use, primarily as a drinking water supply. The methods used are taken from M. L. Dhumal [55] and determined from nine physico-chemical parameters (pH, TDS, chloride, nitrate, sulphate, fluoride, phosphate, and suspended solids). The WQI was calculated using the Weighted Arithmetic WQI equation through three steps [55]. Each parameter was assigned a unit weight (Wn) factors by using the formula:

$$\mathrm{Wn} = \frac{\mathrm{K}}{\mathrm{Sn}} \tag{1}$$

where

$$\mathrm{K} = \frac{1}{1/\mathrm{S1} + 1/\mathrm{S2} + 1/\mathrm{S3} + +1/\mathrm{Sn}} = \frac{1}{\sum\left(\frac{1}{\mathrm{Sn}}\right)} \tag{2}$$

Sn-Standard desirable value of n-th parameters;

On summation of all selected parameters unit weight factors, Wn = 1 (unity);

Second, the Sub-Index (Qn) value was calculated using the formula:

$$\mathrm{Qn} = \frac{[(\mathrm{Vn} - \mathrm{V_o})]}{[(\mathrm{Sn} - \mathrm{V_o})]} \tag{3}$$

where

Vn—mean concentration of the n-th parameters;

Sn—Standard desirable value of the n-th parameters. Drinking water requirements are used as reference values;

V_o—Actual values of the parameters in pure water (generally V_o = 0 for most parameters except for pH).

$$\mathrm{QpH} = \frac{[(\mathrm{VpH} - 7)]}{[(8.5 - 7)]} \times 100 \tag{4}$$

Third, the overall WQI was calculated combining these two steps, as follows:

$$\mathrm{WQI} = \frac{\sum \mathrm{WnQn}}{\sum \mathrm{Wn}} \tag{5}$$

Calculated WQI was then used to classify beneficial water uses according to the standard ranges provided by Hussain Ali Jawadi et al. [56] and M. L. Dhumal [55].

The computed WQI was classified according to the following ranges shown in Table 3.

Table 3. The standard ranges and water quality status according to the Water Quality Index.

	Ranges	**Water Quality Status**
WQI	0–25	Excellent Water
	26–50	Good Water
	51–75	Poor Water
	76–100	Very Poor Water
	>100	Unsuitable for drinking

To assess the condition of benthos at monitoring stations in the river, two primary methods were employed: the Woodiwiss Biotic Index Score [57] and the saprobity system [58]. The Biotic Index Score was used to calculate the biotic index for each research period at selected stations. Meanwhile, the saprobic system identified saprobic zones, which varied according to the level of pollution.

To apply a holistic environmental flow assessment, information on water use in the Alijanchay basin was collected through meetings with representatives of local municipalities and organizations responsible for drinking water supply and irrigation water distribution, and a survey was conducted among the population of the villages located along the rivers.

4. Results and Discussion

The Kura II project, entitled "Development of Integrated Water Resources management (IWRM) through the implementation of transboundary agreed activities and national plans in the Kura river basin", was implemented in 2018–2020 and applied a methodology based on holistic (integrated) approach to assess the environmental flow in the Alijanchay River basin [24]. The ecological status of the river in this project was classified according to these guidelines as "good" using holistic methodology, and the ecological regime of the flow consists of three components:

1. The flow volume ensuring the existence of river fauna. This flow volume is taken as the minimum daily water discharge observed in the driest years.
2. Low water periods. This volume of flow is necessary to maintain indicator species and their habitats, ecological processes, and important social and cultural functions. The duration of the low water flow should be one to six months and be provided continuously throughout the year.
3. Maximum water discharge with a duration of at least 5 days. These water inflows are necessary to maintain the morphology of the riverbed and ecosystems of the river basin. The recommended regime of environmental flow is given in the conclusion.

Information on the characteristics, general ecological condition, and recommended environmental flow regime at each of the monitoring points of the studied river is presented below, starting furthest upstream.

