Developing a transboundary groundwater model in the water scarce region of Central Asia: a case study of the Pretashkent Transboundary Aquifer

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MSc Thesis WSE-GW.19-03
01/08/2019

Updated Version, 30/11/2019

Developing a transboundary groundwater model in the water scarce region of Central Asia: a case study of the Pretashkent Transboundary Aquifer

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This thesis is submitted in partial fulfilment of the requirements for the academic degree of

Master of Science in Water Science and Engineering
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Master of Science in Environmental Engineering
Instituto Superior Técnico, Universidade de Lisboa, Portugal

Master of Science in Hydro Science and Engineering
Technische Universität Dresden, Germany

MSc research host institution
IHE Delft Institute for Water Education

August 2019

Chirchik River in Khodzhikent. Source: https://commons.wikimedia.org

Abstract

Due to climate change and increased human impact, water use and protection have become one of the major regional issues in Central Asia. As availability of surface water is decreasing and becoming erratic, the reliance and pressure on groundwater resources are continuously growing. That is also a case with the Pretashkent Transboundary Aquifer (PTBA), located between the Republic of Kazakhstan and Uzbekistan. Groundwater withdrawal from the aquifer is increasing, responding to high demand for water supply and irrigation. Aquifer-sharing countries have started dialogue about water policy and management tools for the PTBA, including development of an operational numerical model. This model is required for better understanding of the aquifer dynamics.

The aim of this research was to develop a test conceptual hydrogeological and a test numerical model of the PTBA based on available data. The model allowed to assess the presence of cross-border groundwater flow, estimate the potential amount of groundwater in the system and analyse the possibility of brackish/saline water leakage from top layers to the Pretashkent Transboundary Aquifer. The test model does not represent field conditions due to data limitations but serves as an exercise in using modelling software for a complex hydrogeological system.

The model was developed using the Groundwater Modeling System software (GMS). The model input preparation, including transboundary harmonization is conducted using the datasets and information from the Committee of geology and hydrogeology of Kazakhstan and results of the "Governance of Groundwater Resources in Transboundary Aquifers" project (GGRETA). The test conceptual model included the simplification of the groundwater system consisting of 6 layers. The test conceptual model was converted into steady-state numerical model. Due to the lack of data on observation heads, calibration was not implemented. Test of hydrogeological parameters was conducted with increased and decreased values of river and head-dependent boundary conductance as well as assigning head-dependent boundary first for the top layer and then for all layers. Sensitivity analysis of hydraulic conductivity and recharge rates helped to understand the possible behaviour of the aquifer system and its response to changes. It was decided to use reduced conductance for rivers and assign discharge boundary for the first layer only with increased conductance to obtain the results. The test model showed that groundwater circulation consists of downward and upward flows in the system. Downward flow dominates in higher elevation where hydraulic heads vary from 410 till 650 m. The upward flow was detected in lower elevation with heads reaching 350 m, especially in discharge zones to rivers. The predicted total amount of groundwater inflow in the system is 1,849,949.9 m^3/day. Recharge in the inflow (97.5% of contribution to the total inflow) and river leakage in the outflow (61.0% of contribution to the total outflow) are two main terms of the flow budget. 662,119.4 m^3/day flows from Uzbekistan to Kazakhstan and 249,554.0 m^3/day from Kazakhstan to Uzbekistan in the PTBA system. The test model confirmed the presence of the transboundary groundwater flow. Two wells, namely 48(11tn) and 43(7tn), on the territory of Kazakhstan might abstract groundwater flowing from Uzbekistan. The simulation of saltwater leakage potentially predicted decrease of groundwater quality in the PTBA in 488 years.

The application of the test model can be considered for further development of an advanced model for the PTBA and its management. The test model presented major processes in the aquifer system and potential risks.

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Abbreviations

CA – Central Asia

DA - the Draft Articles on the law of transboundary aquifers

DEM – Digital Elevation Model

EIA – Environmental impact assessment

GDP – Gross domestic product

GGRETA – Governance of Groundwater Resources in Transboundary Aquifers (Project)

IGRAC - International Groundwater Resources Assessment Centre

NGO – Non-governmental organisation

PTBA – Pretashkent Transboundary Aquifer

RK – Republic of Kazakhstan

RU – Republic of Uzbekistan

TWAP – The Transboundary Waters Assessment Programme (TWAP)

UNESCO – The United Nations Educational, Scientific and Cultural Organization

UNWC – The Convention on the Law of the Non-Navigational Uses of International Watercourses

Chapter 1   Introduction

1.1 Background

Water scarcity is one of the most serious problems worldwide, affecting all the sectors of human activities and the environment (Declaration, 2006; Ratnayaka et al., 2012). With the growth of population, it is getting more and more challenging to satisfy increased water demand, including domestic water supply, agriculture and industry. It is expected that the number of people on the planet will grow from 7.7 billion in 2019 to 8.5 billion in 2030. However, the rate will vary from region to region. In Central and Southern Asia, the population is predicted to increase by 25% (UN-Habitat, 2019). In the last century, water use has been growing at more than twice the rate of population increase (Declaration, 2006). Next to human activities, climate change increases the stress on groundwater in some parts of the world, including Central Asia.

Groundwater makes up the largest resource of fresh water in the world (Howard, 2015). Groundwater provides almost half of the world population with drinking water (IGRAC, 2018; Margat and Van der Gun, 2013; Zhou, 2009). Groundwater systems deliver a variety of services to support and advance human well-being (Daily, 1997). The Millennium Ecosystem Assessment divides groundwater services into four groups:

1. Provisioning services – water for domestic, agricultural and industrial purposes, geothermal water for energy;
2. Supporting services – springs, baseflow of streams, sustaining wetlands, subsurface microbes;
3. Regulating services – buffering floods and droughts, dry and wet seasons, water purification;
4. Cultural services – mineral water, hot springs for recreation (MEA, 2005).

Expressing groundwater through the services increases the awareness of the benefits we receive from this precious natural resource (Griebler and Avramov, 2014). Sustainable use of groundwater services asks for adequate management to prevent depletion of aquifers and degradation of their quality. Challenges such as fragmented management responsibilities, centralised decision-making, lack of capacity and insufficient valuation of groundwater hamper groundwater management (Chen et al., 2018; Knueppe, 2011). When aquifers are shared between two or more states, their management becomes even more challenging, especially in arid and semi-arid regions.

Goal 6.5. of the United Nations 2030 Agenda for Sustainable Development is dedicated to the implementation of integrated water resources management at all levels, including transboundary cooperation. Indicator 6.5.2. specifically addresses transboundary water cooperation. The following criteria define operational cooperation:

- Existence of a Joint body for transboundary cooperation;
- Regular and formal communication between riparian states;
- Joint management plans or objectives;
- Regular exchange of data and information.

The Goal is reached only when all four criteria are satisfied. Every three years countries should monitor and report the data related to the indicator 6.5.2. (UN Water, 2017).

Responding to the need to improve transboundary groundwater management, a project "Governance of Groundwater Resources in Transboundary Aquifers" (GGRETA) was set up in 2013, supported by Swiss Development Cooperation and executed by UNESCO-IHP and IGRAC with the engagement of national and regional specialists across three continents (UNESCO-IHP, 2016). Capacity building, exchange of knowledge and technical support were the scope of the project. The Pretashkent aquifer, shared between the Republic of Kazakhstan and Uzbekistan, was one of the three pilot cases in the project. The first phase of it was conducted from 2013 till 2015, and the very first steps were made towards building trust and cooperation between the aquifer countries. The meetings within the project brought stakeholders together acknowledging the risk of aquifer overexploitation.

The Pretashkent Transboundary Aquifer (PTBA) is one of transboundary aquifers located in the Aral Sea Basin in Central Asia. The region is landlocked, and it is not receiving enough moisture from the oceans, turning the climate into arid and semi-arid (Zhou et al., 2019). In recent years, water use and protection have become one of the major issues in Central Asia (CA) (Yarullina, 2011). Wada and Heinrich (2013) also confirmed the status of the PTBA being overexploited, showing the increase in stress of 100 – 250 % from 1960 till 2010; the aquifer stress indicator was estimated using data on groundwater abstraction, natural groundwater recharge, additional recharge from irrigation as return flow and groundwater contribution to environmental flow. Further, there were monitoring records reported of significant lowering of groundwater head in the aquifer.

With the growth of population, Kazakhstan and Uzbekistan are challenged by rapid depletion of groundwater resources. Moreover, climate change and increased human activities could easily cause significant ecosystem changes or even ecological disasters deeming their fragility in arid and semi-arid regions more pertinent (Levintanus, 1992). Uneven distribution of water resources in the region creates competition between upstream and downstream countries. This adds to difficulties in the assessment and management of the PTBA (Chalov and Gunin, 2013).

The hydrographic networks in the countries are unevenly distributed and (in particular in the Republic of Uzbekistan) only a limited amount of the water resources are formed within the country. This is one of the reasons that the industry in Uzbekistan focuses more on groundwater. Abstracted groundwater resources are mainly used for drinking water supply and irrigation, 40% and 25% respectively (Khidirov, 2016). In Uzbekistan, the PTBA is located in the Tashkent region, where the population reached 2.48 million people in 2018[1], with intensive agricultural and industrial production. In Kazakhstan, the PTBA is located in the Turkestan administrative region. In terms of surface- and groundwater resources, this is the most favourable part of the Republic: 55% of groundwater resources in the country are concentrated here, being mainly used for drinking water supply (Veselov et al. 1999). Without cooperation

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[1] https://www.uzdaily.uz/en/post/44755

between aquifer states on use and protection of the PTBA, the future of groundwater resources in the region (and those who depend on those resources) cannot be secured.

1.2 Problem statement

The last groundwater storage revaluation of the Pretashkent Transboundary aquifer was conducted in 1982-1983 by the Ministry of Geology of the USSR. Based on this work, the safe yield was divided between Kazakhstan and Uzbekistan, 1,464 m^3/day and 2,044 m^3/day, respectively. Till 1991, the water supply companies of the two countries applied the agreed yield limits in their operations or their discharge control. However, after the disintegration of the Soviet Union when two states gained their independence, any mechanism of control and enforcement disappeared.

In the first phase of the GGRETA Project, the technical report of the Pretashkent aquifer was produced. It included the assessment of the aquifer and development of a conceptual model for the Kazakhstani part only.

The management of transboundary groundwater resources is not possible without jointly agreed actions from both parties. The initial development of a common conceptual and numerical model of the aquifer could motivate decision-makers and groundwater authorities to continue the work by establishing long-term cooperation and continuous data exchange. Once developed, the model will help to understand better the aquifer dynamics and assist the water policy and management decisions. These were the main incentives for the research described in this document.

1.3 Research questions and objectives

This research aims to develop a test conceptual hydrogeological model and steady-state numerical model for the Pretashkent Transboundary aquifer, considering the growth of the population, economic development, and its importance in a water-scarce region of Central Asia. Specific tasks were designated to achieve the main objectives of the research:

- To classify aquifers and aquitards in the system of the Pretashkent Transboundary aquifer;
- To analyse flow patterns in the aquifer between Kazakhstan and Uzbekistan and the resulting groundwater-surface water interactions;
- To assess possible leakage of brackish groundwater from top aquifers;
- To estimate water balance;
- To analyse legal and policy aspects of transboundary groundwater management.

The tasks help to answer research questions as follows:

- Is there any transboundary groundwater flow?
- Is there any effect of leaking brackish groundwater from top layers to the Pretashkent Transboundary Aquifer?
- How much water is flowing to the PTBA?

1.4 Outline

The Thesis consists of seven Chapters:

Chapter 1 introduces the background information and motivation for building the test conceptual and numerical model of the PTBA.

Chapter 2 provides aquifer details including physiography and climate, aquifer geometry and hydrogeological characteristics. It also briefly assesses environmental and socio-economical aspects, including the comparison of legislation in groundwater management of Kazakhstan and Uzbekistan.

Chapter 3 presents the research methodology, modelling environment and data collection.

Chapter 4 introduces the development of the groundwater flow model.

Chapter 5 describes the results and analysis of the model.

Chapter 6 discusses data limitations, model uncertainties, addresses quantitative and qualitative assessment of the transboundary groundwater resources.

Chapter 7 concludes the main points and provides recommendations for the future.

Chapter 2   Study Area

2.1 Location

The Pretashkent Transboundary Aquifer (PTBA) is shared between the southern part of Kazakhstan and the north-eastern part of Uzbekistan. The total area is 17,000 km^2; 10,840 km^2 on Kazakhstani and 6,160 km^2 on Uzbekistani territory (UNESCO IHP, 2016). The range of coordinates is 12411230 – 12594570E and 4523030 – 4679470N, Pulkovo 1942/Gauss-Kruger zone 12, *Figure 2.1.1*.
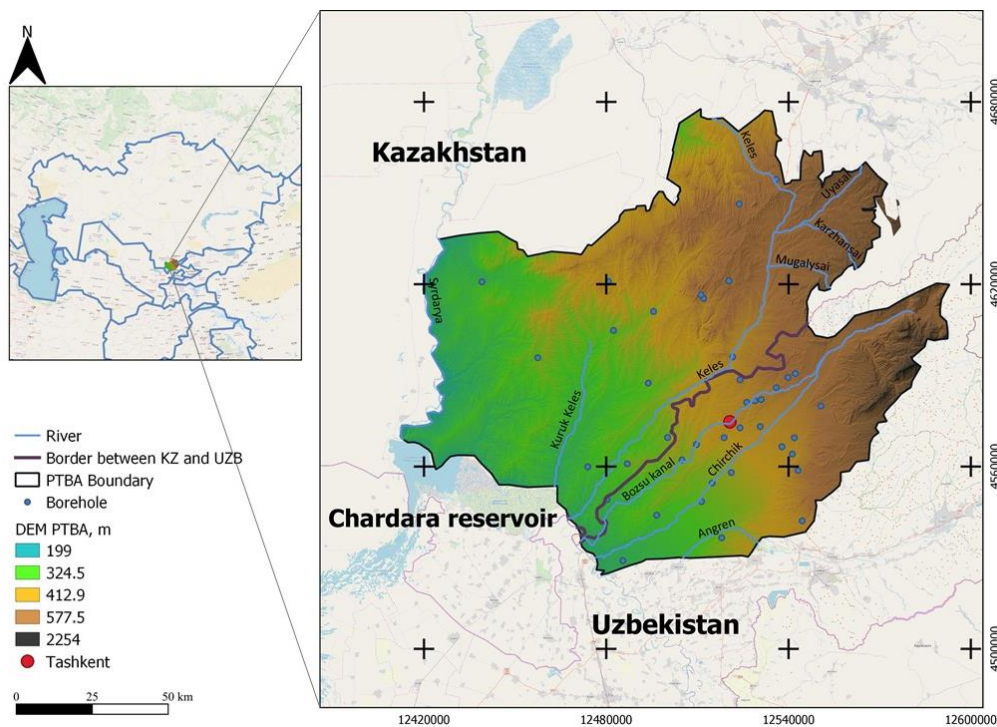
Figure 2.1.1 Location of the Pretashkent Transboundary Aquifer

2.2 Physiography and climate

2.2.1 Topography

The Pretashkent submontane trough is located between Chatkal and Kuramin ranges in the north-east part of the PTBA, where the maximum elevation is 2305 m (above MSL). In the south, the boundary is closed with Turkestan and Nuratin ranges, 400 – 1000 m. River valleys of Syrdarya, Keles and Chirchik decrease from 382 till 177 m ('Hydrogeology of the USSR, Volume XXXIX Uzbek SSR', 1972). The steepness of the slopes increase from south-west to the north-east, from 0 to 28.8 degrees, *Figure 2.2.1* Only in the south-eastern part of the aquifer where elevation goes up to 2254 m, the slopes are around 40 degrees.
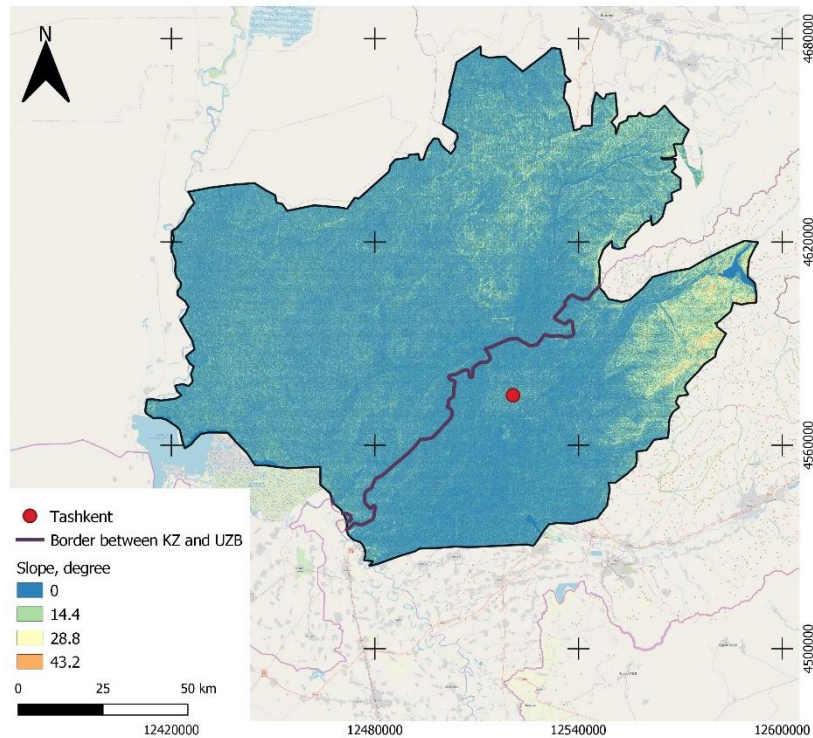
Figure 2.2.1 Slope map of the PTBA

2.2.2 Temperature

Summers are hot with average temperatures ranging between $25^{\circ} – 30^{\circ}$C. Winters are relatively warm, -4° to 0°C (UNESCO IHP, 2016). Monthly average temperatures of the station UZM00038457 in Tashkent (NOAA Climate Data Source) for a period from 1980 till 2017 indicate 6.8°C for January and December and 23.7°C for June, *Figure 2.2.3*. However, Yao and Chen (2015) state there is an increasing trend in annual temperature of 0.14°C/decade. Late research also concluded the temperature rise in Central Asia is occurring faster than the global average (Yu et al., 2018).
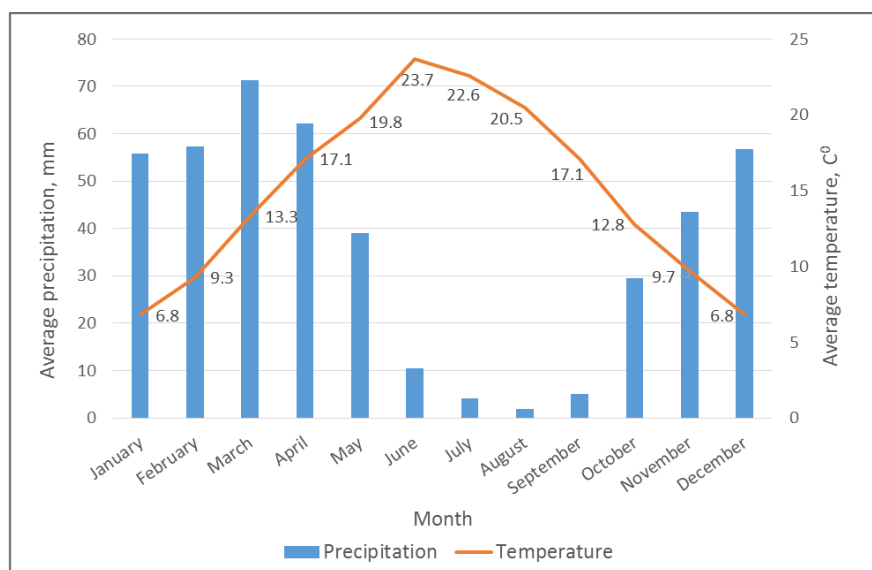
Figure 2.2.2 Average monthly temperatures from 1980 till 2017 and precipitation from 1963 till 2005 in Tashkent

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2.2.3 Precipitation and evaporation

Rainfall generally occurs from November till May. In winter, it mostly falls in solid forms. The values depend on the elevation, from 400 – 600 mm/year in the mountains of Ugam Range in the east of the aquifer till 200 – 350 mm/year in the south-west and the west of the aquifer. Precipitation deficit happens mostly during the summer (Klein et al., 2012; UNESCO IHP, 2016). Actual evapotranspiration defined by the operational Simplified Surface Energy Balance (SSEBop) model varies between 0 till 750 mm/year, changing from south-west to north-east in descending order (Senay et al., 2011).