At the Khal-Khal monitoring point, the river runs in a wide valley and consists of a large gravel bed in a main wandering single channel, splitting into several channels in some seasons. The riverbed is bordered by riparian wooded buffer that covers part of the floodplain. Except for COD, most of the physico-chemical parameters of water quality are within the permissible limit of concentration according to drinking water standard AZS929:2023 [59]. For example, the concentration of ammonium, which may be an indicator of organic pollution by municipal wastewater, as well as biodegradable organic matter, in the water is very low (2 mg/L of BOD_5) (Table 4). Chemical oxygen demand exceeded 10 mg/L in a few samples, and the generally low concentration of nutrients (NO_3 and PO_4) suggests a classification in good state.

Table 4. Physico-chemical parameters of water at Khalkhal monitoring point.

Physico-Chemical Parameters	Average	Min	Max
Dissolved oxygen, mg/L	9	7.54	11.07
Total Dissolved Solids, mg/L	165	114	195
Turbidity, NTU	143	1.97	990
pH	8.20	7.60	8.49
Conductivity, µs/sm	323	228	386
Temperature, C	19.3	8	28.6
Ammonium (NH_4^+), mg/L	<0.02	<0.02	<0.02
Fluoride (F^-), mg/L	0.13	0.09	0.15
Chloride (Cl^-), mg/L	4.29	<3	7.1
Nitrite (NO_2^-), mg/L	<0.03	<0.03	<0.03
Bromide (Br^-), mg/L	<0.05	<0.05	<0.05
Nitrate (NO_3^-), mg/L	2	0.9	3.1
Sulfate ($SO4^{2-}$), mg/L	51.25	30	72.5
Phosphate (PO_4^{3-}), mg/L	<0.04	<0.04	<0.04
COD, mg O_2/L	20	<5	48.3
BOD_5, mg O_2/L	4	2	19.8
Suspended solids, mg/L	99	<2	710

The number of benthic species observed in this section of the river ranges between 9 (during cold months) and 54 (July 2019). In the spring and autumn season, 10–15 benthic species were detected. The benthic biomass increases during late spring and summer months. Only once (August 2020) were juveniles found of one fish species (Catfish—*Siluris glanus*). Based on these data, the state of the benthic environment was assessed by months. Considering that the low species richness is recorded in cold months (from October to March), the condition of this section of the river could be classified as moderate state.

According to the protocol proposed by the EU Kura TACIS project, the hydromorphological state (the state of the natural riverbed, objects of anthropogenic origin, etc.) of Alijanchay at the Khalkhal monitoring point was classified as being in a *high state* [60]. Thus, the results of the analysis of three different groups of quality elements (physico-chemical parameters, the number of species of benthic invertebrates, hydro-morphological elements) were synthesized, and the ecological status of Alijanchay at the Khalkhal monitoring point was classified as being in a moderate state. The high flow period of the water regime of the river falls in April through June. According to the available data of hydrological observations, the average monthly water discharge during this period ranges from 0.90–2.40 m^3s^{-1}, the maximum water discharge is 25.0 m^3s^{-1}, and the minimum water discharge is 0.30 m^3s^{-1} in January and February. During two monitoring periods on 19 January and 7 March 2020, it was found that the riverbed was dry at the upstream Khalkhal monitoring point (Figure 1). Based on a simple hydrologic assessment, the seasonal water flows were determined (Table 5) and are shown in Figure 2.

Table 5. River discharge of the environmental flow regime at Khalkhal monitoring point.