2.2.4 Land use

On the territory of Kazakhstan 10,027 km^2 (92.5% of the PTBA land) is agriculture land. The land use consists of 74.7% of pasture, 20.9% of irrigated land, 3.4% of hayfield, 1% of perennial crops (UNESCO IHP, 2016). In Uzbekistan, 334.8 km^2 (5.43 %) is an urban area; other major type is agriculture with irrigated land, arable land, grassland and forest (Usmanov et al., 2016).

2.2.5 Surface water network

Three rivers and one irrigational canal are dominant on the territory of the Pretashkent Transboundary Aquifer, namely Syrdarya in the west, Keles, Chirchik, and Bozsu canal in the middle. Chirchik river and Bozsu canal flow on the territory of Uzbekistan only, Keles – on the territory of Kazakhstan, and Syrdarya is a transboundary river. Minor rivers are tributaries of Syrdarya and Keles.

- Syrdarya is a snow-fed river. It is the main discharge zone in the region. Maximum discharge is 1160 – 1480 m^3/s in July, the minimum is 315 – 410 m^3/s in January. During low water season, the width varies between 200 – 230 m and depth between 1 – 6 m. The values of salinity change between 700 – 2500 mg/l. The river flow is controlled by three reservoirs, one of them is Chardara reservoir, being the western boundary of the PTBA (Hydrogeology of the USSR, 1972).
- Keles is also a snow-fed river. It starts in Karazhantau mountains and discharges into Syrdarya with the mean annual discharge – 30.44 m^3/s. The salinity varies between 300 and 500 mg/l. Total length is 220 km (UNESCO IHP, 2016).
- Chirchik is snow and glacier-fed river with 161 km of the total length. It starts from Charvak reservoir and discharges into Syrdarya (Usmanov et al., 2016). Mean annual discharge – 219 m^3/s. Maximum discharge occurs in June - 581 m^3/s, and the minimum is in February – 69.1 m^3/s. Mean annual discharge at the mouth decreases to 150 m^3/s. Water is mostly used for irrigation (Hydrogeology of the USSR, 1972).
- Bozsu canal transfers water from upstream of Chirchik River and flows through Tashkent delivering water for irrigation.
- Chardara reservoir is in the south-west with the surface area of 900 km^2. It started to operate in 1967 for irrigation and hydropower purposes. Active capacity is 4200 million m^3, and the normal maximum operating level is 252 m ('CAWater-Info', 2019).

Figure 2.2.3 Syrdarya river

Figure 2.2.4 Keles river

Figure 2.2.5 Chirchik river

Figure 2.2.6 Bozsu canal

2.3 Aquifer geometry

2.3.1 Hydrogeological map

The map was adapted from the Internal assessment Report submitted to the Committee of geology and hydrogeology of Kazakhstan by JSC "Kurort" in 2010, *Figure 2.3.1*. The system of aquifers in the Pretashkent region was formed during Paleozoic, Mesozoic and Cenozoic ages. River valleys were accumulated during Mesozoic-Cenozoic time, comprising of alluvial-proluvial depositions (UNESCO IHP, 2016).

The layers of the aquifer system are folded being structured between boundaries of a mountain fold and river plain. Paleozoic fundament is the bottom of the aquifer system, and the deepest part is in the Chirchik-Akhangaran river basin on the territory of Uzbekistan, ranging between 3000 – 3500 m deep. The next group is comprised of Lower and Upper Cretaceous age formations. The Pretashkent Transboundary aquifer is dated by Cenomanian age presenting the same group. It is deep-lying aquifer, ranging between 810 in the north-west and 2200 m in Chirchik depression ('Hydrogeology of the USSR, Volume XXXIX Uzbek SSR', 1972). The middle part of it forms the dip with outcrops in the north-east of the area. On top of it, Mesozoic – Cenozoic aged layers cover the PTBA. Neogen formations play a significant role in the aquifer system. They present the thickest part of the first layer being grouped with the Quaternary formations ('Hydrogeology of the USSR, Volume XXXIX Uzbek SSR', 1972). The detailed stratigraphic sequence with lithology is presented in *Table 2.3.1*.
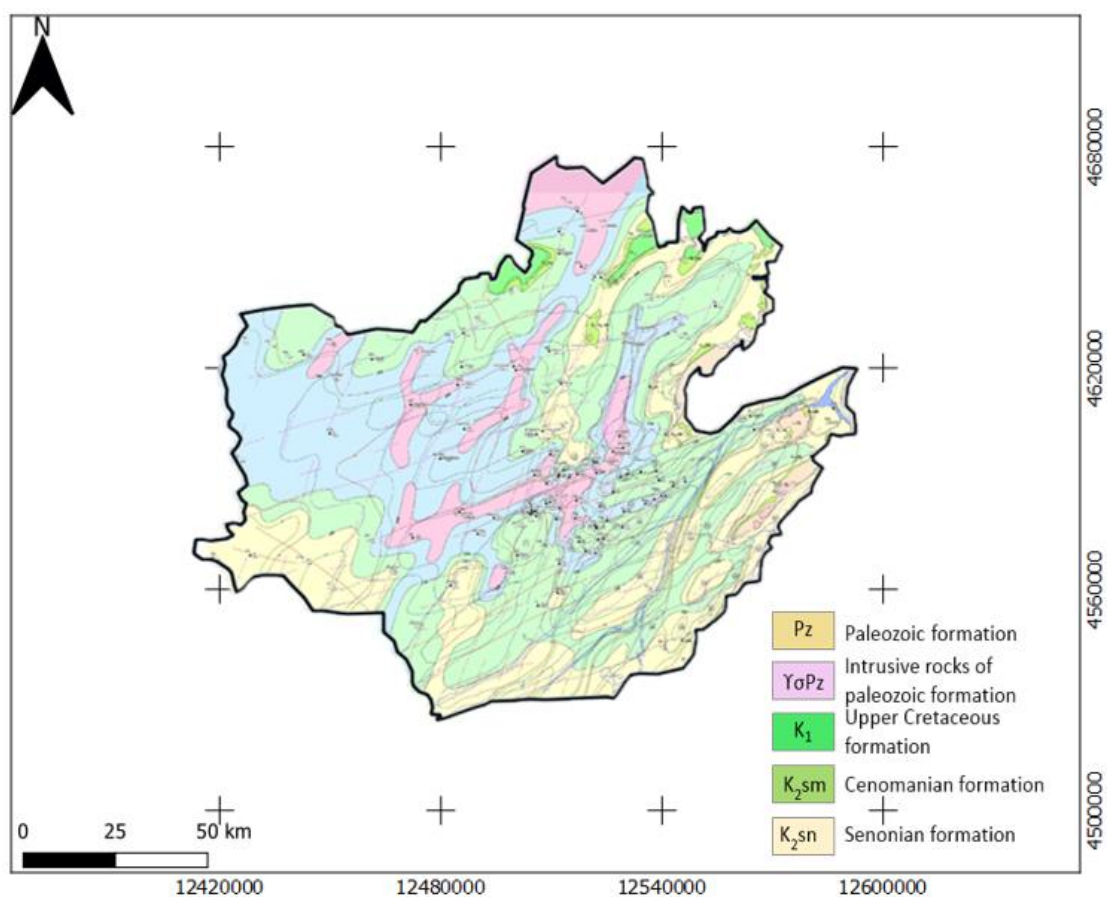
Figure 2.3.1 Hydrogeological map of the PTBA. Modified from JSC Kurort, 2010

Table 2.3.1 Hydrogeological Units of the PTBA. Modified from Hydrogeology of the USSR, Volume XXXIX Uzbek SSR, 1972; UNESCO IHP, 2016

Age		Name	Symbol	Lithology	Hydrogeological characterisation
Cenozoic	Quaternary	Upper-Quaternary-Modern alluvial aquifer	aQIII-IV	Boulders, cobble gravel, sand interbedded with loam. Thickness 1.5 – 20 to 40 – 60 m.	Widespread in the Pretashkent TBA territory. Non-artesian.
		Middle-Quaternary alluvial-proluvial aquifer	apQII	Cobble gravel, sands, loam. Thickness: 5 – 42 m.	Non-artesian.
	Tertiary	Miocene local aquifer	N1	Sands, sandstone, gritstone and conglomerates in clay mass. Thickness: 10 – 45 m.	Locally present. Weakly artesian.
		Middle-Eocene aquifer	P_2^2	Fine and medium sands, poorly consolidated sandstones. Thickness: 13.5 – 75 m.	Weakly artesian.
		Paleocene local aquifer	P1	Fractured limestone bedded as interlayers in clay.	Locally present.

		Turonian-Senonian aquifer complex	$K_2 t_2$ +sn	Sands and sandstone interbedded with clay and silts. Thickness: 135 – 561 m.	Artesian.
Mesozoic	Cretaceous Upper	Lower-Turonian aquitard	$K_2 t_1$	Clays with thin local sandstone layers and lenses. Thickness: up to 140 m.	Regional aquitard.
		Cenomanian aquifer complex	$K_2 s$	Sandstone, sand, gritstone, conglomerates, clays, siltstone, limestone. Thickness: few meters – 200 m.	Pretashkent Transboundary aquifer (PTBA). Artesian, except its outcrops.
	Cretaceous Lower	Lower-Cretaceous Albian aquifer complex	K_1 al B	Badly graded sand, poorly consolidated sandstones. Thickness: 340 – 350 m.	Highly artesian.
		Neocomian-Aptian aquifer complex	K_1 ne+a	Sandstone, sand, rarely conglomerates and gritstone in clay/silt mass. Thickness: 10 – 200 m.	Highly artesian.
Palaeozoic		Fractured Palaeozoic aquifer	PZ	Fractured sedimentary and magmatic rocks.	Studied on the basis of some wells in Uzbekistan.

2.3.2 Geo-referenced boundary of the Pretashkent Aquifer

The boundary of the aquifer was analysed based on the availability of three maps received from internal sources: map from the Institute of hydrogeology and geoecology in Kazakhstan and the report of a national expert from Uzbekistan. The aquifer was delineated using the published report of the GGRETA Project in the Pulkovo 1942/Gauss-Kruger zone 12 projection, *Figure 2.2.1*.

2.3.3 Cross-sections

The depth to top aquifer formation and vertical thickness of layers were collected from the cross-sections of the Internal Report submitted to the Committee of geology and hydrogeology of Kazakhstan by JSC "Kurort" (2010). The cross-sections compile the well data for two countries.
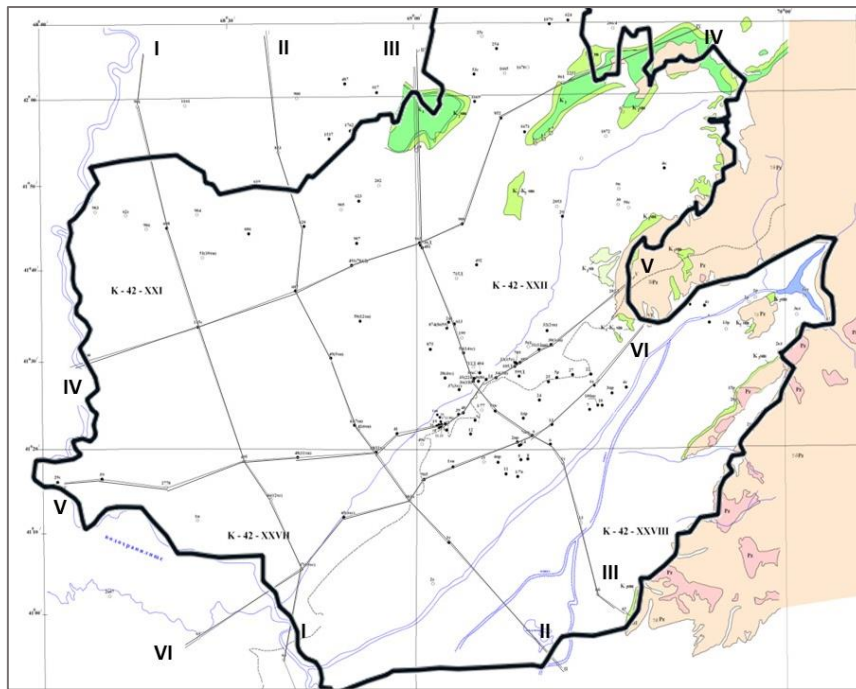
Figure 2.3.2 Location of the PTBA cross-sections. Source: JSC Kurort, 2010

Six cross-sections are presented in Appendix I.

2.4 Hydrogeological characteristics

Recharge

The GGRETA report introduces four main zones of recharge in the aquifer. No additional data was found during the literature review. Outcrops are the first recharge zone of the aquifer, where precipitation enters the system. The second zone is in the area of connection between Cenomanian layer and small losing seasonal rivers. The third zone is indicated through recharge from the upper aquifers, and in their turn, they get recharge through connected losing small rivers and seasonal streams. The forth zone is introduced with recharge through tectonic faults. During the last hydrogeological assessment of the aquifer, 3598.6 m^3/day was estimated as recharge from the first three zones on the area of 301.8 km^2 and 760.3 m^3/day as recharge from faults. The same assessment with the isotope test indicated that the age of the PTBA groundwater is around 6,000 years. It proved the non-rechargeable character of the aquifer (UNESCO IHP, 2016).

Aquifer lithology

The lithology of the aquifer system is presented in *Table 2.3.1*. The PTBA is structured by conglomerates, poorly sorted sandstones, siltstones and sandy limestones.

Soil

The territory of the PTBA is characterised by soil types:

- Light-brown grassland-steppe soils;
- Mountain brown soils, dark and typical sierozem;
- Transient grassland-sierozem and sierozem-grassland soils (Usmanov et al., 2016).

In Kazakhstan the soil along river valleys is mostly meadow-sierozems non-saline. However, sands sierozem ridge-hummocky fixed characterise the Syrdarya valley within the PTBA boundary. In the north and east, major soil types are grey brown carbonates. Ordinary sierozems occupy the largest territory of the aquifer in the north and middle part of the aquifer on Kazakhstani part. The plain above Chardara reservoir is comprised of light sierozems, Appendix II (UNESCO IHP, 2016). The soils of the middle region of the PTBA in Uzbekistan are indicated as newly irrigated grey and typical grey in the study of Usmonov et al. 2016, Appendix II. The eastern part of the aquifer in Uzbekistan is defined by brown soils.

Porosity, transmissivity, hydraulic conductivity

Table 2.4.1 combines available data on hydrogeological characteristics of aquifers and aquitards in the PTBA system collected from the Internal report submitted to the Committee of geology and hydrogeology of Kazakhstan by JSC "Kurort" (2010) and the book – Hydrogeology of the USSR (1972). However, the values are not provided for every layer. Map of transmissivity values for Kazakhstani part is presented in Appendix III.

Table 2.4.1 Hydrogeological information of the PTBA system layers

Hydrogeological unit	Hydraulic conductivity, m/day	Porosity	Transmissivity, m^2/day
Upper-Quaternary - Modern alluvial aquifer (aQIII – IV)	17-50 – 200 ('Hydrogeology of the USSR, Volume XXXIX Uzbek SSR', 1972)	-	-
Middle – Quaternary alluvial – proluvial aquifer (apQII)	0.54 – 1.9 ('Hydrogeology of the USSR, Volume XXXIX Uzbek SSR', 1972)	-	-
Miocene local aquifer (N1)	27 ('Hydrogeology of the USSR, Volume XXXIX Uzbek SSR', 1972) 7.7 – 15.3 (JSC Kurort, 2010)	0.3 ('Hydrogeology of the USSR, Volume XXXIX Uzbek SSR', 1972)	163 (JSC Kurort, 2010)
Middle – Eocene aquifer (P_2^2)	-	-	-
Paleocene local aquifer (P₁)	-	-	-
Turonian – Senonian aquifer complex (K₂ t₂ +sn)	5.1 (JSC Kurort, 2010)	-	255 (JSC Kurort, 2010)
Lower – Turonian aquitard (K₂ t₁)	-	-	-
Cenomanian aquifer complex (K₂s)	-	-	-
Lower – Cretaceous Albian aquifer complex (K₁al)	-	-	-
Neocomian – Aptian aquifer complex (K₁ ne+a)	-	-	-

Jurasic aquifer (J)	0.28 – 0.3 ('Hydrogeology of the USSR, Volume XXXIX Uzbek SSR', 1972)	-	-
Fractured Palaeozoic aquifer (Pz)	-	-	-

Total groundwater volume

Total groundwater volume on the territory of Kazakhstan is equal to 97.6 km^3. Elastic groundwater volume is 5.15 km^3 (UNESCO IHP, 2016). The total amount of groundwater in the PTBA for the two countries is not indicated in available sources.

Groundwater depletion

Extensive exploitation of the aquifer started from 1981 when 48 wells were drilled for drinking, domestic and pastures flooding purposes on Kazakhstani part only. However, the process wasn't monitored (JSC Kurort, 2010). The assessment conducted by the JSC "Kurort" presents the change of piezometric heads between 1981 and 2009. The area of change in piezometric heads for 200 m increases around Tashkent becoming larger towards the south direction, *Figure 2.4.1*. The general pattern for 150 m piezometric heads drop has its pronounced expansion to the east, north and west.
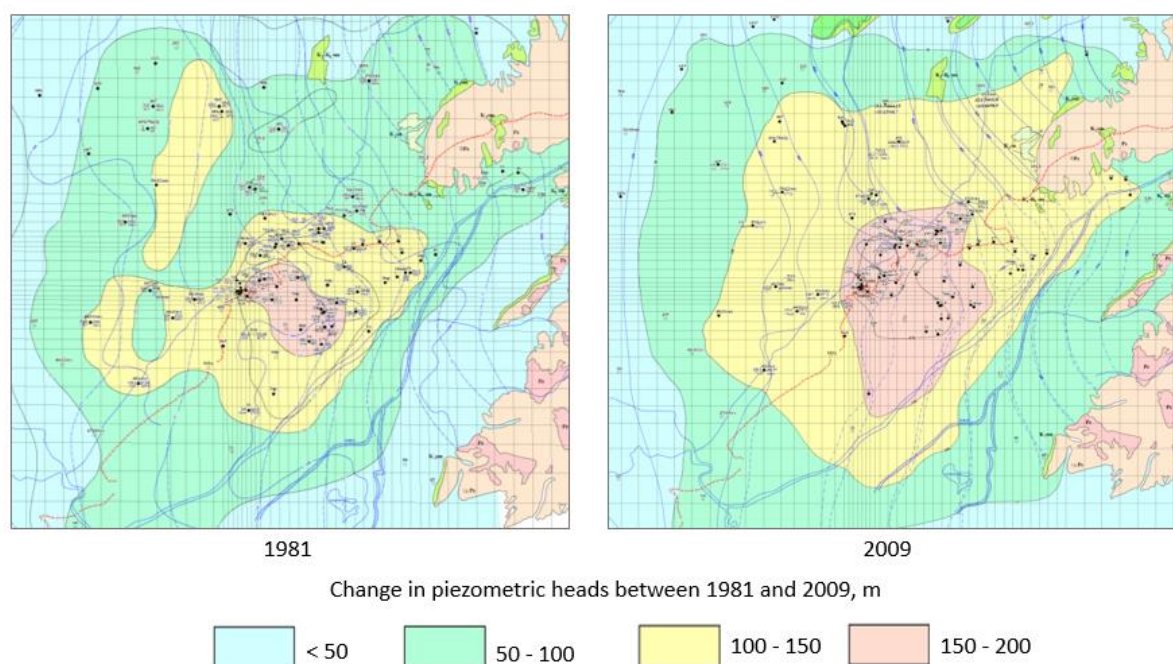
Figure 2.4.1 Change in piezometric heads of the PTBA between 1981 and 2009. Source: modified from JSC Kurort, 2010

Discharge mechanism

The previous numerical model built by the JSC "Kurort" resulted in identifying two discharge zones: springs and groundwater flow to Kyzylkum artesian aquifer. Discharge to springs was estimated as 1659 m^3/day (UNESCO IHP, 2016).