	Survival Flow		
Period	Effective dates	Discharge (m^3s^{-1})	Discharge of relevant duration
Annual	Jan–Dec	0.10	Q_{355}
	Low flow periods		
Criterion	Effective dates	Discharge (m^3s^{-1})	Discharge of relevant duration
Habitat maintenance for benthic fauna and plant community	Jun 15–Aug 31	1.20	Q_{270}
	High flow events		
Motivation	Timing	Duration	Magnitude
Floodplain flooding	(Feb 15–Apr 15)	5 days 1 day	>15.0 m^3s^{-1} >20.0 m^3s^{-1}

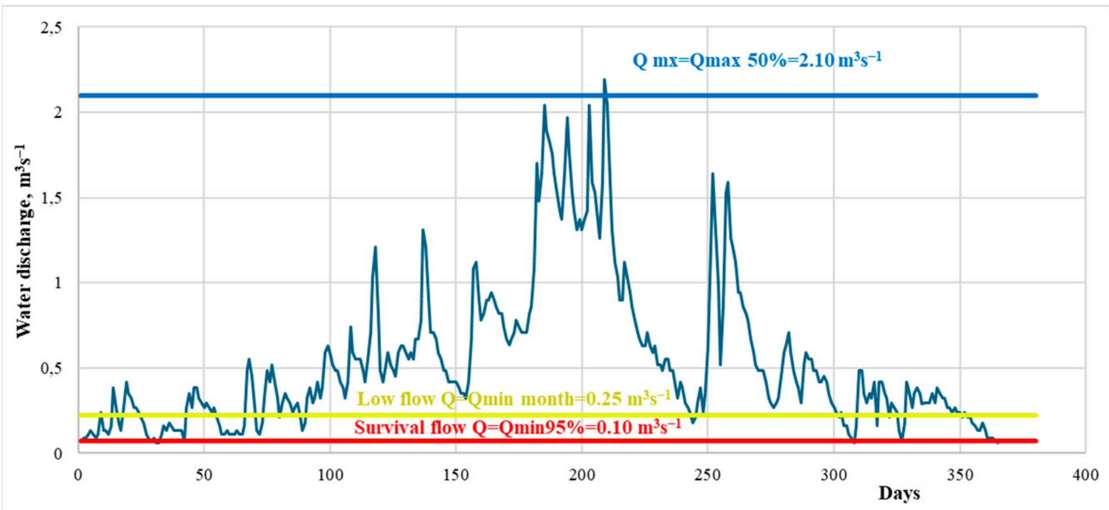

Figure 2. Environmental flow regime at Khalkhal monitoring point.

At the Chaygovushan monitoring point, the riverbed is composed of sand and gravel deposits and a meander is formed in this part of the river. Just below the monitoring point, there are two drinking water intakes and an irrigation canal. The physico-chemical parameters of water quality do not change significantly from the corresponding indicators at the Khalkhal monitoring point located upstream of the river (Table 6), and in Chaygovushan, the water quality is classified as "good" for drinking water.

Table 6. Physico-chemical parameters of water at Chaygovushan monitoring point.

Physico-Chemical Parameters	Average	Min	Max
Dissolved oxygen, mg/L	10.7	8.42	12.69
Total Dissolved Solids, mg/L	289	197	367
Turbidity, NTU	262	4.13	>2000
pH	8.12	7.72	8.40
Conductivity, µs/sm	557	404	722
Temperature, C	17	6	29.5
Ammonium (NH_4^+), mg/L	<0.02	<0.02	<0.02
Fluoride (F^-), mg/L	0.14	0.13	0.17
Chloride (Cl^-), mg/L	10.93	4	18
Nitrite (NO_2^-), mg/L	0.03	<0.03	0.06
Bromide (Br^-), mg/L	<0.05	<0.05	<0.05
Nitrate (NO_3^-), mg/L	2	1.06	5.6
Sulfate ($SO4^{2-}$), mg/L	98	8	125.3
Phosphate (PO_4^{3-}), mg/L	0.46	<0.04	6.28
COD, mg O_2/L	22	<5	91.4
BOD_5, mg O_2/L	3	2	3
Suspended solids, mg/L	130	<2	1268

The number of benthic species recorded at the Chaygovushan point ranges from 15 (in cold months) to 68 (July, 2019). A large number of baby fish (Catfish—*Siluris glanus*, Carp—*Cyprinus carpio*, and Barbel—*Barbus lacerta*) were collected. The condition of the benthic environment was assessed by months; then, these data were summarized, and the state of the water body was classified as being in a moderate state. The hydro-morphological state of the river section was classified as "*good*" [60]. Thus, the ecological status of the river at the Chaygovushan monitoring point was classified as being in a moderate state by synthesis of various qualitative elements. The water discharge measured during the field studies ranged from 0.30 to 3.50 m^3/s. The designed water discharge of the recommended regime of environmental flow was calculated (Table 7; Figure 3).