2.5 Environmental aspects

Groundwater quality

Salinity varies between hydrogeological units as follows (JSC Kurort, 2010):

- *Upper-Quaternary - Modern alluvial aquifer (aQIII – IV) -* from 700 till 1100 mg/l.
- *Middle – Quaternary alluvial – proluvial aquifer (apQII) -* from 600 till 1370 with large variability. Some cases result in salinity with 2190 mg/l.
- *Miocene local aquifer (N1) –* from 600 till 3000 mg/l, sometimes reaches 59700 mg/l.
- *Middle – Eocene aquifer* (P_2^2) *–* from 600 till 2800 mg/l.
- Paleocene local aquifer (P1) – from 2300 till 3700 mg/l on the outskirts of the Chulinsky uplift, where there are outcrops. Salinity changes till 6000 – 11000 mg/l as it moves towards the depression.
- *Turonian – Senonian aquifer complex (K2 t2 +sn) –* in the northern and western part from 5200 till 7500 mg/l. Well 901 in the north-west, at the Syrdarya River monitored salinity values from 1000 till 3000 mg/l.
- *Lower – Turonian aquitard (K2 t1) –* from 1800 till 2300 mg/l.
- *Cenomanian aquifer complex (K2s) –* till 1000 mg/l with low hardness and presence of silicic acid, fluorine, barium, iodine, boron, molybdenum.
- *Lower – Cretaceous Albian aquifer complex (K₁al) –* from 500 till 2200 mg/l.
- *Neocomian – Aptian aquifer complex (K₁ ne+a) –* from 5000 till 14600 mg/l. Recharge zones – 400 mg/l (well 202d).
- *Jurasic aquifer (J) –* from 600 till 1000 mg/l.
- *Fractured Palaeozoic aquifer (Pz) –* 6400 mg/l.

Along with low salinity and high content of sodium bicarbonate, the PTBA groundwaters are characterised by a presence of fluorine. The gas composition of these waters contains nitrogen and carbon dioxide. The PTBA analysis of the geological and paleogeographic conditions of the deep alkaline groundwaters formation timed to areas of intense subsidence and accumulation of alluvial and alluvial-lake sediments (JSC Kurort, 2010). Chemical analysis of water samples from some wells in Kazakhstan from 2000 till 2010 didn't show a significant change in the quality (JSC Kurort, 2010). The salinity distribution map is presented in *Figure 2.5.1*.
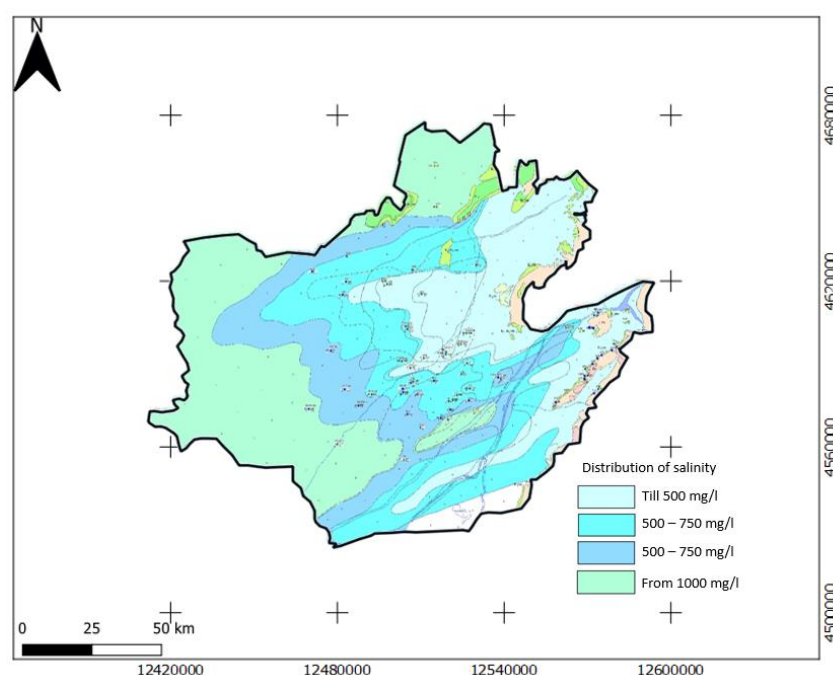
Figure 2.5.1 Distribution of salinity in the PTBA system. Source: JSC Kurort, 2010

Groundwater pollution

The PTBA is a deep aquifer that currently has risks of pollution from outcrops or upper aquifers. There are several potential polluters such as farms, poultry farms, irrigated lands, pesticide warehouse and animal burial site. Some of these entities were found to violate environmental protection measures. One of the main concerns is the situation with animal burial sites on Kazakhstani part. They were built in 1970 and require reconstruction (UNESCO IHP, 2016). Another polluter is rural settlements without centralised wastewater treatment plants and sewage systems (Rakhmatullaev et al., 2012). In Kazakhstan, containment ponds accumulate sewage, and the water is not transferred or pumped further. So that the level rises, leading to an increase of polluted groundwater level. Sometimes discharge is done without preliminary treatment. 53 registered and 194 illegal polygons of solid waste are another large-scale polluters on the territory of the PTBA. (UNESCO IHP, 2016). On the side of Uzbekistan, the major polluter is agriculture, which intensely applies fertilisers to support the growth of crops (Rakhmatullaev et al., 2012).

2.6 Socio-economic aspects

Kazakhstan

The population in Kazakhstan is 18.04 million (World Bank, 2017). The PTBA is located in Turkestan oblast[2] (till 2018 South-Kazakhstani oblast). From 2009 till 2018, the population growth rate was 5.96% with a density of 17 inhabitants/km^2. The most significant difference between rural and urban dwellers in the country was noticed in Turkestan oblast, 80.3% comparing to 19.7%, *Figure 2.6.1*. Ethnically, Kazakhs represent more than 75% of the population in the oblast, *Figure 2.6.2* (UNFPA, 2018).

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[2] Oblast is an administrative division in Kazakhstan

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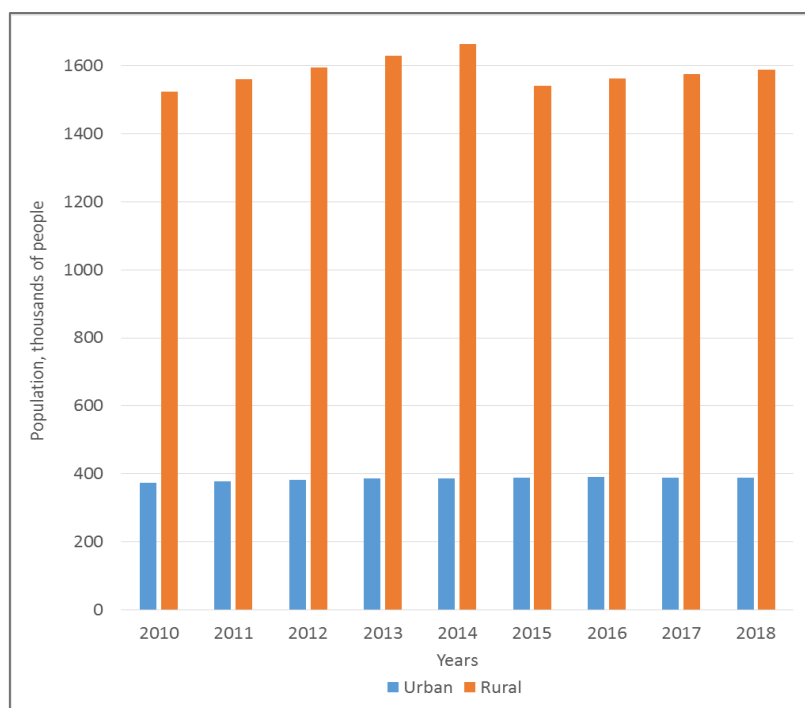
Figure 2.6.1 Urban and rural population in Turkestan oblast, Kazakhstan
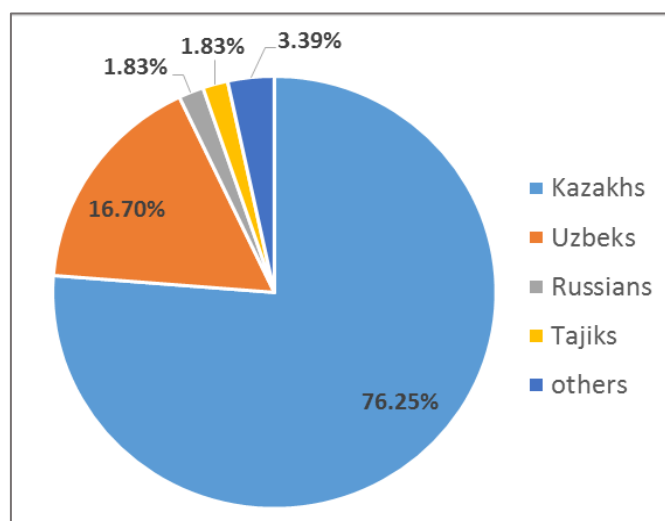
Figure 2.6.2 Distribution of the population in Turkestan oblast by nationality in 2018

Uzbekistan

The population in Uzbekistan is 32.39 million (World Bank, 2017). It is almost two times higher than in Kazakhstan. The density is 7380 inhabitants/km^2 in Tashkent and 187.6 inhabitants/km^2 in Tashkent region[3]. Total population growth rate is 1.17% per year from 2010 till 2018, calculated based on the data from the State Committee of the Republic of Uzbekistan on statistics, *Figure 2.6.3*.

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[3]https://stat.uz/en/official-statistics/demography-and-labor/statistical-tables/219-ofytsyalnaia-statystyka-en/demografiya-i-trud-en/4313-population-density
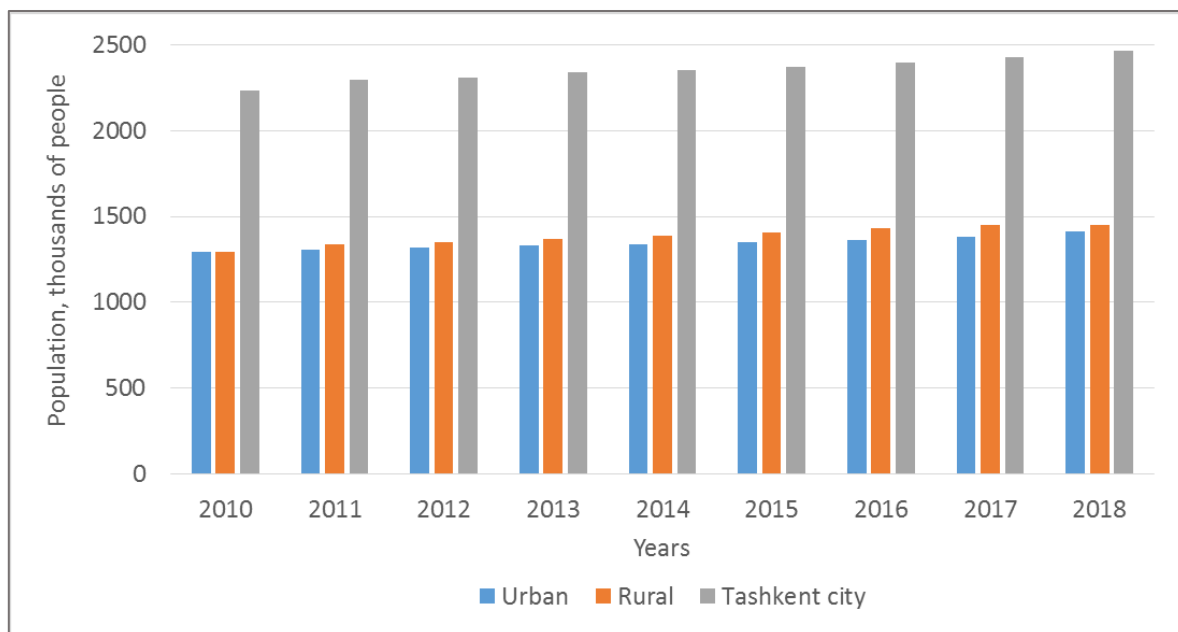
Figure 2.6.3 Urban and rural population in Tashkent region and city, Uzbekistan

Major ethnic groups are Uzbeks and Tajiks with minor representation of Kazakhs, Russians and Karakalpaks as monitored by the State Committee of the Republic of Uzbekistan on statistics, *Figure 2.6.4*.
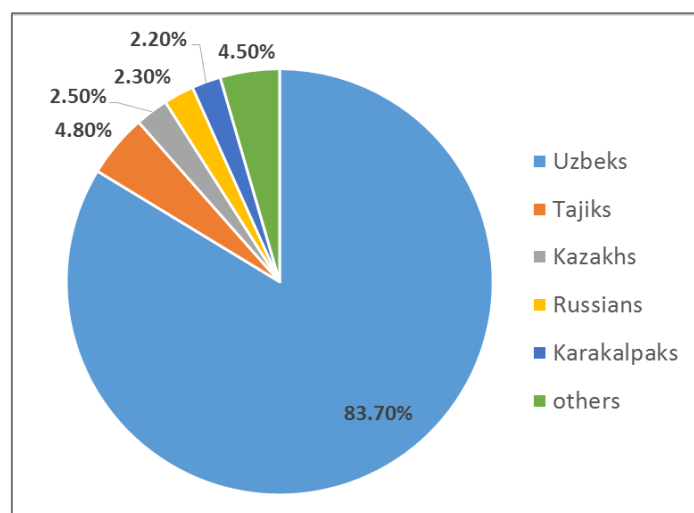
Figure 2.6.4 Distribution of the population in Uzbekistan by nationality in 2018

Kazakhstan and Uzbekistan were socio-economically interdependent within the centrally planned Soviet economy. Agriculture accounted for 10 to 45 % of the gross domestic product (GDP) during Soviet time (Qushimov et al., 2007). To date, it has occupied a crucial part of the economy in Central Asia, contributing 5.2% of the GDP in Kazakhstan and 18.5% in Uzbekistan (Bobojonov et al., 2016). Last 30 years, there was economical and population growth in Central Asia. However, the development wasn't balanced for two countries. GDP in Kazakhstan has increased four times more than in Uzbekistan from 1993 till 2017. In general, the natural-resource-oriented and uneven industrial approach were the pillars for the economic expansion (Yu et al., 2018).

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2.7 Legal and policy aspects

After the disintegration of the Soviet Union, two Republics went through the transitioning process from centralised towards integrated water resources management (Janusz-Pawletta and Gubaidullina, 2016). During the Soviet era, water management was aimed to satisfy demands for centrally identified production (Black et al., 2016). Maintenance of water distribution and irrigation facilities after the disintegration declined due to the lack of financial support leading to the degradation of the system (O'Hara, 2000). Services such as water supply had to adapt to a new market economy (Tussupova et al., 2015). The transformation from centralised to market-oriented economy went with changes of institutional, political and technical aspects of water management (Abdullaev and Rakhmatullaev, 2015). National water bodies became transboundary requiring new agreements.

2.7.1 Domestic legal and institutional framework

In 1993 the Republic of Kazakhstan (RK) signed the Water Code as the primary document for water resources management, and it was amended in 2003. The Code comprises of 194 articles. The Water Law of the Republic of Uzbekistan (RU) came into effect on March 6, 1993, consisting of 119 articles. Appendix IV provides detailed information on national legal and institutional frameworks for Kazakhstan and Uzbekistan.

Both documents, namely the Water Code and the Water Law, are relevant for groundwater. The Land Code, the Code on soil and subsoil use, Environmental Code are other main complementary policy documents for groundwater in Kazakhstan. In Uzbekistan, the Resolution of the President of the RU from 04.05.17 № PP-2954 on Measures to regulate the control and accounting the rational use of groundwater reserves for 2017–2021 adds to the policy on groundwater.

Groundwater in both countries is a state property as stated in the Water Code for Kazakhstan in Article 8 and the Water Law of Uzbekistan in Article 3. According to the Land Codes in Kazakhstan and Uzbekistan, the right to use the land (an area) is coming together with the right to use mineral resources within the borders of that land. In the case of Kazakhstan, the Land Code specifies that the use of groundwater is carried out simultaneously with the provision of land. In Uzbekistan, the definition of the use of groundwater with the land is not coupled with the right to utilise the land. It is allowed to "to use minerals, forests, water bodies and exploit other useful properties of the soil following the established procedure for the needs of the farm". The legislation on master plans or water resources plan is the legislative subject only for Kazakhstan, covered by the Resolution of the Government of the Republic of Kazakhstan from 8.04.16 № 200.

Groundwater abstraction and use is regulated through licencing in both countries. There is a difference how legal documents incorporate it: for Kazakhstan – in the Water Code, for Uzbekistan – in the Resolution of the President of the RU from 04.05.17 №. PP-2954 on Measures to regulate the control and accounting the rational use of groundwater reserves for 2017–2021. Kazakhstan presents regulations on groundwater abstraction through the definition of special water use. It considers "the use of surface and ground waters with or without uptake from a water body to satisfy drinking and domestic needs of citizens…including water uptake facilities equipped with pumping units and other water-lifting facilities for extracting groundwater." The permit issued by the governmental authorities is applied to abstract groundwater. In Kazakhstan, it is not specified which authority is in charge of the licencing. In

Uzbekistan, the State Committee on geology and mineral resources (Goskomgeologiya) is in charge of it. Permission is not required when abstraction is less than 50 m³/day from the first aquifer (not used for centralised water supply) in Kazakhstan and not more than 5 m³/day (fewer than 25 m deep) for individual use in Uzbekistan. Moreover, there is no need to apply for the permit when groundwater is collected during mining or solid materials exploration as well as for free-flowing wells in Kazakhstan. In the Republic of Uzbekistan, the Goskomgeologiya conducts development and production programs of the mineral resources at the state level. The duration of permits validity varies significantly. Kazakhstan divides the special water use into two larger groups: temporal and constant. Constant use is followed without any time restrictions; temporal use can be long-term (from 5 to 49 years) and short-term (up to 5 years). Since a special water use takes into account the abstraction of groundwater and only possible with the permission, this time division is assumed to be applied for groundwater abstraction permits validity. The permit system in Uzbekistan is less complicated: the validity set for the period of operations but not longer than for one year, and it is free of charge. The information on payment for the permits is not provided in legislative documents in Kazakhstan. Amendments and review in both regulations: the Water Code in Kazakhstan and the Resolution №. PP-2954 in Uzbekistan allow renewing permits in case of elimination of inconveniences. One of the main criteria for the termination of the permit is the submission of inaccurate information or its refusal. The Water Code of Kazakhstan provides more conditions under which the permit is terminated, including, as an example, the death of an individual acting as a water user, natural or artificial disappearance of a water body and refusal or transfer of the water rights. None of those mentioned regulations covers the topic on the right to trade with permits.

Approvals of the environmental and sanitary-epidemiological inspections are required documents to receive the permit for abstraction — Article 72. Water User Responsibilities of the Water Code in Kazakhstan states that water users are obliged to timely submit to state authorities reliable and complete information on the use of a water body in the form established by the legislation of the Republic of Kazakhstan. Article 120 of the same document highlights the necessity to monitor groundwater to prevent pollution and depletion. The exact parameters are not specified. In Uzbekistan, only state monitoring of groundwaters is introduced. Illegal well drilling and water abstraction are sanctioned in both countries with fines, as an example for small businesses – 150, medium-sized business – 300, large businesses – 1000 in the amount of monthly calculated indicator (2525[4] tenge for 2019) in Kazakhstan and for citizens of Uzbekistan from 2 till 5 of minimum monthly wages (223 000[5] som for 2019), on officials – from 15 till 20. Special conditions for the administrative fine are described in Appendices I.