Table 7. Water discharge of the environmental flow regime at Chaygovushan monitoring point.

Survival Flow			
Period	Effective dates	Discharge (m^3s^{-1})	Discharge of relevant duration
Annual	Jan–Dec	0.70	Q355
Low flow periods			
Criterion	Effective dates	Discharge (m^3/s)	Discharge of relevant duration
Habitat maintenance for benthic fauna and plant community	Jun 15–Aug 31	3	Q270
High flow events			
Motivation	Timing	Duration	Magnitude
Floodplain flooding	(Feb 15–Apr 15)	5 days 1 day	>15 m^3s^{-1} >20 m^3s^{-1}

At the Turan monitoring point, the river has formed two terraces. The floodplain has several manmade ponds, gardens, and fields. There is a slight increase in the concentration of BOD_5 and NO_3 in the water content, and the water quality in this point could be classified as moderately good according to the physicochemical parameters (Table 8).

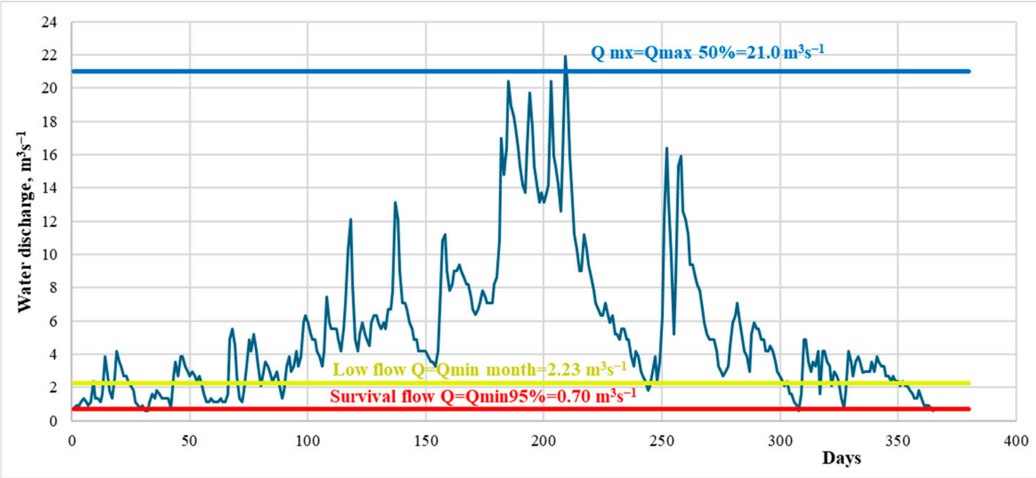

Figure 3. Discharge regime at Chaygovushan monitoring point.

Table 8. Physicochemical parameters of water at Turan monitoring point.

Physicochemical Parameters	Average	Min	Max
Dissolved oxygen, mg/L	10	8.22	11.77
Total Dissolved Solids, mg/L	537	200.4	673
Turbidity, NTU	1756	1.91	>2000
pH	806	7.77	8.48
Conductivity, µs/sm	1057	399	1346
Temperature, C	19.8	11	29
Ammonium (NH_4^+), mg/L	<0.02	<0.02	<0.02
Fluoride (F^-), mg/L	0.14	0.09	0.17
Chloride (Cl^-), mg/L	38.4	6	56
Nitrite (NO_2^-), mg/L	0.08	<0.03	0.60
Bromide (Br^-), mg/L	0.05	<0.05	0.07
Nitrate (NO_3^-), mg/L	17.8	3.4	24.4
Sulfate ($SO4^{2-}$), mg/L	314	81	478
Phosphate (PO_4^{3-}), mg/L	0.46	<0.04	0.57
COD, mg O_2/L	26	<5	98
BOD_5, mg O_2/L	3	2	5
Suspended solids, mg/L	325	<2	3600

In this part of the river, the benthic state was classified as “good” more often (6 times) during the year. Considering that the benthic community is judged between high and good during summer months of the year, the state of the river at the Turan monitoring point could be classified between a good and moderate state. In general, the ecological status of the river at the Turan monitoring point was classified as being in a moderate state. The natural flow regime at the Turan and Salamabad monitoring points of the Alijanchay is similar to the regime at Chaygovushan, which is located upstream of the river and is the closing point of the flow formation zone. Above both the Turan and Salamabad monitoring points, water is taken from the river for irrigation purposes. Considering the recommended specific water discharge and the regime of environmental flow, monitoring points were adopted in Turan and Salamabad as in Chaygovushan.

At the Salamabad monitoring point, the Alijanchay has a large floodplain near Salamabad village located downstream. The increase in water content of the river is clearly shown. Water quality was classified as moderate state according to physicochemical parameters (Table 9).

Table 9. Physicochemical parameters of water at the Salamabad point.

Physicochemical Parameters	Average	Min	Max
Dissolved oxygen, mg/L	9.67	8.22	11.19
Total Dissolved Solids, mg/L	491	274	679.5
Turbidity, NTU	250	3.98	>2000
pH	8.06	7.72	8.35
Conductivity, µs/sm	908	542	1359
Temperature, C	19.9	9.6	30
Ammonium (NH_4^+), mg/L	<0.02	<0.02	0.04
Fluoride (F^-), mg/L	0.16	0.14	0.18
Chloride (Cl^-), mg/L	52	14.2	85
Nitrite (NO_2^-), mg/L	0.06	<0.03	0.34
Bromide (Br^-), mg/L	0.05	<0.05	0.08
Nitrate (NO_3^-), mg/L	5.1	2.1	6.8
Sulfate ($SO4^{2-}$), mg/L	268	85.2	390
Phosphate (PO_4^{3-}), mg/L	0.47	<0.04	0.8
COD, mg O_2/L	24	<5	91
BOD_5, mg O_2/L	4	2	12.1
Suspended solids, mg/L	241.5	<2	1920

Compared to the most upstream monitoring points, there is a sharp decrease in the number of benthic species, which ranges between 2 (during cold months) and 28 (in June 2019). The general condition of the benthic community of the river at the Salamabad monitoring point was classified as being in a poor state. Taking into account all three groups of quality elements (physicochemical parameters, the number of benthic invertebrates, and hydro-morphological elements), the ecological status in the considered section of the river as a whole was classified as being in a poor state. In the considered holistic method, the water discharges corresponding to all three components determining the environmental flow regime can be determined from the average daily water discharge curve (Figure 4):

1. The water discharge that ensures the existence of river fauna—$Q_{95\%}$ or Q_{350};
2. Low water discharge—$Q_{75\%}$ or Q_{270};
3. Maximum water discharge lasting at least 5 days—$Q_{8\%}$ or Q_{30}.