The topic of groundwater pollution is also reflected in legal documents. Wastewater discharges can be processed only with the special water user permission in Kazakhstan and with so-called "technical condition" in Uzbekistan that is free of charge. All the criteria on the duration of the permit, its termination and review are falling under the special water use regulations of the Kazakhstani legal system. Article 89 of the Water Code in Kazakhstan and Article 19 of the Water Law in Uzbekistan define the use of surface waters for the sewage disposal. Two additional documents, namely Order of the Minister of National Economy of the RK from 20.07.15 №546 on approval of the rules for the reception of wastewater in drainage system of settlements and the Resolution of the Cabinet of Ministers of the RU from 03.02.10 №11 on

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[4] https://online.zakon.kz/document/?doc_id=1026672
[5] https://www.gazeta.uz/ru/2019/07/12/wages/

additional measures to improve environmental protection in the system of communal services support the regulations on sewage disposal. The quality of sewage should meet the requirements of environmental standards in both countries. The interesting fact arises when looking at the approval of effluent quality standards. In Uzbekistan, Resolution №11 provides all fixed limits of maximum acceptable concentrations, including toxic pollutants. It is not the same case for Kazakhstan. Article 84. Standards of maximum acceptable harmful impacts on water bodies mention that the authorised body establish standards based on not changing the environmental system of a water body. Order of the Minister of Agriculture of the RK from 15.05.15 №19-1/441 presents the formula calculating the maximum acceptable harmful impacts, and it varies from one water body to another. The formula includes such variables as average annual river discharge, uptake by water users and total discharge of sewage and factual concentrations of polluting substances. EIA is required for wastewater projects under the Water Code of the RK supported by the Environmental Code Article 225. Environmental requirements for sewage discharge and the Resolution №11, Chapter III. Order of issue of technical conditions to discharge wastewater, point 19 in Uzbekistan. In both countries, water quality monitoring of discharges is the matter of an obligation. For Kazakhstan, it works within the same regulations as for abstraction. In Uzbekistan, it is regulated by the Resolution №11, Chapter IV. Control over industrial wastewater discharge and a customer is obliged to submit the data on the qualitative and quantitative composition of industrial wastewaters every month. The control, use, and disposal of hazardous substances rules are marked in the Environmental Code of the RK and the Resolution of the Cabinet of Ministers of the RU on the approval of a monitoring program for the environment for 2016-2020 in Uzbekistan. Illegal discharge of wastewaters has an administrative penalty under Article 326 and 72 of the Codes on administrative offences in Kazakhstan and Uzbekistan, accordingly. Current regulations are not very advanced in the matter of covering additional protection measures such as identification of land cultivation practices to avoid groundwater pollution and the impact of urban and land development.

The Water Code of the RK and the Water Law of the RU also reflect the institutional[6] aspects of water resources management. On a national level, the Government of the RK is responsible for establishing the state policy, regulations and relations between regions and foreign states in the field of use and protection of water funds, water supply, and disposal. There are two institutions on a national level in Uzbekistan that manage and determine state policy on water and water use: Oliy Majilis of the RU and the Cabinet of Ministers. The State Committee on geology and mineral resources of the RU is assigned to manage groundwater. The intermediate level is controlled through Authorized State Administration bodies - Basin (territorial) administrations in Uzbekistan and Authorized bodies as determined in the Water Code of Kazakhstan. Article 8 and 37 present their roles in the system, respectively. The role of local governmental authorities in Uzbekistan is concentrated mostly on the policy measures to protect water resources through ensuring law, monitoring and improving conditions of water bodies. Local representative bodies in Kazakhstan establish the rules on water use, approve payment rates for surface water uptake and establish the regulations on the use and withdrawal of water facilities. Local executive bodies work in close collaboration with basin water management entities in the field of integrated and rational use and protection of water resources.

Once the countries became independent, the concept of Water User Organizations started appearing in the late 90th (Veldwisch and Mollinga, 2013; Wegerich, 2000; Zinzani, 2015).

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[6] Used in the meaning of administrative structure/key organization

Article 79 of the Water Code of the RK and Article 18 of the Water Law of the RU includes the objectives of the organisations and principles of their establishment.

The Water Code of the RK, Article 9. Principles of water legislation of the RK states that the availability of data on the water fund is one of the principles of the Code. In the case of Uzbekistan, all the data is collected and stored at the State Committee on geology and mineral resources on groundwater, and it is not publicly available and counts as state secret information.

The comparison shows there are slight discrepancies in the regulation documents of both countries, for example different threshold values of abstraction rates allowed for non-licence utilization, fine system for illegal pumping or the period of licence validity. Overall, assessed aspects have general coverage in both legal documents, namely the Water Code and the Water Law with some deviations in details.

2.7.2 Transboundary legal and institutional framework

Regulations on transboundary aquifers on a global scale are covered in three documents:

1) the Convention on the Law of Non-Navigational Uses of International Watercourses (UNWC, adopted in 1997, in force from 2014);

2) the Convention on the Protection and Use of Transboundary Watercourses and International Lakes (UNECE Water Convention, adopted in 1992, in force from 1996), supported by the Model Provisions on transboundary groundwaters from 2014 (Model Provisions);

3) the Draft Articles (DA) on the law of transboundary aquifers (UN General Assembly resolution, 2008).

The UNWC and the UNECE Water Convention act as binding instruments, on the other hand DA don't have obligatory force (Stephan, 2019).

On 04.09.2007 the Republic of Uzbekistan and 11.01.2011 the Republic of Kazakhstan joined to the UNECE Water Convention. The Convention provides a legal framework for transboundary water cooperation and strengthens basin approach. Chu and Talas transboundary river basins in Kazakhstan and Kyrgyzstan are among cases where the governments implement the Convention on the ground. Uzbekistan also signed the Convention on the Law of the Non-Navigational Uses of International Watercourses by 04.09.2007.

All three documents incorporate two principles of international water law, namely the Principle of Equitable and Reasonable Utilization and the Obligation Not to Cause Significant Harm. The first principle is aimed to regulate water resources issues between riparian states based on equity and fairness. The UNECE Water Convention 1992 adopts the principle in Article 2.2c and the UN Watercourses Convention 1997, in Articles 5, 6, 7, 15, 16, 17, 19. No Significant Harm principle declares that states are allowed to use shared water resources, including aquifers based on the preservation of environmental and water quality, and there has to be no significant harm to other basin states. The principle is included into the UN Watercourses Convention 1997, (Articles 7, 10, 12, 15, 16, 17, 19, 20, 21.2, 22, 26.2, 27, 28.1, 28.3). The DA codes this principle in a more specific way, mentioning "Aquifer States shall, in utilizing transboundary aquifers or aquifer systems in their territories, take all appropriate measures to prevent the causing of significant harm to other aquifer States or other States in whose territory a discharge zone is located". Overall, the DA is focused not only on transboundary aquifers but also broadens its

perspective towards a wider picture through considering impacting activities such as recharge in a non-riparian country.

These documents serve frameworks for development of specific individual (bilateral) agreements between aquifer states where international law and domestic need to be harmonised. The Water Code of the RK identifies international cooperation in water use and protection as a separate chapter where Articles 141 – 145 in a detailed way deliver main directions, principles, mechanisms and economic basis of international cooperation in transboundary waters use and protection without specifying if this definition includes both surface- and groundwater. Chapter XXIX. International agreements, Article 119 of the Water Law of the RU states that if international agreements of the Republic of Uzbekistan establish other provisions than by the Water Law, then the provisions of the international agreement apply.

On a regional level on March 17, 1998, the Republic of Kazakhstan, the Republic of Kyrgyzstan and the Republic of Uzbekistan signed the Agreement on use of water and energy resources of Syrdarya River Basin. Its objective was to define the most efficient and equitable use of water and energy resources. Article 2 of the Agreement identifies that Parties should coordinate and make decisions on water release, energy production, and distribution as well as compensation for energy losses on the equivalent basis of the Naryn - Syrdarya reservoirs cascade. This Agreement is a part of transboundary regulations related to the Aral Sea basin. Other provisions cover issues on cooperation and institutional configurations, but none of them addresses groundwater management.

The Interstate Commission for Water Coordination of Central Asia (ICWC) is a regional organisation that determines water policy with "taking into account all needs of economic branches, integrated and rational water resources use, long-term regional water supply program and measures for its implementation" and approves water use limits. Syrdarya Basin Water Organization is an executive body of ICWC. Among regional institutions, there are also the Interstate Council for the Aral Sea (ICAS), the Interstate Sustainable Development Commission and the International Fund for Saving the Aral Sea (IFAS). It can be concluded that international and national institutions are in the place, and they can act as an initiating mechanism for transboundary cooperation. In meantime, the countries need to agree about concrete regulations for use and protection of specific and individual aquifers such as the Pretashkent Transboundary aquifer.

Chapter 3   Research methodology

3.1 Research framework

The following research framework was applied to achieve the objectives of the Thesis and consists of three main parts, *Figure 3.1.1*. The development of the Pretashkent Transboundary groundwater conceptual and numerical model included:

Data collection and preparation

- Establishing first contacts with people from hydrogeological institutes of Kazakhstan and Uzbekistan during the training on groundwater modelling organized by the IGRAC
- Requesting for the data
- Literature review
- Assessment of the transboundary aquifer including environmental, socio-economic and legal aspects
- Collecting data from open sources and formatting as input files for the model

Development of a model

- Hydrogeological characterization: defining layers, hydrogeological properties and processes
- Building a conceptual model in GMS
- Its conversion to a steady-state numerical model in MODFLOW
- Introducing chloride concentration with MT3DMS
- Sensitivity analysis

Model output analysis

- Groundwater flow and salinity analysis
- Assessment of water budget

Figure 3.1.1 Research steps

3.2 Modelling environment

Admitting the fact that groundwater is an invisible resource and commonly there is lack of data, groundwater models could be justifiable tools to understand the system and estimate aquifer properties (Anderson et al., 2015). There are various existing modelling software with their capabilities, operational characteristics and limitations (Kumar, 2012). Groundwater modelling system (GMS) MODFLOW-based software was used to construct the model of the Pretashkent Transboundary Aquifer because of its user-friendly interface, ability to convert the conceptual model into numerical, GIS-based data interface and its support of finite-difference and finite-element groundwater models in 2D and 3D. The applied tools of GMS for building the model are described briefly in *Chapters 3.2.1 – 3.2.4*.

3.2.1 Conceptual model approach

The conceptual model approach was implemented to set up a MODFLOW simulation by using GIS tools in the Map module. Hydrogeological parameters can be first assigned to the conceptual model and then converted to grids. The process is run automatically by the software. Overall, 14 coverages were identified for various parameters with their particular zonations in shapefiles. Each coverage setup allows to select options for sources/sinks/boundary conditions, areal properties and observation points, and the model was built using the following options:

1. Sources/sinks/BC:
- "Layer range" allows defining the layer to which specific parameters are assigned;
- "River" is introduced as an individual point where the head stage and bottom elevation are input parameters. Only two points are necessary for the data fill, and the software interpolates the values along the arc;
- "Wells" support the input of flow rate both for extraction and injection wells.

2. Areal properties:
- "Recharge rate" introduces values;
- "Horizontal conductivity (K)" introduces values;
- "Vertical conductivity (K)" introduces values;
- "Porosity" introduces values;
- "Longitudinal dispersivity" introduces values;
- "Starting concentration" introduces values;
- ICBUND indicates active and inactive cells in MT3DMS;
- Zone budget divides the output for indicated zones.

3. Observation points:
- "Head" represents water table elevations. The input data also includes the interval of observation heads for calibration, confidence interval and standard deviation (Aquaveo LLC, 2012).

3.2.1 2D Scatter data and 2D Grid Module

GMS supports different input data formats such as .txt, .xlsx, .csv and allows to display it as points when XY coordinates are indicated. Then, it permits to interpolate a file to 2D Grid Data. The thickness of layers from cross-sections was incorporated and transferred to 3D Grid with ordinary kriging. The technique estimates the regionalised variable as a result of interpolation

between deterministic and random variables. The accuracy of the interpolated value depends on spatial distribution. The closely located points have a higher correlation than widely spread ones (Aquaveo LLC, 2017). Ordinary kriging uses experimental and model variograms to estimate the weight of the scatter point and minimises expected error in a least-squares sense (Aquaveo LLC, 2017).

3.2.2 3D Grid

The 3D Cartesian grid can be created in the 3D Grid Module. Further, these grids can be used for finite-difference model. More options for interpolation, constructing isosurface and cross-sections are available in the 3D Grid Module. Cell centred type of the grid was used to build a conceptual model of the PTBA. A single point data was introduced to a grid.

3.2.3 Code for groundwater flow model

MODFLOW is a software that uses a finite difference method to find solutions for the three-dimensional groundwater flow equation in a porous medium (McDonald and Harbaugh, 1986). To simulate different processes of the groundwater system, the program integrates packages. They present separately such hydrologic processes as leakage to rivers, recharge and evapotranspiration. Solution options are also presented as packages: Basic Package, Preconditioned Conjugate Gradient (PCG), Strongly Implicit Procedure (SIP) and Direct Solution (DE4) (Harbaugh, 2005). The PTBA numerical model was run in MODFLOW-2005 with Layer Property Flow internal/hydrologic package and Preconditioned Conjugate Gradient solver.

Packages

Following MODFLOW packages were used:

- *Layer Property Flow (LPF)* is an internal package and allows to formulate the internal flow processes. It can work with confined and convertible layers. Transmissivity in confined layer is constant and varies depending on heads in convertible layer. Such processes as cell drying, wetting, vertical flow capabilities are inactive for confined layer, and contrary, in a convertible layer it is possible to apply cell wetting or vertical flow correction capabilities (Harbaugh, 2005).
- *Preconditioned Conjugate Gradient (PCG)* is a solver package that estimates iteration parameters internally (default is 50) and externally (less than 100) (Harbaugh, 2005; Hill, 1990). The package has an option to specify the number of iterations to avoid long computation time when the solution is not converging. There are two criteria for convergence: head change and residual change criterion. MODFLOW-2005 includes additional variable DAMP in PCG to solve problems with convergence. Value of 1 should be assigned for DAMP. When the problem with convergence occurs, the reduction of that value can be tried (Harbaugh, 2005).
- *General Head Boundary (GHB1)* estimates the flow from or in cells linked to a distant external water source. The boundary flow is calculated as the difference of heads between an external source and a cell multiplied by conductance (Anderson et al., 2015). The GHB Package doesn't limit incoming and outgoing flow, and that is its difference from River, Drain and Evapotranspiration Packages (Harbaugh, 2005).
- *Recharge (RCH1)* is a package aimed to simulate recharge to the groundwater system through precipitation or infiltration. There are three options how recharge rates (length/time) can be incorporated in a model in GMS. The first option is "Recharge only

at the top layer", second – "Recharge at specified vertical cells", and third – "Recharge at highest active cells" (Aquaveo LLC, 2017). For the first two options if a cell is no flow or constant head, then recharge won't be assigned. The Package doesn't allow to introduce recharge rates at the same time at different depths in one vertical column because it enters the system only from the top layer. For the third option if a cell is a constant head and no variable cell is above, then recharge will be also intercepted and not introduced into the system (Harbaugh, 2005).

- *River (RIV1)* simulates the flow processes between surface waters and groundwater system, so-called aquifer seepage but not the flow in a river. Depending on the head differences, an aquifer can gain or lose water. The river-aquifer flow is calculated as the multiplication of river-aquifer interconnection conductance and the difference between the water level in a river and head at the node in the cell. When the value of a flow is positive, the aquifer is gaining water from a river. There are two assumptions: first – head losses between river and aquifer are limited by the bottom of the river; second – underlying cell is fully saturated. In case when the head at the node is lower than a river bed, then the flow is proportional to the conductance and the difference between the water level in the river and river bottom elevation (Harbaugh, 2005).

- *Well(WEL1)* is a package that allows introducing pumping rates at the location of a well. The positive rate indicates injection wells, and the negative rate is for abstractions. The package doesn't provide wells that are open in several layers. Such option can be introduced through a group of one-cell wells with individual abstraction or injection rate for each stress period or with Multi-Node Well Package (Harbaugh, 2005).

3.2.4 Code for solute transport model

Additionally, MT3DMS was used to simulate the effect of salinity on the PTBA when there is leakage from Layer 3. MT3DMS solves advection, dispersion and chemical reactions of contaminants in the saturated zone. It also interfaces with MODFLOW and supports hydrologic and discretisation options of MODFLOW (Zheng et al., 2012). Following packages were utilized:

- *Basic Transport Package* is always required and defines problems, specifies boundaries and initial conditions, indicates step size, prepares mass balance information and controls printing the output (Aquaveo LLC, 2017).
- *Advection Package* is involved in solving advection in the concentration change (Aquaveo LLC, 2017). Third-order total variation diminishing (TVD) scheme was selected as a solver. It acts well as a bridge between the particle-tracking based method of characteristics (MOC) and the finite-difference method (FDM). TVD conserves the mass while limiting numerical dispersion and artificial vibration (Zheng et al., 2012).
- *Dispersion Package* solves problems of concentration change with the explicit finite difference method (Aquaveo LLC, 2017).
- *Source/Sink Mixing Package* assigns concentrations to point sources (well, river, general and specified heads) and areal sources (recharge, evapotranspiration). In most cases, it is water coming to a system which has a specific concentration of a solute (Aquaveo LLC, 2017).
- *GCG Package* is a generalised conjugate gradient solver, and it is always active to solve dispersion, sink/source, reaction terms without stability constraints (Zheng et al., 2012).

3.3 Data collection and availability

The data was collected from three main sources:

- Outputs of the first phase of the GGRETA project available in the IGRAC;
- Internal report submitted to the Committee of geology and hydrogeology of Kazakhstan by JCS "Kurort" in 2010 and received through personal communication with a representative from the Committee;
- Open-sources.

3.3.1 Groundwater data

Aquifers and aquitards thickness was obtained from cross-sections provided in .jgp format of the Internal Report submitted to the Committee of hydrogeology and geology of Kazakhstan by JSC "Kurort" (2010). The thickness was measured and converted into absolute values using the scale on images. Cross-sections cover the territory of the PTBA in Kazakhstan and Uzbekistan, Appendix I.

Groundwater level time-series from observation wells wasn't included among available datasets. However, there were measurements of static groundwater levels from abstraction wells in 1981, *Table 3.3.1*. The Internal report also stated that those wells were ceased for some time to establish the balance of the groundwater system. Since the last available measurement was monitored in 1981 for the wells in Uzbekistan, other well readings were included for the same year.

Table 3.3.1 Static heads from abstraction wells in the PTBA in 1981

ID	X	Y	Static Head, m
1tn	12521137	4557788	524.5
609	12536583	4585690	512.1
908	12520514	4620816	534.1
44(11tc)	12504944	4561774	478.5
36(1B)	12526867	4580707	452.5
48(11tn)	12487257	4560778	334.6
481	12512075	4615335	450.1
491(784D)	12495633	4611069	429.0
613	12522134	4595904	474.0
865	12511204	4616550	368.5
9	12538078	4566009	526.8
6	12541565	4564016	517.9
13	12542063	4568999	545.5
1tk	12530604	4572486	482.4
3t	12517899	4536364	549.5

Annual abstraction rates from the boreholes were also provided from the Internal report, *Figure 2.1.1*. For the steady-state model abstraction rates from 25 wells were introduced as averages from 1955 till 2009 and multiplied by five due to low and unrealistic values, *Table 3.3.2*. However, most wells have the data from 1969 till 1981.

Table 3.3.2 Initial average abstraction rates from the PTBA wells

ID	X	Y	Flow rate, m³/day	Screen	
				from layer	to layer
620	12480739	4620902	-30.6	4	4
49(5tn)	12493816	4587470	-404.3	5	5
43(7tn)	12500169	4569587	-368.8	5	5
44(11tc)	12504934	4562203	-1020.0	5	5
3t	12517999	4536581	-172.8	5	5
481	12512027	4615344	-263.8	5	5
613	12521619	4596107	-119.2	5	5
1tk	12530675	4573194	-331.8	5	5
9	12537821	4566542	-224.3	4	5
6	12541214	4564128	-252.6	5	6
908	12520346	4621149	-460.8	5	5
865	12511159	4616564	-301.5	5	5
491(784D)	12495570	4611048	-277.6	5	5
607	12482397	4604815	-60.0	6	6
48(11tn)	12486938	4560914	-230.7	5	5
44(11tc)	12504934	4562203	-1020.0	5	5
41	12509659	4567250	-259.2	5	5
40	12524026	4572769	-456.1	5	5
14	12528950	4581606	-374.2	5	5
609	12535965	4585991	-443.1	5	5
31(13tn)	12539793	4589331	-93.3	5	5
13	12541904	4569485	-150.2	5	6
1tn	12521162	4558045	-129.6	5	5
965	12514857	4554620	-31.0	4	5
45(6tc)	12496604	4544001	-278.6	5	5

No data on recharge estimations and discharge measurements were found.