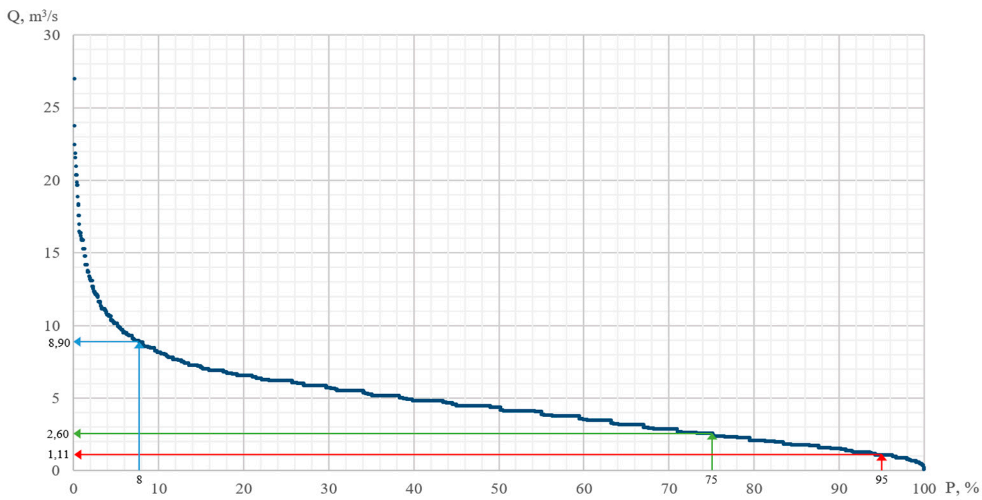

Figure 4. Average duration curve of daily water discharge (Alijanchay—Gayabashı, 2001–2010).

The values of these components for Alijanchay (Gayabashi station) are 1.11 (red line), 2.60 (yellow line), and 8.90 (blue line) m^3/s, respectively (Figure 4). When calculating the annual volume of environmental flow by taking these water discharges into account, 48.24 million m^3 is obtained, which constitutes 27.7% of the average annual flow volume of the river (174 million m^3).

The environmental flow of Alijanchay (Gayabashi station) was calculated by six different hydrological methods [20].

The values of environmental flow calculated by different hydrological methods range between 23.7 and 47.2 million m^3 or from 13.6 to 32.9% of the annual flow volume (Table 10). In 2010, an agreement was reached between Azerbaijan and Russia on the allocation of water resources of the Samur River. According to this document, the volume of environmental flow was accepted as 30.5% in years with 75–95% exceedance probability. The volume of the environmental flow of Alichanchay determined by the holistic method (27.7%) is quite close to this value. Currently, it is impossible to fully apply this holistic method to the majority of Azerbaijan rivers, as there is no required monitoring data on the physicochemical and hydrobiological indicators of water. However, the environmental flow of these rivers can be approximately determined from the curve of the average duration of daily water discharge [61,62]. Compared to many existing hydrological methods, the main advantage of this approach is that the value of environmental flow is calculated not according to a single value of water discharge but according to three different values of water discharges that determine the environmental flow regime.

Table 10. Summary of environmental flow. See [20] and method section for calculation details.

№	Method	Environmental Flow Volume, Million m^3	Percentage in Relation to the Annual Flow Volume, %
1	Montana	37.0	21.2
2	7Q10	39.7	22.8
3	Q95%	47.2	27.1
4	Fashevsky	23.7	13.6
5	Imanov	37.2	21.5
6	UNDP/GEF Kura 1 project	32.4	18.6
7	Holistic	48.2	27.7

5. Water Quality Indices (WQI)

In addition to determining environmental flow, a Water Quality Index (WQI) was used to evaluate the water quality status of the Alijanchay. Different types of WQI calculations were reviewed [55,56] and calculated using the Weighted Arithmetic WQI equation. Seasonal results of WQI for four sample points—Khalkhal, Chaygovushan, Turan, and Salamabad—are presented in a graph (Figure 5).

The calculated WQI value, water quality status, and percentage of different statuses of water are presented in Table 11. According to the data, the WQI ranges from 25 to 132. Excellent quality status (14%) of sampled water occurs in the upper stream of the Alijanchay River (Khalkhal). Winter and autumn river water composition produces most of the excellent status in Khalkhal. Approximately 56% of the sampled water was found to rank as excellent, and 19% of seasonal samples were found to be of good quality based on this index. Poor and very poor quality show the same percentage (6%), while 13% of the sampled water was unsuitable for drinking quality condition. Unsuitable WQI for drinking waters occurred in the downstream station on the Alijanchay River in spring, which can be explained by the flow of substances along the river and because of the high river flow.

Based on WQI calculations shown on the above table, 56% of the measurements were classified as excellent, 19% are good, 6% are poor, and 6% are very poor conditions. Only 13% of WQI values were found to be unsuitable for drinking water conditions.

A Pearson's correlation matrix was built between the WQI and water quality parameters. The matrix is a very good tool to see the strength of linear relations between two different values. The correlation can be positive or negative. The higher the nominal value, the stronger the relationship.

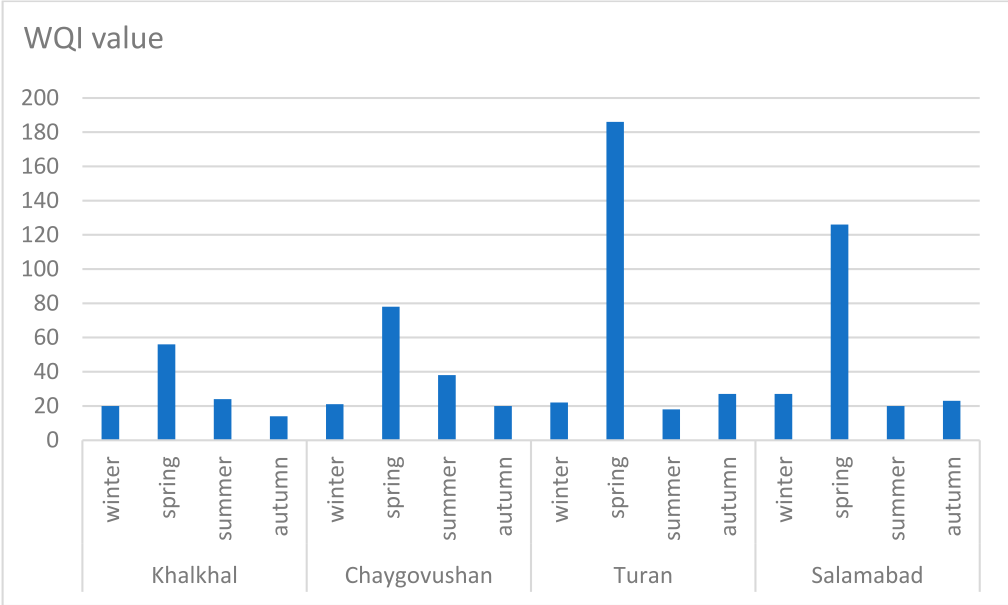

Figure 5. Seasonal WQI variation for 4 sample points.

Table 11. WQI results in different seasons for all sample points.

Sample Points	Season	WQI	Water Quality Status
Khalkhal	winter	20	Excellent
	spring	56	Poor
	summer	24	Excellent
	autumn	14	Excellent
Chaygovushan	winter	21	Excellent
	spring	78	very poor
	summer	38	Good
	autumn	20	Excellent
Turan	winter	22	Excellent
	spring	186	unsuitable for drinking
	summer	18	Excellent
	autumn	27	Good
Salamabad	winter	27	Good
	spring	126	unsuitable for drinking
	summer	20	Excellent
	autumn	23	Excellent

The correlation coefficient has a value between +1 and −1, where ±1 refers to a perfect, r > 0.9 to a strong, and r > 0.8 to a moderate linear relationship between the two variables. Table 12 shows the correlation matrix of different parameters with WQI. We used winter results for correlation because we obtained more stable results during winter. Turbidity, TSS, and anions such as sulphate and chloride show a strong correlation with WQI. The other parameters, like conductivity, TDS, and nitrate, have a good positive correlation with the WQI. Dissolved oxygen, conductivity, and TDS have a strong negative correlation with temperature. Conductivity and TDS have a very strong correlation (r = 1). TSS has a strong correlation with turbidity (r = 0.969). Sulphate has a strong correlation with turbidity (r = 0.965) and TSS (r = 0.974). Chloride correlates with turbidity (r = 0.969), TSS, (r = 0.985) and sulphate (r = 0.998).