3.3.2 Meteorological data

Monthly values of rainfall were collected through Climate Data Online (CDO) open source provided by the NOAA's National Centers for Environmental Information (NCEI). 10 stations from Uzbekistan and 11 stations from Kazakhstan were detected from the region. However, only six stations are located on the territory of the PTBA, *Figure 3.3.1*. Six stations (Shymkent, Dukanat, Tuaybuguz, Syr Darja, Ilyich in Uzbek and Cardara (or Chardara)) outside the boundary of the PTBA were indicated as influencing for zones in the north-east, south, south-west and west.
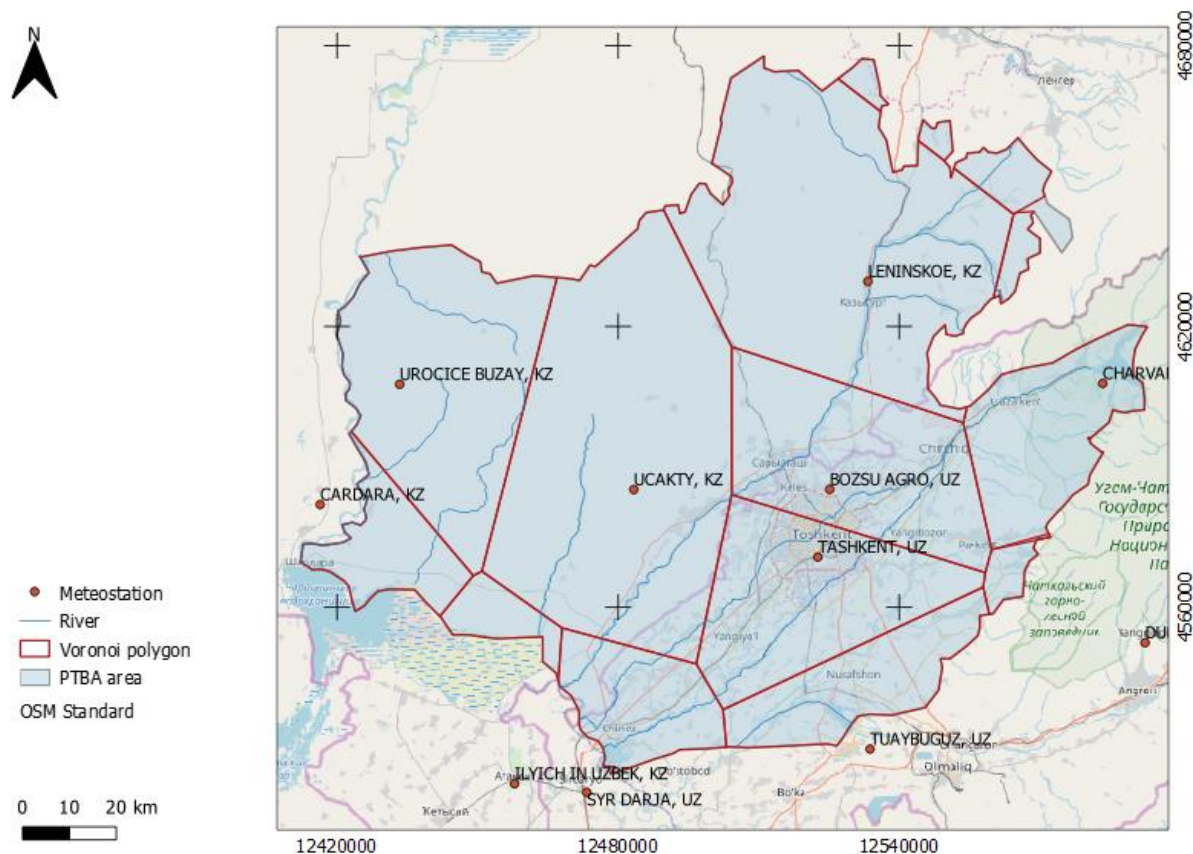
Figure 3.3.1 Meteo stations affecting zones of the PTBA

Most of the stations have datasets from 1963 till 1991. The latest year of monitoring in the CDO dataset is 2005/2006 for Tashkent, Syr Darja and Tuyaubuguz. Average annual rainfalls from selected stations are presented in *Table 3.3.3*.

Table 3.3.3 Average annual rainfall

Station	Country	X	Y	Elevation	Avg. annual rainfall
Syr Darja	UZ	12473316	4520361	264	270.9
Tashkent	UZ	12522634	4570655	477	436.4
Tuaybuguz	UZ	12533765	4529607	428	412.4
Bozsu agro	UZ	12525148	4585101	489	400.4
Charvak	UZ	12583428	4607753	971	809.5
Dukanat	UZ	12592469	4552323	2020	808.3
Ucakty	KZ	12483336	4585077	331	307.5
Urocice Buzay	KZ	12433367	4607580	205	223.7
Ilyich in Uzbek	KZ	12457887	4522210	266	302.0
Leninskoe	KZ	12533304	4629561	575	467.1
Cardara	KZ	12416394	4581876	275	254.7
Shymkent	KZ	12557768	4687146	604	560.6

Temperatures were derived from the same source and stations. Evaporation was collected from the Global Land Evaporation Amsterdam Model (GLEAM). The data is based on reanalysis of net radiation and air temperature, satellite and gauged-based precipitation, and satellite-based

29

VOD, soil moisture, and snow water equivalent (Martens et al., 2017; Miralles et al., 2011). The scale is global and available format is .nc.

3.3.3 Surface water

River discharges, water levels, cross-sections are required as input data for the model. Global Runoff Data Centre (GRDC) provides historical mean daily and monthly discharges from 161 countries ('BfG', 2018). Four stations were identified from this source, two on the territory of Kazakhstan and two on the territory of Uzbekistan. None of them is located within the boundary of the PTBA, and the period is from 1930/1965 till 1985.

The shapefile of a river network was found from the website of Prof. Daene C. McKinney, the University of Texas at Austin as output from the USAID's Environmental Policy and Technology (EPT) project and Environmental Policies and Institutions for Central Asia (EPIC) Program.

The information on water levels and cross-sections from open sources weren't found.

3.3.4 Maps of the Pretashkent Transboundary Aquifer

Following maps were collected for the study:

- Topographic map of the PTBA was found in a printed version of the Atlas of Uzbek SSR, published by the Ministry of geology and soil protection of the USSR, 1963. The projection of the map is Lambert conformal conic, and the scale is 1:3 500 000.
- Generalised geologic map for the PTBA was collected from the USGS World Geologic Maps in .shp file format.
- Two hydrogeological maps were available for Kazakhstan and Uzbekistan. The source for Kazakhstan was the output from the first phase of the GGRETA project. For Uzbekistan, it was the Atlas of Uzbek SSR, 1963.
- Contour map of groundwater levels was collected from the Internal report submitted to the Committee of geology and hydrogeology of Kazakhstan by JSC "Kurort" (2010). Groundwater levels of the PTBA are presented in absolute altitude values dated by 1954 before the start of aquifer exploitation.
- The boundary of the PTBA was delineated using the image from the GGRETA report. Shapefile for the boundary was available for Kazakhstani part only.
- Cross-sections were collected in the format of images only, Appendix I.

Previous maps from the first phase of the GGRETA project were all compiled in Pulkovo 1942/Gauss-Kruger zone 12 projection. Added maps were converted into the same projection.

3.3.5 Data for a conceptual model

Classification of aquifers and aquitards were analyzed from cross-sections and grouped as presented in *Figure 3.3.2*.
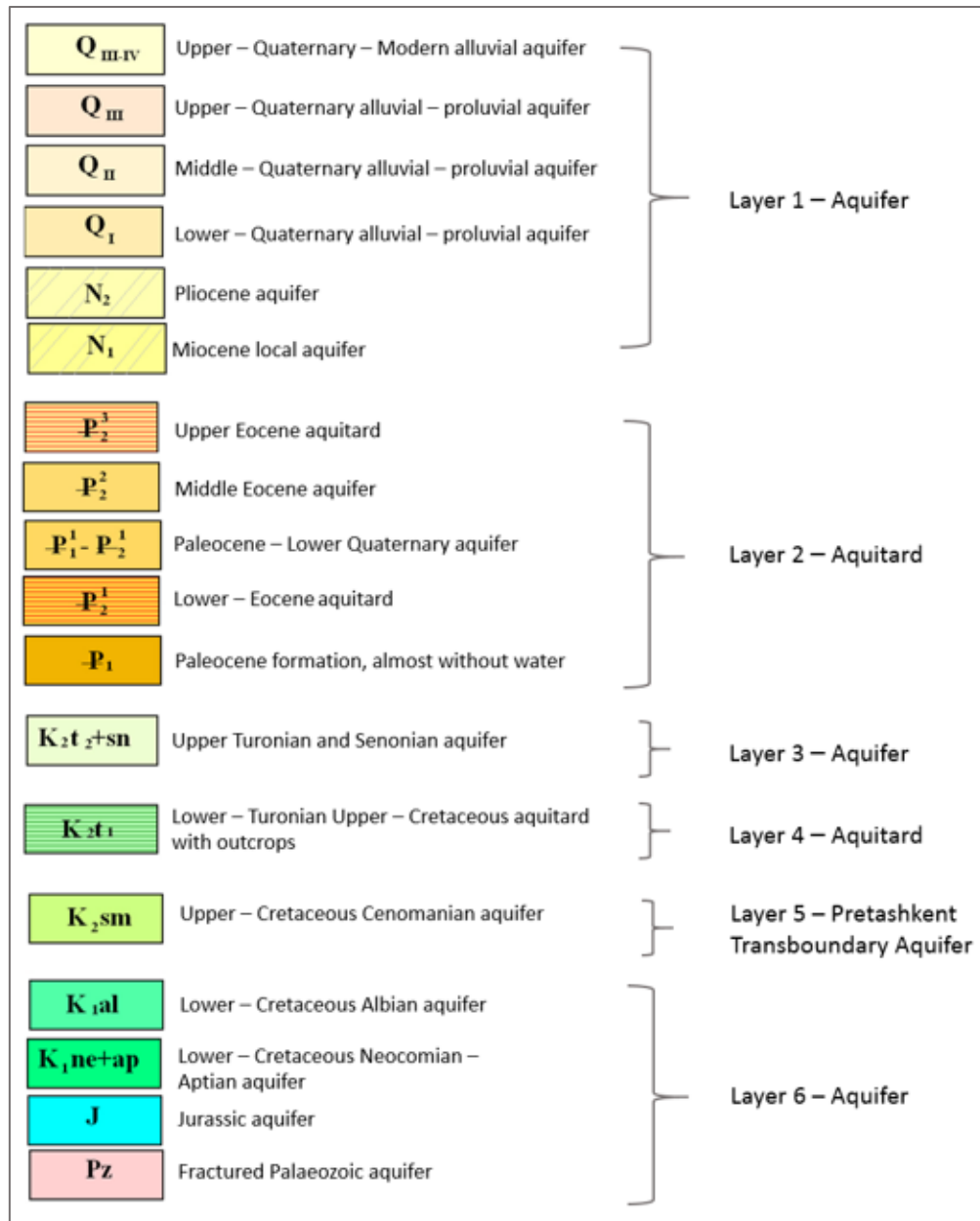
Figure 3.3.2 Layers classification for the PTBA model

Land surface elevation (DEM) was extracted from the Global Multi-resolution Terrain Elevation Data (GMTED2010) provided by the USGS and the National Geospatial-Intelligence Agency (NGA). The data is built from 11 raster-based elevation sources. The initial source dataset for GMTED2010 is NGA's SRTM Digital Terrain Elevation Data (DTED) 1-arc-second data (Danielson and Gesch, 2011). Resolution of 30 arc-seconds (about 1 kilometre) was used for the study.

Values of **hydrogeological parameters** (hydraulic conductivity, porosity, transmissivity) of aquifers and aquitards from available sources are listed in *Table 2.4.1*.

Recharge zones were assumed based on an assemblage of geological zonation, Voronoi polygons and topography, *Figure 3.3.3*. The human factor was not considered.
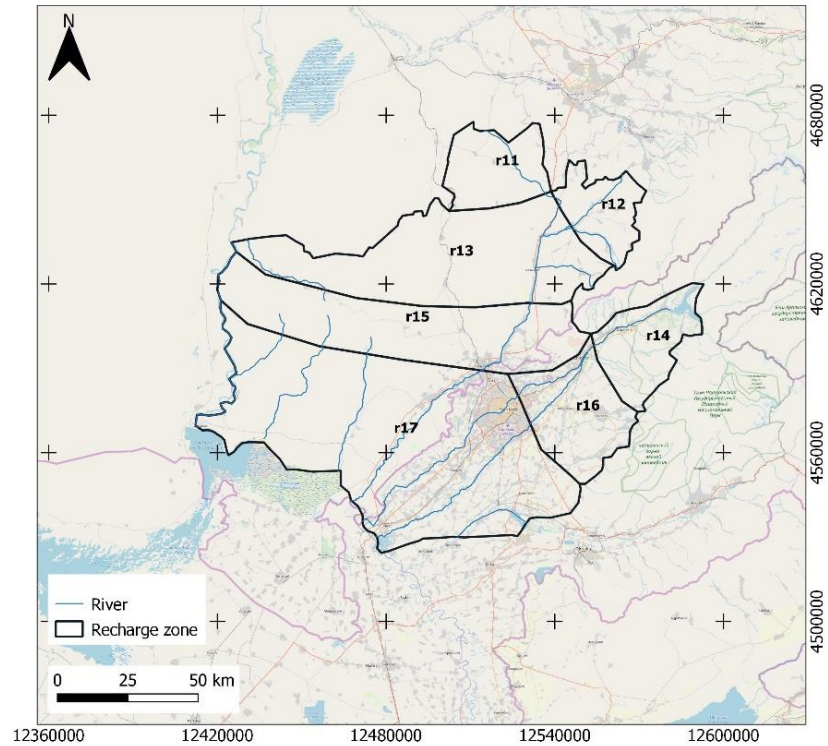
Figure 3.3.3 Recharge zones of the PTBA

Due to the lack of data, water balance or water table fluctuation methods weren't applied to estimate recharge rates to the aquifer. They were assumed as percentage from precipitation, from 6 till 18%, *Table 3.3.4*. r12 and r11 zones are characterized with recharge rate as 6% from precipitation based on the steepness of the slopes. The highest rates are assigned for zones r16 and r17 located on the river valleys.

Table 3.3.4 Recharge rates of the PTBA

Zone	Recharge rate, m/day	Rainfall, m/day	Rainfall, mm/year	% from rainfall
r11	0.00009	0.0015	560.6	6.0%
r12	0.00009	0.0015	560.6	6.0%
r13	0.0001	0.0008	307.5	12.5%
r14	0.0002	0.0022	809.5	10.0%
r15	0.0001	0.0006	223.7	16.6%
r16	0.0002	0.0011	412.4	18.0%
r17	0.0001	0.0007	270.0	14.3%

Chapter 4   Groundwater flow model development

4.1 Construction of a conceptual model

A conceptual model of the Pretashkent Transboundary aquifer for Kazakhstan and Uzbekistan was constructed based on the results from the GGRETA project and supported by literature in Russian and from the Internal Report submitted to the Committee of geology and hydrogeology of Kazakhstan by JSC "Kurort" (2010). *Table 4.1.1* presents coverages for implied hydrogeological processes in the PTBA.

Table 4.1.1 Conceptual model coverages of the PTBA

Types of coverage	Hydrogeological process	Parameters/values
Boundary	Head dependent flow boundary	Heads and conductance
	No flow boundary	-
Layer property	Hydrogeological parameters in every layer	Horizontal and vertical hydraulic conductivities, effective porosity, longitudinal dispersivity for saltwater leakage
Areal property	Recharge from rainfall	Recharge rates
Sources and sinks	Interaction with rivers	Head stages and bottom elevations of river start- and endpoints, conductance
Sources and sinks	Abstraction wells	Location, flow rates
Observation	Observation wells	Observed head, layer range, observed head interval

4.1.1 Boundaries

The western boundary of the top layer was selected as discharge boundary (GHB1 Package) based on information from Hydrogeology of the USSR (1972) where top layer is mentioned as discharging through Syrdarya river. The head stages of Syrdarya and Chardara reservoir start and end points were read from DEM, *Table 4.1.2*. Conductance was assumed as 10 m^2/ day both for Syrdarya and Chardara reservoir. Boundaries of other layers along the perimeter were indicated as No Flow.

Table 4.1.2 Head stage values of Head dependent boundary

ID	River	Head stage, m	Conductance, m^2/day
291	Syrdarya – start point in KZ	236	1.0
292	Syrdarya – end point in KZ	236	1.0
293	Chardara – start point	236	1.0
294	Chardara – end point	263	1.0
295	Syrdarya – end point in UZB	265	2.5

4.1.2 Model layers

The groundwater system was grouped into six layers, *Figure 4.1.1*. The east view indicates the bending of the system towards the south where the depth drops till 2000 m. The areas along Chardara reservoir and Syrdarya river valley are characterized by thinner thickness comparing to other parts of the aquifer. The actual intensely folded layering structure couldn't be introduced to the model to avoid problems with the numerical model. The thickness was modified and averaged in GMS.
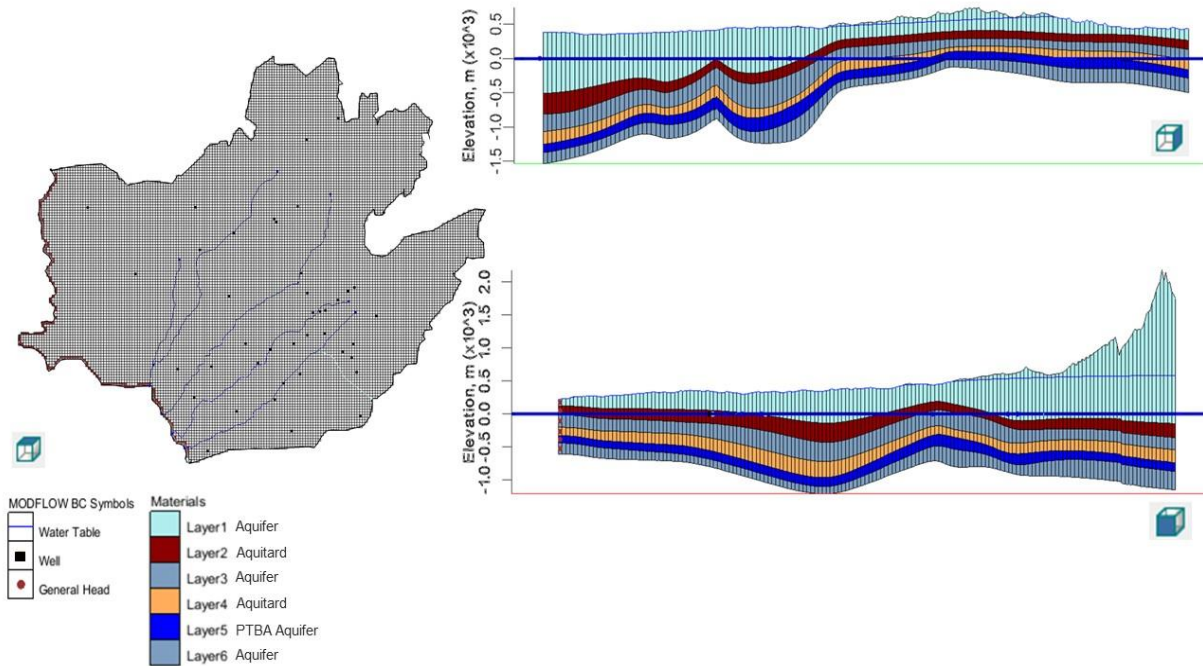
Figure 4.1.1 Top, east side and front view of the PTBA

4.1.3 Layer properties

Layer 1

The first layer is unconfined aquifer, and top elevations were indicated as values from DEM. The material is defined as sands with cobble gravel. The groundwater is fresh and brackish. The first layer is also divided into zones as presented in *Figure 3.3.3*. No values of hydraulic conductivities were found; thus, they were assumed based on lithology, *Table 4.1.3*. The numbering of zones is the same as in *Figure 3.3.3*, the letter index presents a hydrogeological parameter, r for recharge and k for hydraulic conductivity. Assumed porosity is 0.2. Longitudinal dispersivity is 50 m.

Table 4.1.3 Assumed values of hydraulic conductivities for the first layer

Zone	Horizontal conductivity, m/day	Vertical conductivity, m/day
k11	5.0	0.5
k12	5.0	0.5
k13	6.0	0.6
k14	3.0	0.3
k15	4.0	0.4
k16	3.0	0.3
k17	1.5	0.15

Layer 2 – 4

Layers from 2 till 4 have one polygon, no zonation was assigned.

The second layer is an aquitard composed of Upper and Lower Eocene clay. The aquitard was divided into two zones. Horizontal hydraulic conductivity was assumed as 0.1 m/day and vertical – 0.01 m/day in the north-eastern part; horizontal conductivity – 0.01 m/day and vertical – 0.001 m/day in the south-west. The depth of the modified top varies from 492 till –793 m (MSL). Assumed porosity is 0.05. Longitudinal dispersivity is 20 m.

Layer 3 is an aquifer, and it mostly consists of sandstone. Assumed horizontal hydraulic conductivity is 1 m/day, vertical – 0.1 m/day. The modified change of depth fluctuates between 382 and -1028 m (MSL). Assumed porosity is 0.1. Longitudinal dispersivity is 50 m.

Layer 4 is an aquitard of Lower – Turonian Upper – Cretaceous clays with assumed two zones of horizontal hydraulic conductivity of 0.1 m/day and vertical – 0.01 m/day in the north-east and ten times lower in the south-west. The depth of the top changes from 272 till -1448 m (MSL). Assumed porosity is 0.05. Longitudinal dispersivity is 20 m.

Layer 5 – Pretashkent Transboundary Aquifer and Layer 6

Layer 5 is composed of sands, sandstones and conglomerates. The averaged depth of the top varies from 162 till -1868 m (MSL). Assigned horizontal hydraulic conductivity is 2 m/day, and vertical is 0.2 m/day. Assumed porosity is 0.2, and longitudinal dispersivity is 50 m for two bottom layers.

The sixth layer is an aquifer with sands, sandstone and lenses of clays, and the depth varies between -100 till -2228 m (MSL). Assumed horizontal hydraulic conductivity is 1 m/day and vertical - 0.1 m/day.

4.1.4 Areal property

Recharge zonation and rates were introduced in *Chapter 3.3.5*, *Figure 3.3.3* and *Table 3.3.4*. The rates were kept as maximum possible for the system not considering land use aspects. Generally, in arid zones where precipitation is less than 400 mm/year, it doesn't contribute to any recharge (Nonner, 2015). The studies of North American prairies show that recharge is 2 - 9% from annual precipitation (Pétré et al., 2016; Rehm et al., 1982). The climate is continental and annual rainfall is around 480 mm there, that is similar to the PTBA area.

4.1.1 Sources and Sinks

Rivers and abstraction wells are components of sources and sinks in the conceptual model of the PTBA.

Five major rivers were introduced into the system, *Figure 4.1.1*. The head stage was extracted from DEM, bottom elevation was considered two meters lower than the head. Only bottom elevations at the boundaries - discharge areas were ten meters below the head. Conductance was assumed due to data availability, *Table 4.1.4*.

Table 4.1.4 Input values for rivers (Sources and sinks coverage) in the conceptual model of the PTBA in GMS

Name	Part	Conductance, m/day	Head stage, m	Bottom elevation, m
Keles	Upper	0.8	574	572
	Middle		432	430
	Discharge area		249	239
Chirchik	Upper	0.1	519	517
	Discharge area		252	242
Bozsu canal	Upper	0.1	564	562
	Discharge area		258	248
Kuruk Keles	Upper	0.75	332	330
	Middle	0.5	275	273
	Discharge area	0.1	248	238

Location of abstraction wells is presented in *Figure 4.1.2*, and abstraction rates from the Internal report are indicated in *Table 3.3.2*. However, total amount of extracted water from the PTBA gives low value – 7,753.8 m³/day. It was decided to increase the provided abstraction rate five times, and the sum resulted in 38,769 m³/day of extracted groundwater from the PTBA, except two wells that pump water from Layer 4 and 6.
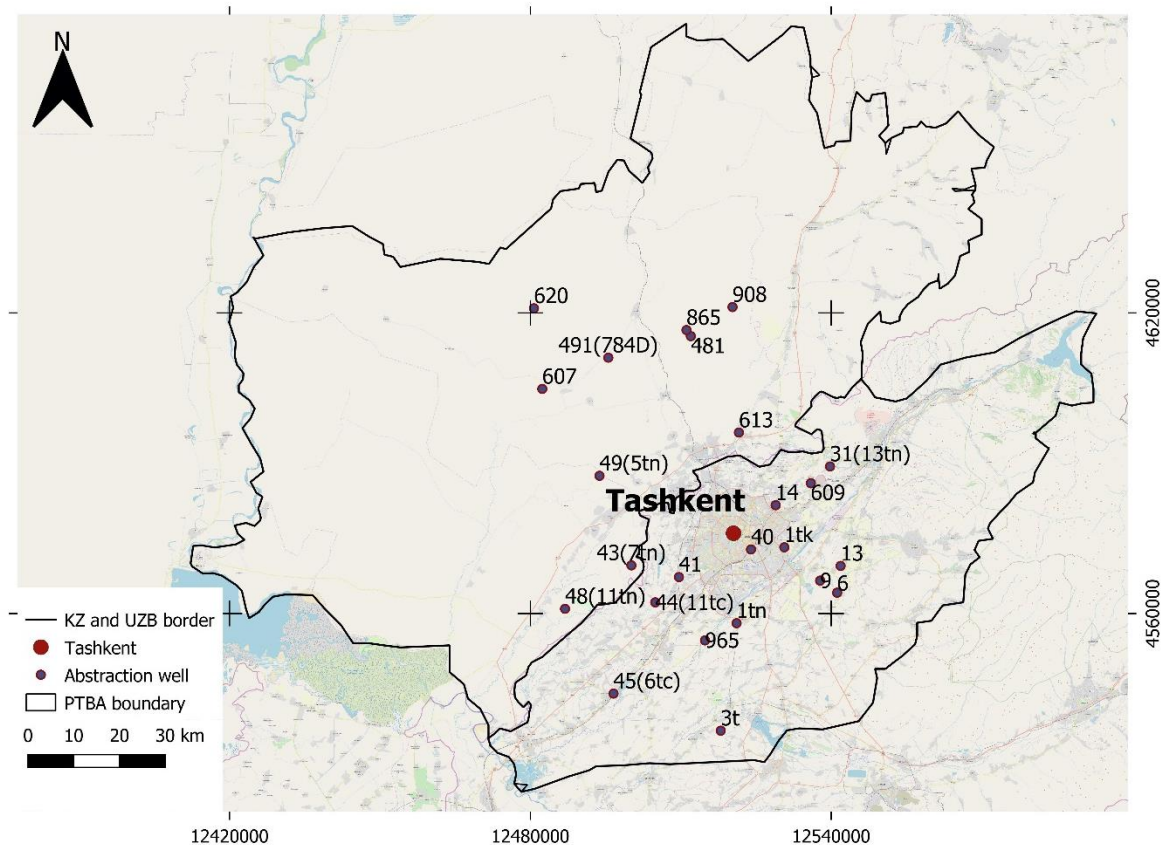
Figure 4.1.2 Location of abstraction wells in the PTBA system

The previous research also indicates the existence of faults and springs in the area, but the absence of data doesn't allow to assess the processes depending or influenced by them.

Two top aquifers are used for drinking and agricultural purposes. Their quality of groundwater ranges from fresh to brackish. However, increasing agricultural activities may lead to the degradation of the groundwater state forcing people to start using more water from deep-lying aquifers such as the PTBA. To estimate the processes in this groundwater system, a conceptual model was converted into numerical, allowing to analyse the quantity of water, the direction of flow and potential salinisation of the PTBA.

4.2 Design of a numerical model

Model Type

The objective of the study is to analyse the flow and major components of the water balance in the PTBA groundwater system. It can be reached by simulating a steady-state model.

Model Grid

All the coverages created for the conceptual model were converted to a 3D grid frame with characteristics in *Table 4.2.1* and visualisation in *Figure 4.2.1* using Projection: Transverse Mercator, Zone, Pulkovo 1942, m. Cell dimension 1 km×1 km and grid type – cell centred.

Table 4.2.1 3D Grid

Parameter	X	Y	Z
Origin, m	12411230.0	4522830.0	340.0
Length, m	184000.0	157000.0	600.0
AHGW origin, m	12411230.0	4679830.0	940.0
Number of cells	j184	i157	k6
AHGW Rotation angle	90		
Minimum scalar	308.5		
Maximum scalar	320.6		
Number of nodes	204610.0		
Number of cells	173328.0		
Active cells	95091.0		
Inactive cells	78237.0		

The upper surface was derived from the USGS and the National Geospatial-Intelligence Agency (NGA) Global Multi-resolution Terrain Elevation Data. The dataset was converted to 2D scatter point dataset. Top elevations of layers and bottom of the sixth layer were obtained from cross-sections and were introduced to the 2D scatter point dataset. Further, the 2D dataset was interpolated using ordinary kriging to MODFLOW layers. Once every layer had the elevation, the model was checked, and the result gave errors due to thickness overlapping. Then, GMS allows to fix the interpolation with four approaches: average, preserve top, preserve bottom and truncate to bedrock. The overlapping was corrected using average and preserve top options.
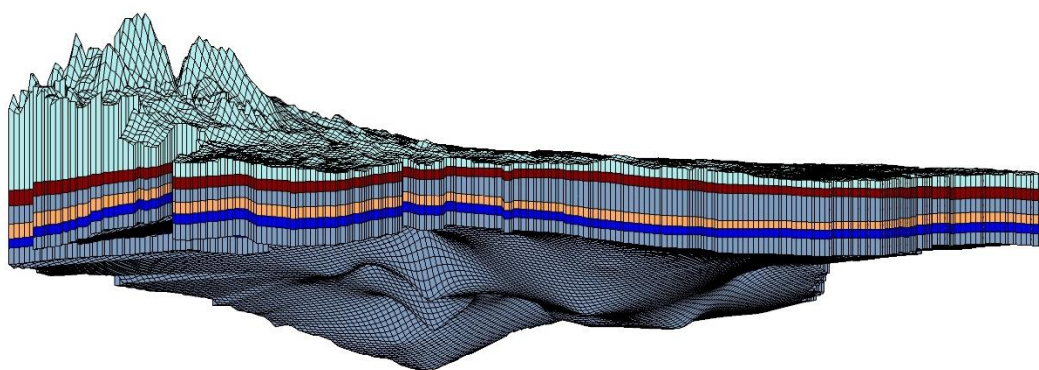
Figure 4.2.1 Active model grid cells of the PTBA – view from the north

4.3 Flow model

All the coverages of the Conceptual Model were converted to the numerical with packages presented in *Table 4.3.1*. Selected MODFLOW version is 2005 Parallel, and run option is forward. The solver is Preconditioned Conjugate Gradient. Starting heads are equal to the grid top elevations. The input file for top elevations is the DEM. Bottom elevations are interpolated from 2D scatter data.

Table 4.3.1 Conversion of conceptual model coverages to a numerical

Model components	Conceptual model	MODFLOW
Boundary	Boundary coverage	General Head boundary and No-flow
Hydraulic properties	Layer property	LPF package
Recharge	Areal property	Recharge - RCH1 package
Optional processes	Sources and sinks	River – RIV1 Package
	Sources and sinks	Well – WEL1 package
Observations	Observation coverage	Observation package

Boundary Conditions

General Head boundary was assigned to the first layer in the west and south-west representing the Syrdarya river and Chardara reservoir. The other boundaries for all the layers are characterised as no-flow boundaries. Ìn addition, General Head boundary was also incorporated along six layers to analyse the behaviour of a river as discharging or recharging area of the aquifer.

Hydraulic properties

For the steady-state model Layer Property Flow was selected as flow package. Data arrays were used to import data on horizontal and vertical hydraulic conductivities. Layer type is confined.

Recharge

Recharge was assigned to the top layer using seven zonations and rates as 6-18% of precipitation, *Figure 3.3.3* and *Table 3.3.4*.

Optional processes

River package was assigned to the top layer. Values of conductance for five rivers and their head stages were introduced through arcs using GMS Map tools, *Figure 4.1.1* and *Table 4.1.4*.

Well package covered the incorporation of abstraction wells with input data on rates and their locations for the PTBA, *Figure 4.1.2* and *Table 3.3.2*.

Observations

Observation wells have the same location as abstraction wells, observed heads are presented in *Table 3.3.1*.

4.3.1 Test of hydrogeological parameters

As a result of running the first simulation, computed hydraulic heads were compared to the observed (available dataset for static heads in a resting groundwater system), *Figure 4.3.1*. The application of static heads for calibration is a significant assumption (Berehanu et al., 2017). Thus, for this data scarce region logical values were set as introduced in the previous chapters, and the test model was accepted without the calibration.
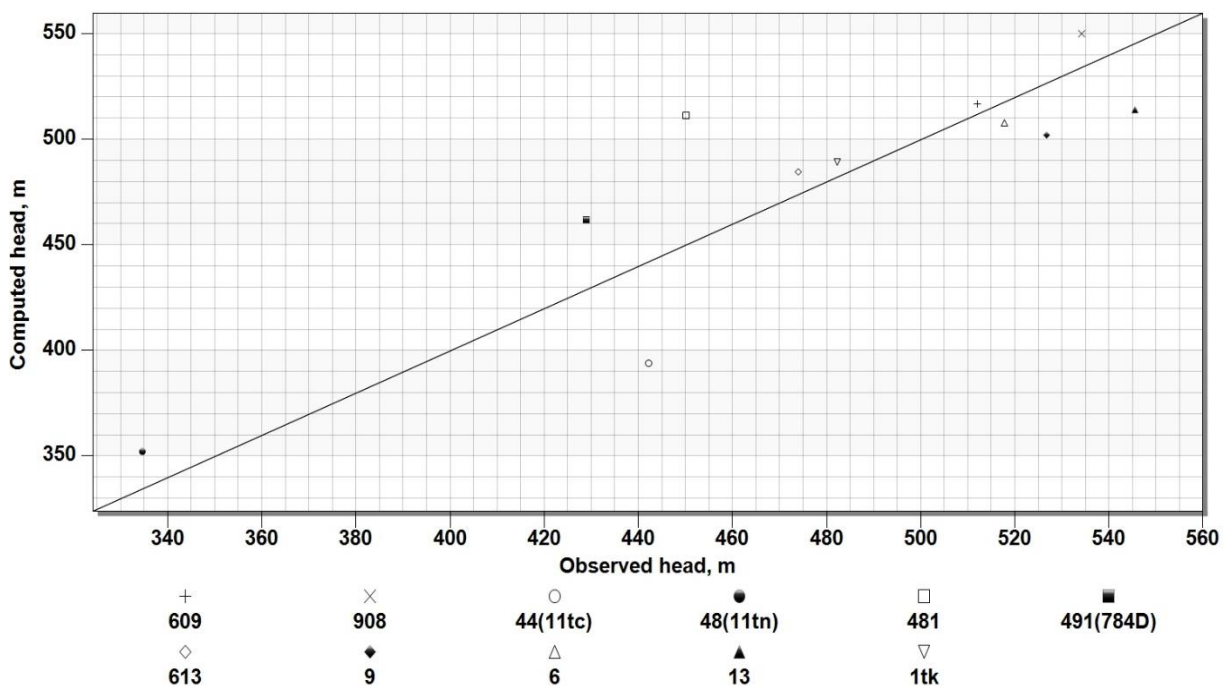
Figure 4.3.1 Computed vs Observed Heads

Test of discharge boundaries

Two scenarios were run with the discharge boundary package. The first trial included the head dependant boundary for the first layer only, the second trial assigned it to layers from 1 to 6. Heads of the first layer don't vary significantly between two scenarios. However, the difference

along Syrdarya river appears in layer 5 for around 50 m, where they drop in case of head dependant boundary assigned to all layers, *Figure 4.3.2* and *4.3.3*.
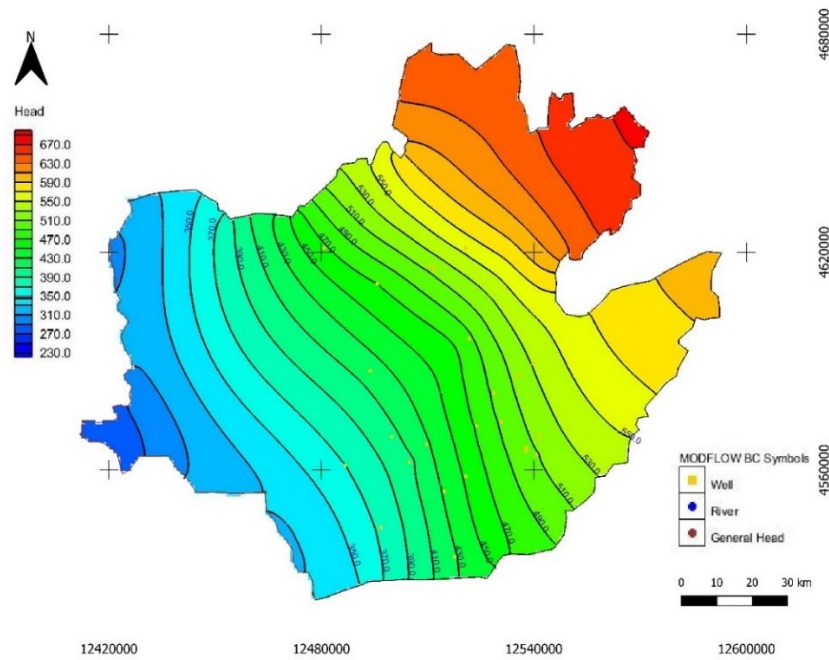
Figure 4.3.2 Hydraulic head in Layer 5 – Discharge boundary Layer 1
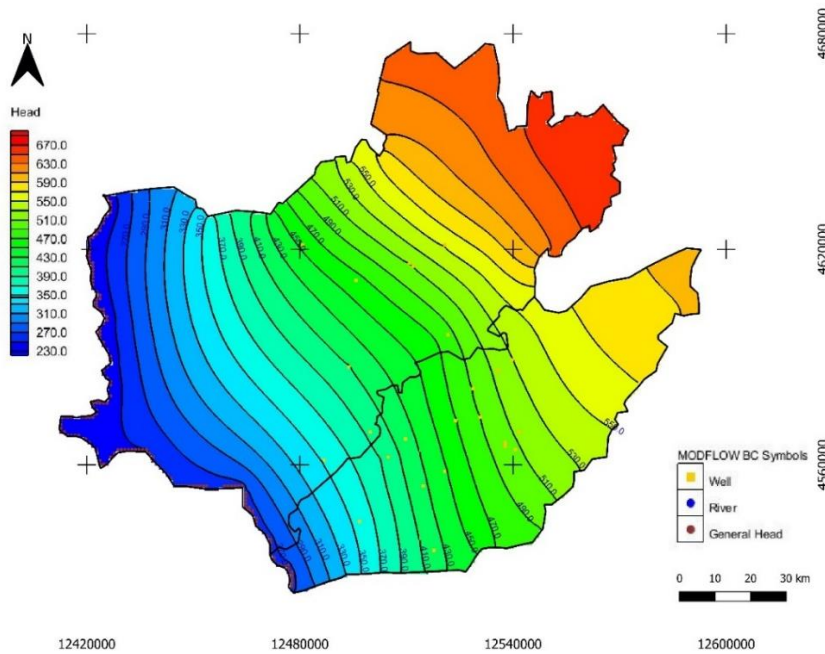
Figure 4.3.3 Hydraulic head in Layer 5 – Discharge boundary Layer 1-6

The analysis of the flow budget show the amount of water present in the system increases with introducing head dependant boundary for all layers. River leakage and discharge boundary increase from 2% to 2.5% and from 0.5 to 0.8% accordingly of contribution to the total inflow, *Table 4.3.2*.

The aquifer system loses more water through outflow boundary in the second scenario, 36.7% in the first scenario to 43.4% in the second case of contribution to the outflow. Contrary, the

component of river leakage in the outflow part of the budget reduces from 61% in the first scenario to 54.4% in the second scenario, contributing to the total outflow.