Table 12. Correlation coefficient matrix of physico-chemical parameters of Alijanchay River water samples.

Variables	Temp	pH	DO	EC	TDS	Turbidity	TSS	SO_4^{2-}	Cl^-	NO_3^-	F^-	COD	WQI
Temp	1	0.776	**−0.923**	**−0.994**	**−0.992**	−0.569	−0.755	−0.688	−0.711	−0.618	−0.207	−0.385	−0.729
pH		1	−0.8754	−0.783	−0.788	−0.503	−0.626	−0.712	−0.697	−0.248	−0.778	−0.840	−0.656
DO			1	0.890	0.887	0.311	0.522	0.511	0.520	0.275	0.433	0.671	0.514
EC				1	**1.000**	0.654	0.821	0.760	0.782	0.683	0.225	0.361	0.799
TDS					1	0.668	0.831	0.773	0.794	0.688	0.237	0.365	0.810
Turbidity						1	**0.969**	**0.965**	**0.969**	0.883	0.229	0.026	**0.975**
TSS							1	**0.974**	**0.985**	0.897	0.231	0.124	**0.996**
SO_4^{2-}								1	**0.998**	0.786	0.431	0.280	**0.989**
Cl^-									1	0.816	0.385	0.246	**0.996**
NO_3^-										1	−0.218	−0.313	0.863
F^-											1	**0.913**	0.303
COD												1	0.176
WQI (Winter)													1

Note: Coefficients with strong correlations (r > 0.9) are marked bold.

6. Conclusions

Based on the results of our comprehensive study carried out at four monitoring stations in the Alijanchay River basin, a holistic method for assessing the environmental flow of the river has been developed. In each of the four monitoring points located from the source to the mouth of the river, using data on hydro-morphology, hydrological regime and characteristic water flows, physicochemical parameters of river water, hydrobiological indicators, and data on water intakes from the river, an assessment of the ecological status of the river was carried out. To maintain a good ecological status of the river, a scheme for determining the amount of environmental flow, which has three components, is proposed. For the river section where the dam of the designed reservoir will be built, the amount of environmental flow according to the proposed method is 27.7% of the annual river flow. Considering the importance of the projected reservoir for the development of agriculture in the arid climate of Azerbaijan, the value of the environmental flow of the Alijanchay River was also calculated using various hydrological methods, ranging from 13.6 to 32.9% of the annual flow volume. Considering the value of a holistic method, it is recommended to use a river's environmental flow calculated using this method whenever possible. While the lack of data on hydrobiological indicators of other rivers makes the application of the proposed method difficult, it may be applied by comparison to similar watersheds and climates. The natural regime of many rivers occurring in the mountainous part of the basin is very similar, and the major downstream use is for agriculture. Determining each component of the environmental flow, it is possible to approximately estimate its value. Moreover, application of a WQI to describe the quality of river water provides an understanding of the most significant impairments and projections for future uses such as drinking. Based on physical chemical results and calculated WQI, it is observed that the quality of the Alijanchay River changes spatially and seasonally. Overall quality is excellent upstream in winter and impaired downstream in spring. Poor water quality is observed in all points during spring, coinciding with increased discharge and erosion. According to the results of this analysis, the total suspended solids most influenced the water quality status during high flow in late spring. Overall water quality was best in winter because of snow melt and low sediment content. All these factors were temporary and impacted water quality seasonally. Overall, this assessment shows the quality of this important tributary decreases from upstream to downstream. Correlations between WQI and other parameters are a good tool to see the relations of monitored parameters. Currently, the holistic method can be applied only for two rivers—the Alijanchay and the Shamkirchay. It is not possible to expand hydrobiology surveys of all rivers in Azerbaijan in the near future, though this is a critically important function of these rivers. Where there is information about water flow for other rivers, corresponding calculations can be performed using surveys from selected rivers. We propose here that holistic water flow can be calculated and summarized using this approach for other regions.

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