Table 4.3.2 Flow budget for the test of discharge boundary

	Head dependant boundary – Layer 1		Head dependant boundary – Layer 1:6	
Inflow:	m³/day	%	m³/day	%
River leakage	37820.1	2.0	47078.0	2.5
Boundary inflow	9040.0	0.5	14657.1	0.8
Recharge	1803089.9	97.5	1803089.9	96.7
Total inflow	1849949.9	100.0	1864825.0	100.0
Outflow:	m³/day	%	m³/day	%
Wells	41904.6	2.3	41904.6	2.2
River leakage	1129255.0	61.0	1013721.9	54.4
Boundary outflow	678790.6	36.7	809202.1	43.4
Total outflow	1849950.3	100.0	1864828.6	100.0

Test of discharge boundary with conductance

When the conductance is reduced two times for the discharge boundary assigned for the top layer, total amount of incoming water reduces for 1,835 m³/day. Inflow boundary of the flow budget changes for 0.1%, being larger in the case of initial conductance. The outflow budget components behave with the same pattern of change. With decreased conductance the only difference is that more water leaves the system through discharge into rivers rather than through western boundary, 75.5% from the total outflow of discharge to river comparing to 74.7% through the same components with initial conductance.

When the conductance is increased twice for the GHB1 package, incoming water to the aquifer system from the rivers is increased to 0.1%. The amount of water leaving the system from the western boundary increased by 0.7%. The change in total inflow and outflow is 2,444.7 m³/day higher comparing to the first scenario with initial conductance, *Table 4.3.3*.

Table 4.3.3 Flow Budget for GHB1 Package with changes in conductance

	Discharge Boundary in Layer 1		
	Conductance initial	Conductance min	Conductance max
Inflow:	m³/day	m³/day	m³/day
River leakage	42266.9	41418.4	43047.9
Boundary inflow	5693.3	4706.8	7357.1
Recharge	1931369.8	1931369.8	1931369.8
Total inflow	1979330.1	1977495.1	1981774.8
Outflow:	m³/day	m³/day	m³/day
Wells	41904.6	41904.6	41904.6
River leakage	1478193.3	1493684.2	1465816.5
Boundary outflow	459232.1	441906.3	474053.7
Total outflow	1979330.0	1977495.2	1981774.9

Test of river conductance

To see the role of rivers in the system, two scenarios were simulated with increased and decreased values of conductance, *Table 4.3.4.*

Table 4.3.4 River conductance test

ID	Name	Part	Initial Conductance	Reduced Conductance	Increased Conductance
6	Keles	Discharge area	0.8	0.8	0.8
4		Upper	0.8	0.1	1
11	Chirchik		0.1	0.1	0.5
12	Bozsu canal		0.1	0.1	0.5
17	Kuruk Keles (tributary)	Upper	0.75	0.01	0.9
1	Kuruk Keles	Upper	0.75	0.01	0.9
4		Discharge area	0.1	0.01	0.2

Keles, Kuruk Keles river and its tributary act as discharge zones of the aquifer system when initial values are assigned to them, *Figure 4.3.2*. Their influence reaches the PTBA – Layer 5, where the pattern of contour lines indicates the location of rivers, *Figure 4.3.3*. Despite when conductance is reduced for Kuruk Keles and its tributary, we see the change of river domination. It switches towards Keles, being the central discharge zone in the aquifer system, *Figure 4.3.4*. The footprint of Keles importance can be slightly noticed in Layer 5, *Figure 4.3.5*. When conductance is increased for all rivers, the character remains the same as with initial values. Minor changes occur for Chirchik and Bozsu canal, where they start gaining more groundwater.

Flow budget was assessed for river leakage and head dependant boundary components, *Table 4.3.5*. Due to the increase or decrease of the conductance, the amount of water that interacts between the groundwater system and rivers reduces or increases accordingly. When river conductance reduced, river leakage to the aquifers decreases from 2.1% to 1.4% of contribution to the inflow of the groundwater budget and goes up to 9.5% of inflow with increased conductance. A considerable change (5 times higher) can be noted between initial and increased conductance scenario for the actual values of river leakage in inflow. The same applies to the amount of water flowing out of the system through rivers. River leakage reduces to 68.8% from 74.7% as a contribution to the outflow, when conductance is decreased. There is no significant rise of river leakage in the outflow when conductance values are higher, the change is from 74.7% of initial values to 78.6% of increased conductance. Head dependant boundary reacts the same way for inflow and the opposite way for outflow to maintain the balance. In the inflow the difference varies between $500 – 700 \ \text{m}^3$/day of water flowing into the system from discharge boundary. The amount of water leaving the system through the western border rises from 23.2% to 29.1% when river conductance is minimum and drops for 3.7% when conductance is maximum.

In the following simulations decreased conductance was used to avoid pronounced discharge roles of Kuruk Keles and its tributary due to their absence of information and their existence on some maps.

Table 4.3.5 River leakage and Discharge boundary components with changes in river conductance

	River Conductance initial	River Conductance min	River Conductance max
Inflow:	m³/day	m³/day	m³/day
River leakage	42266.9	26614.6	202483.2
Boundary inflow	5693.3	4976.3	6190.0
Outflow:			
River leakage	1478193.3	1350244.9	1681119.9
Boundary outflow	459232.1	570814.6	417019.4

Minimum values of river conductance and General Head boundary assigned for the first layer were kept for the sensitivity analysis and the presentation of results.
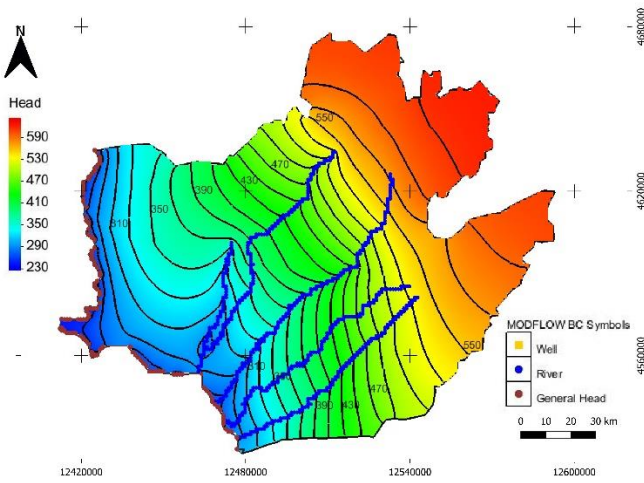
Figure 4.3.4 Hydraulic heads of Layer 1 – River Conductance initial
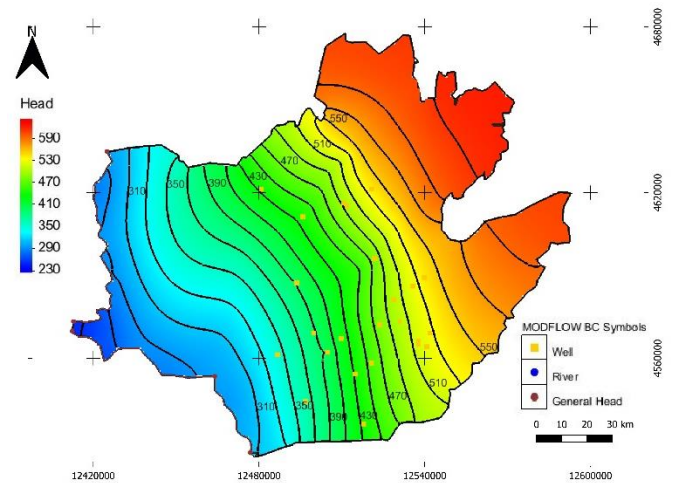
Figure 4.3.5 Hydraulic heads of Layer 5 – River Conductance initial
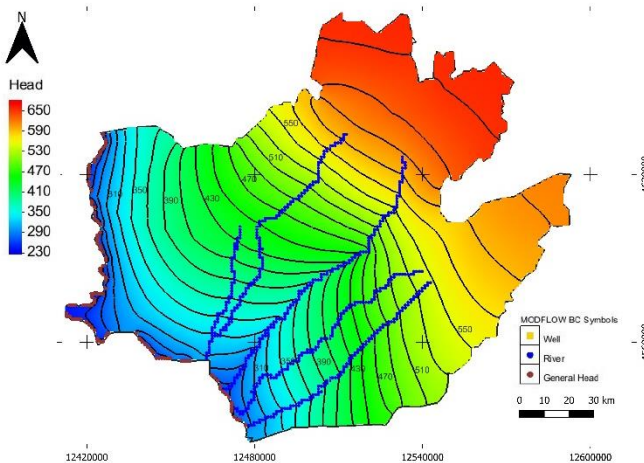
Figure 4.3.6 Hydraulic heads of Layer 1 – River Conductance min
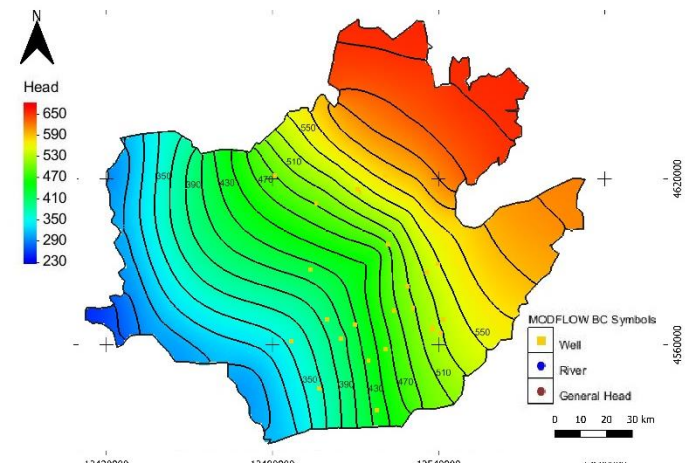
Figure 4.3.7 Hydraulic heads of Layer 5 – River Conductance min
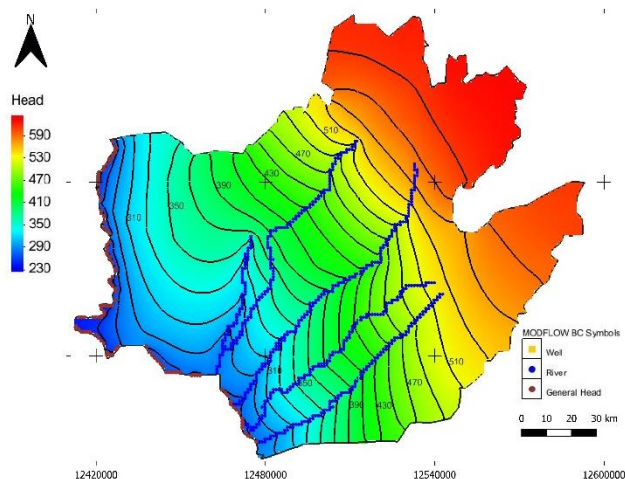
Figure 4.3.8 Hydraulic heads of Layer 1 – River Conductance max   Figure 4.3.9 Hydraulic heads of Layer 5 – River Conductance max
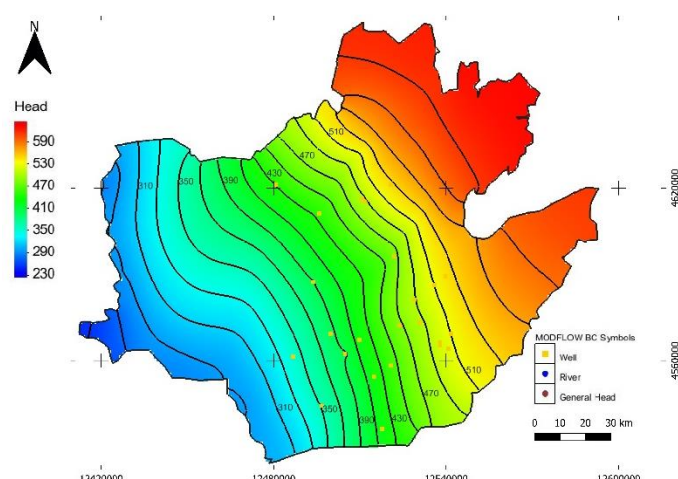
4.4 Cl transport model

There is a possibility the PTBA might receive the leakage from more saline upper aquifers. Cl constant concentration of 1000 mg/l was introduced in every cell of the third layer to see how the PTBA possibly might react to the leakage. Basic Transport, Advection, Dispersion, Source/sink mixing and GCG Packages were used in the MT3DMS model in a steady-state mode.

4.4.1 Model parameters

MT3DMS model included a set up presented in *Table 4.4.1*.

Table 4.4.1 Basic Transport Package

Model	MT3DMS
HTOP equals top of layer 1	On
Species	Cl
Starting concentration	1000 mg/l
Stress periods	1 stress period. Length - 182 500 days – 500 years
Output Control	Print or save at a specified interval - 1
Step size	30 days
Units	Time - day Mass – kg Concentration – mg/l
ICBUND	Layer 1-2, 4-6 – (1) for variable concentration Layer 3 – (-1) for constant concentration
Porosity	Layer 1 – 0.2 Layer 2 – 0.05 Layer 3 – 0.1 Layer 4 – 0.05 Layer 5 – 0.2 Layer 6 – 0.2
Packages	Advection, Dispersion, Source/Sink mixing Package

Advection package

Applied Solution scheme is the Third Order TVD scheme (ULTIMATE). One cell particle is allowed to move per transport step (PERCEL).

Dispersion Package

Dispersion values for all the layers are the same. The ratio of horizontal transverse dispersivity to longitudinal dispersivity (TRPT) is equal to 0.1, and the ratio of vertical transverse dispersivity to longitudinal dispersivity is 0.01 (TRVT), the diffusion coefficient is 0. Longitudinal dispersivities for aquifers is 50 (Layer 1, 3, 5, 6), and 20 for aquitards (Layer 2 and 4).

4.5 Sensitivity analysis

A sensitivity analysis was conducted to find relative sensitivities of the model to hydraulic conductivity and recharge values. The adjustment of parameters was done by reducing and increasing initial values twice for Layer 1 and Layer 5.

4.5.1 Hydraulic conductivity

To assess the response of the groundwater system, four scenarios were simulated with increased and decreased hydraulic conductivity (K) values for the first and fifth layers separately, *Table 4.5.1*. The change of flow components indicates that Layer 1 is more sensitive to adjustments comparing to Layer 5, *Figure 4.5.1*. Outflow processes such as water discharging from the western boundary and to rivers are more dependant on the change of hydraulic conductivity in both layers than inflow processes.

Table 4.5.1 Hydraulic conductivity change for Layer 1 and Layer 5

Layer	Zones	K initial		K min		K max	
		horizontal	vertical	horizontal	vertical	horizontal	vertical
1	k11	5.0	0.5	2.5	0.25	10	1
	k12	5.0	0.5	2.5	0.25	10	1
	k13	6.0	0.6	3	0.3	12	1.2
	k14	3.0	0.3	1.5	0.15	6	0.6
	k15	4.0	0.4	2	0.2	8	0.8
	k16	3.0	0.3	1.5	0.15	6	0.6
	k17	1.5	0.15	0.75	0.075	3	0.3
5	1 polygon	2	0.2	1	0.1	4	0.4

When hydraulic conductivity was increased in the first layer, water flows out more through rivers than from the west boundary. Another remark for the same scenario is linked to inflow processes. River leakage contribution decreased and discharge boundary became lower but only for 3,048 m^3/day comparing to the base scenario. The change of total inflow and outflow results in rising quantity of water for 12,277 m^3/day in the case of increased hydraulic conductivity.

The system reacts in the opposite way when hydraulic conductivity is decreased for Layer 1. Less water is entering the system through rivers and the input from the west boundary rises. In the outflow processes, through discharge boundary 81,371 m^3/day of water flows less than in

the base scenario. Overall, the available amount of water in the flow budget decreases for 19,942 m³/day.

In the case when hydraulic conductivity in the fifth layer (PTBA) is increased, significant changes are noticed for outflow processes. Through rivers, the aquifer system discharges for 39,732 m³/day of less water comparing to initial hydraulic conductivity assigned to Layer 5 and around the same amount of water flows more through the western boundary. There is a slight change for inflow terms: less water coming from the western boundary than from rivers, and for the outflow components – rivers dominate. Total budget declines for 3,356 m³/day.

When hydraulic conductivity is reduced in the fifth layer, both components of the inflow processes are increased, for 1,971 m³/day through river leakage and 356 m³/day through discharge boundary. Inversely for the outflow, the western boundary weakens its role, and more water discharges through rivers to the aquifers, 22,099 m³/day more comparing to the base scenario. The change in total budget is 2,326 m³/day of increase.
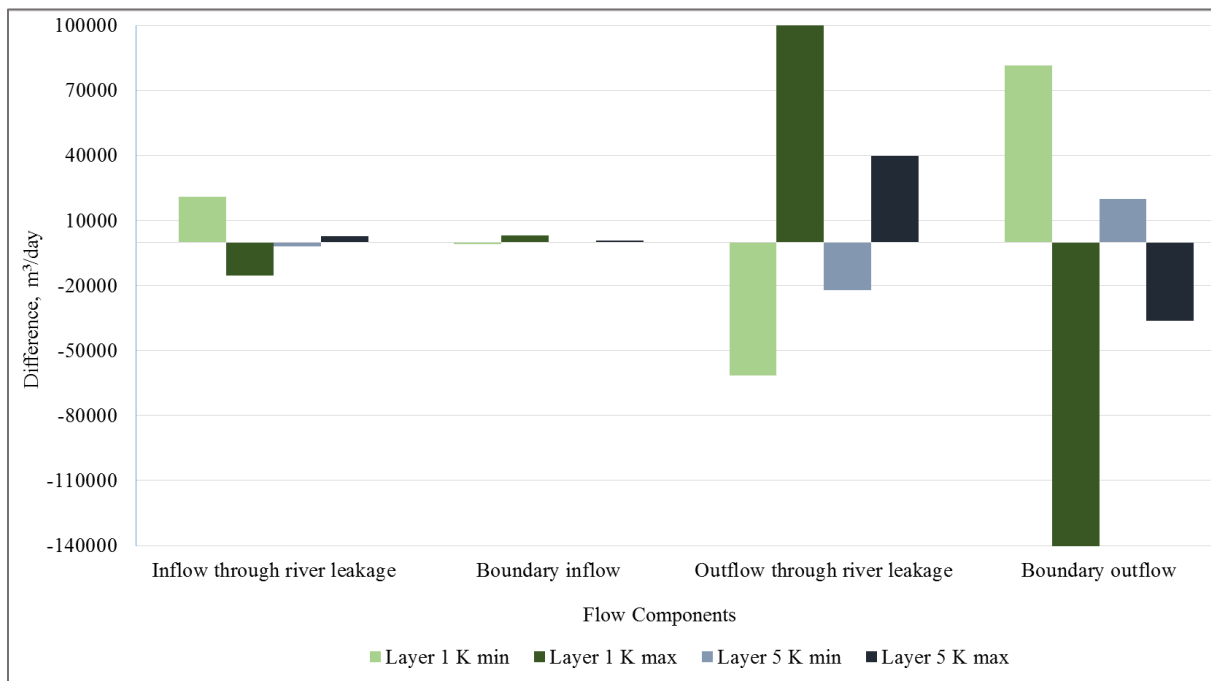
Figure 4.5.1 The change of flow budget components with the increase and decrease of hydraulic conductivity in Layer 1 and 5

Hydraulic heads respond accordingly to alterations in hydraulic conductivity values. When this parameter is changed in the first layer, the following shifts occur, *Figure 4.5.2*:

- Heads increase and the distance between contour lines decreases when K is minimum. The pattern of river dominance in Layer 5 is still visible;
- Heads fall and the distance between contour lines increases, when K is maximum. The influence of river in Layer 5 is not evident.
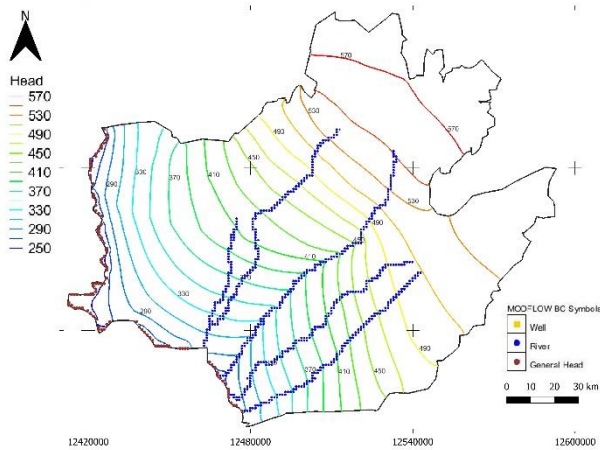
Layer 1 – K max assigned to Layer 1
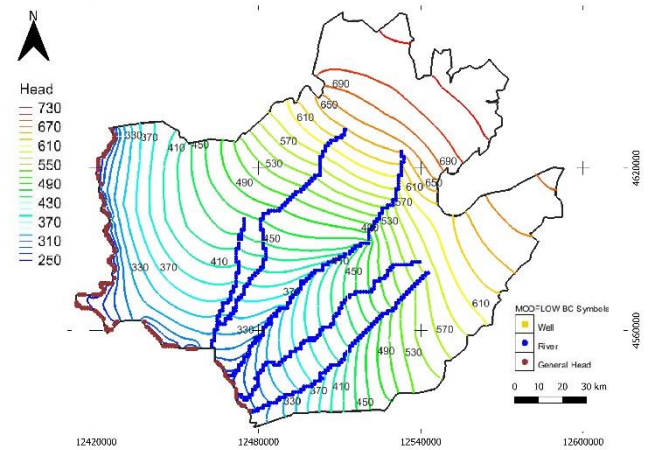
Layer 1 – K min assigned to Layer 1
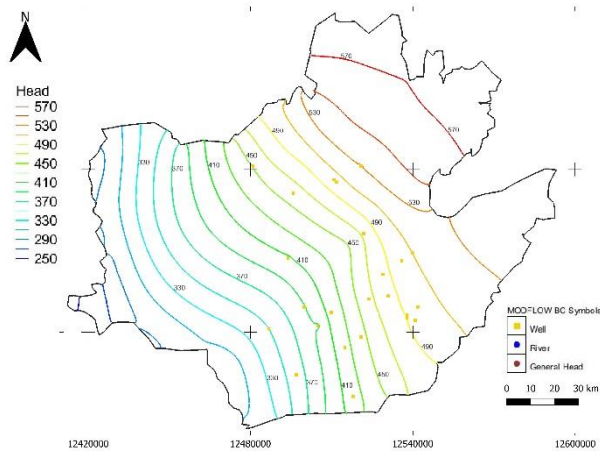
Layer 5 – K max assigned to Layer 1
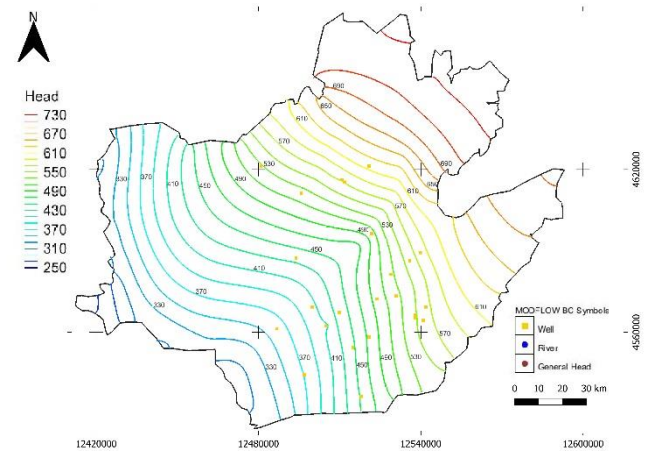
Layer 5 – K min assigned to Layer 1

Figure 4.5.2 Hydraulic conductivity change in Layer 1

The second set of scenario includes the change of hydraulic conductivity in Layer 5 where the role of Keles river is well pronounced throughout the system until Layer 5. An insignificant discrepancy (40 m) is in higher heads when hydraulic conductivity is minimum, *Figure 4.5.3*.
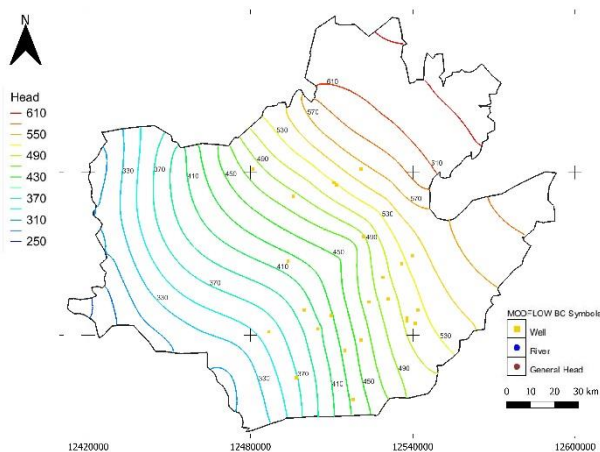
Layer 5 – K max assigned to Layer 5
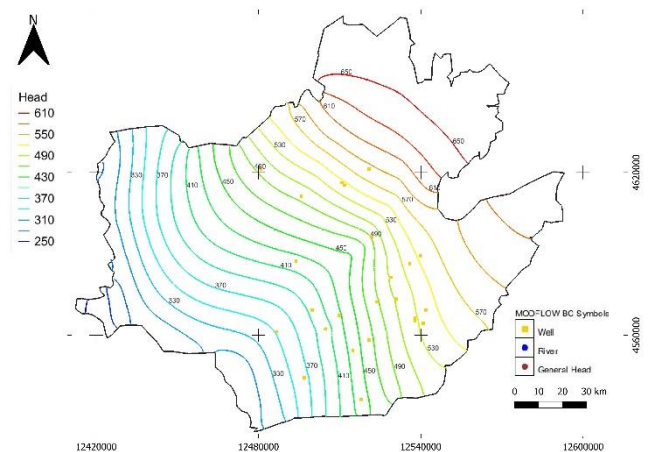
Layer 5 – K min assigned to Layer 5

Figure 4.5.3 Hydraulic conductivity change in Layer 5

The flow budget of the PTBA was assessed separately using zone budget tool in GMS. The largest amount of the flow entering and leaving the PTBA is in scenario with minimum

hydraulic conductivity assigned to Layer 1, *Figure 4.5.4*. The lowest amount of water exchange in the PTBA is with the maximum hydraulic conductivity in Layer 1.
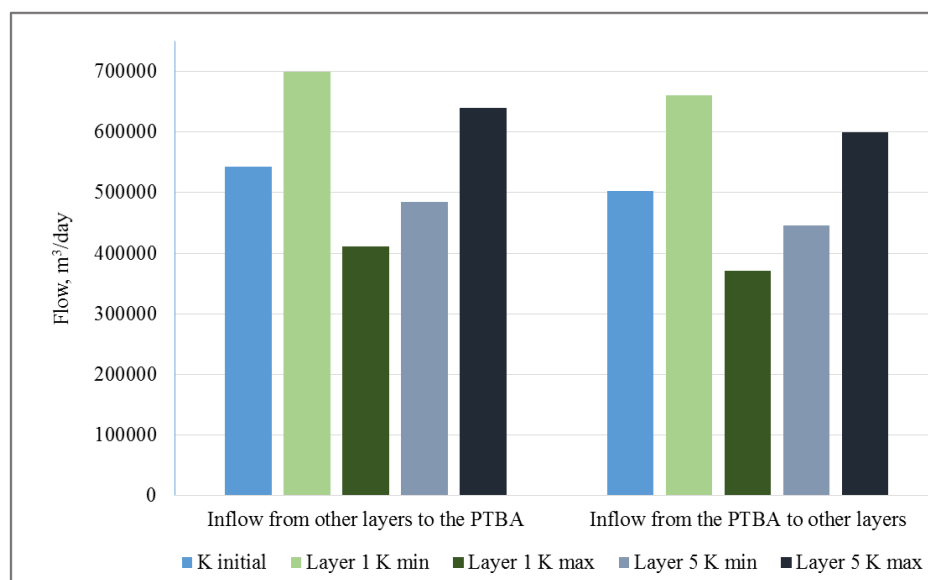
Figure 4.5.4 Zone budget for five scenarios with the change in hydraulic conductivity

4.5.2 Recharge

Recharge (R) is assigned for the first layer and divided into seven zones, the values were also increased and decreased two times, *Table 4.5.2*. Flow components for the outflow are more sensitive than for inflow, *Figure 4.5.5*. In this comparison case, river leakage component influences the groundwater flow system stronger than discharge boundary.

When recharge is decreased, both river leakage and the discharge boundary receive more water comparing to the base scenario with initial rates of recharge. Assessing the contribution of river leakage to the groundwater budget, the indicator increases from 1.4% of base case scenario to 6.3% of minimum recharge rates. The same applies to the discharge boundary with minor changes, from 0.25% to 0.63% of contribution to the total inflow. The absolute values of water flowing out through rivers and the boundary reduces comparing to the base scenario. Looking at the contribution of these terms to the total amount of outflow, river leakage changes from 68.8% in the base scenario to 55.3%. Contrary, outflow from the western boundary increases from 29.1% of the outflow contribution in the base scenario to 40.3% with decreased recharge rates.

When recharge is increased twice, inflow components react differently. More water enters the system through discharge boundary. Rivers leakage in the inflow didn't change from the base scenario. Boundary inflow reduces for 1,267 m^3/day. Increased recharge affects the total amount of water in the system, it rises for 1,766,788 m^3/day. Both components of the outflow increases, much more water discharges through rivers rather than western boundary, 2,785,012 comparing to 902,829 m^3/day accordingly.

Table 4.5.2 Recharge rates for two scenarios

Zone	Initial	Minimum	Maximum
	m/day	m/day	m/day
r11	0.00009	0.000045	0.00018
r12	0.00009	0.000045	0.00018
r13	0.0001	0.00005	0.0002
r14	0.0002	0.0001	0.0004
r15	0.0001	0.00005	0.0002
r16	0.0002	0.0001	0.0004
r17	0.0001	0.00005	0.0002
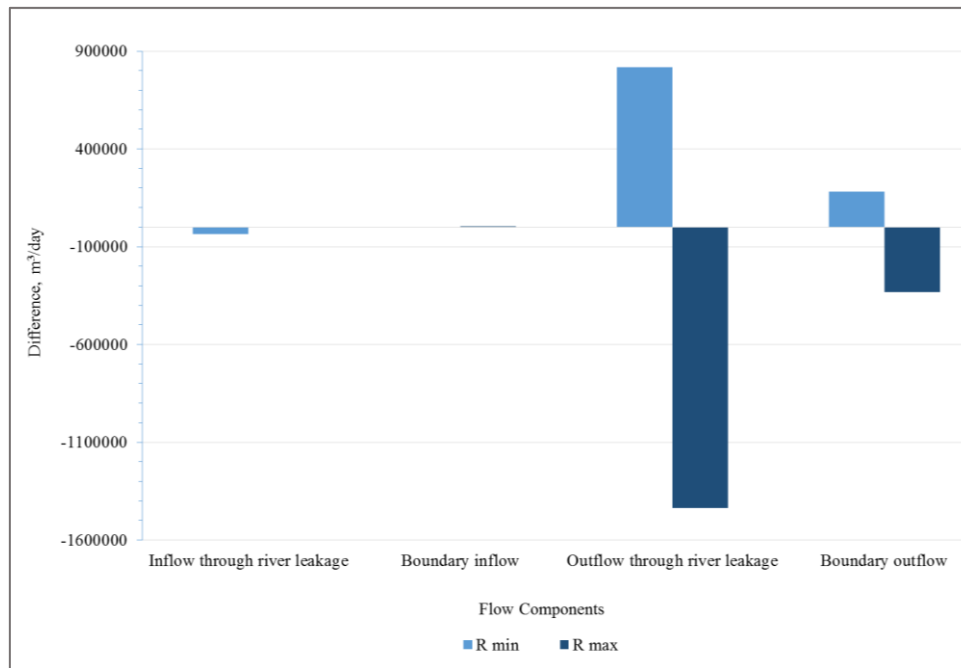
Figure 4.5.5 The change of flow budget components with the increase and decrease of recharge

Heads with increased recharge rates are higher than at minimum rates. Moreover, contour lines are also closely located to each other. This means the velocity of the flow increases when the system receives more water through the infiltration of precipitation or irrigation. With the reduction of recharge rates, hydraulic heads drop for around 250 m. The difference between Layer 1 and 5 for two scenarios results in the impact of the river. In Layer 5, it has fewer effects on the shape of contour lines. Comparing two scenarios with increased and decreased recharge rates, brings the same change: in case of reduced recharge the influence of river is less dominant in Layer 5.

Layer 1 – R max

Layer 1 – R min

Layer 5 – R max

Layer 5 – R min
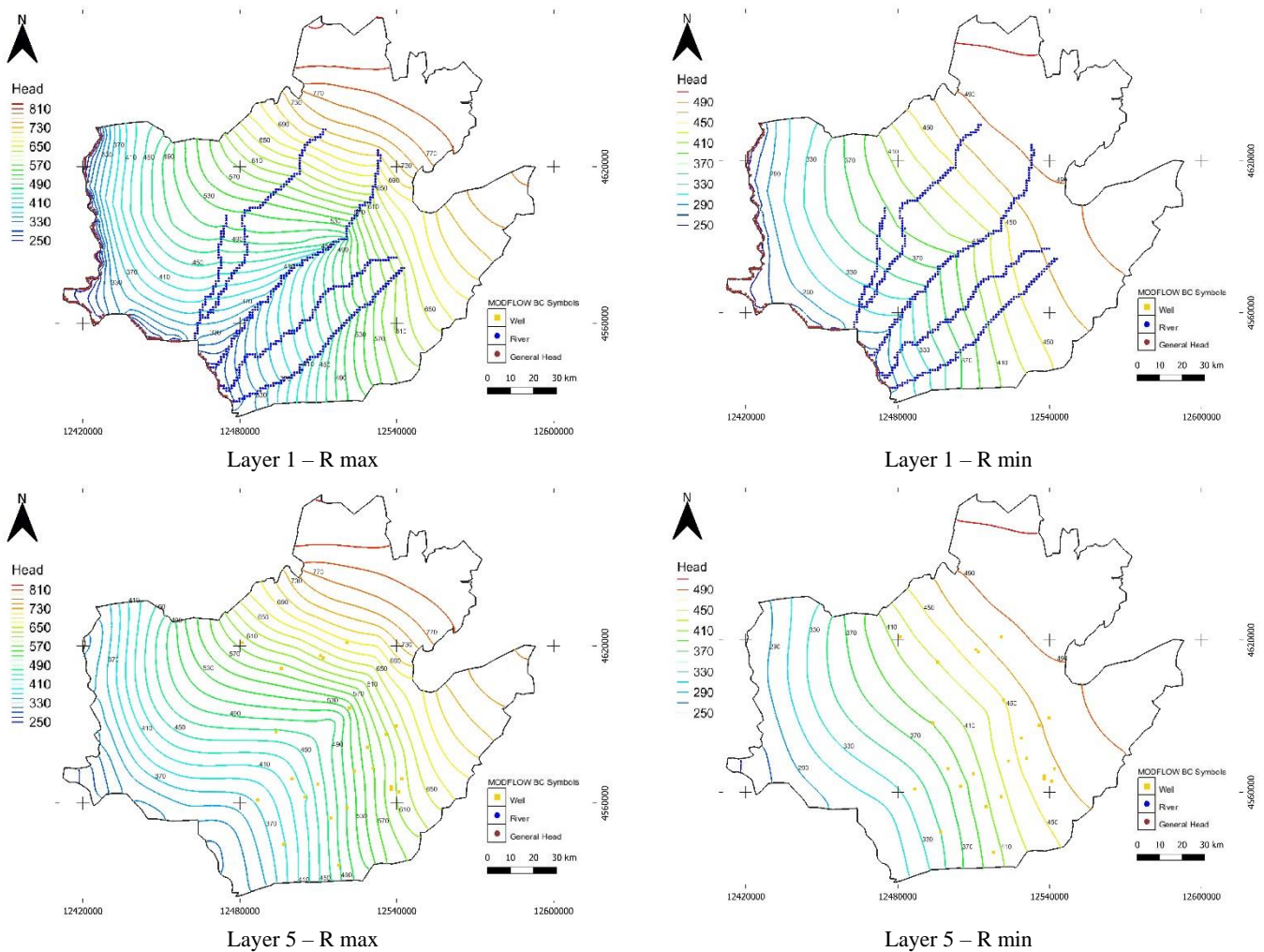
Figure 4.5.6 Change of heads with the increase and decrease of recharge rates in Layer 1 and 5

The change of rates influences the quantity of water flowing in and out of the PTBA, logically when recharge increases, the amount of water present in the transboundary aquifer rises, *Figure 4.5.7*. However, the difference from the initial scenario is higher for increased rates for 359,997 m^3/day comparing to 221,816 m^3/day with minimum rates.
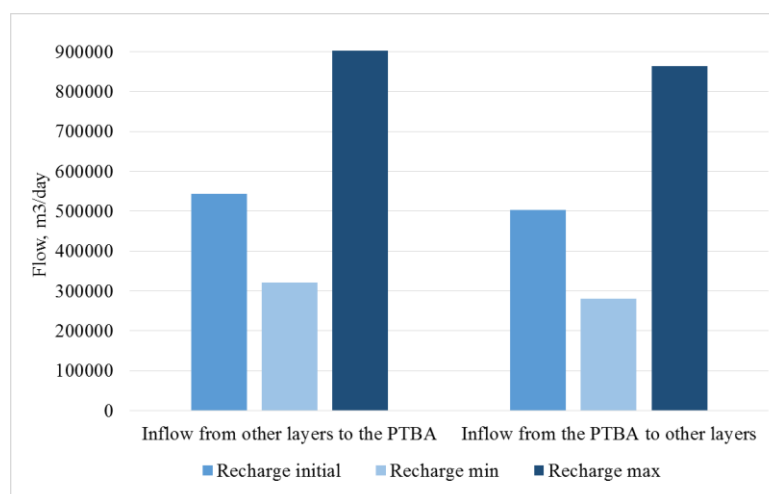
Figure 4.5.7 The amount of water flowing from other layers to the PTBA and back with maximum and minimum recharge rates

Sensitivity analysis of two unknown parameters in the groundwater system of the PTBA allowed understanding the internal processes and dependence of inflow and outflow components on hydraulic conductivity and recharge rates. Reduced values of hydraulic conductivity in Layer 1 and 5 impact the change of heads in increasing direction. Inversely, increased recharge rate might affect its rise.

The PTBA is likely to receive more water in three cases:

-   when hydraulic conductivity in Layer 1 increases;
-   when hydraulic conductivity in Layer 5 decreases;
-   when recharge increases.

River leakage as inflow might rise when hydraulic conductivity increases in Layer 1 and decreases in Layer 5. In the outflow part of the budget, water flowing through rivers may increase when Layer 1 has higher and Layer 5 has lower values of hydraulic conductivity. The inflow from the boundary can possibly increase when hydraulic conductivity drops in Layer 1 and Layer 5. The outflow from the boundary might rise when hydraulic conductivity values increase in Layer 1 and 5.

Sensitivity analysis of recharge rates showed that inflow through rivers might increase with the decrease of recharge. In the outflow, water leaving the system through rivers is likely to increase with the rise of recharge. The inflow through the boundary might go up when recharge goes down. The outflow from the discharge boundary is more significant when recharge increases.

Chapter 5 Results and analysis

5.1 Groundwater flow circulation

The conceptual and numerical test model of the Pretashkent Transboundary Aquifer allowed estimating the possible direction of the flow in the system. Due to the topography and stratigraphical sequence of layers, flow direction has a trend from the north-east to the south-west direction. The key discharge area is the Syrdarya river and Chardara reservoir. The test model presents Keles river as an additional discharge zone of the system.

The particle tracking option was selected in GMS for wells located in the PTBA, *Figure 5.1.1*. Both velocity vectors and flow to the wells confirm the presence of the transboundary flow, discussed in *Chapter 5.3*. Groundwater flowing on the territory of Kazakhstan from the north-east to the south-west diverges into two directions: the northern flow goes to Syrdarya river, and the southern flow goes to Chardara reservoir. Here again, the flow directed to Chardara splits into two: flowing directly to the reservoir and discharging into Keles river. Groundwater flow in Uzbekistan also flows from the higher elevations in the north-east to lower elevations in the south-west, crossing the country border and discharging into Keles river. Some part of the flow is directed to Syrdarya river in the most southern point of the PTBA area. The recharge originates in mountains from precipitation where values vary from 400 to 600 mm/year.
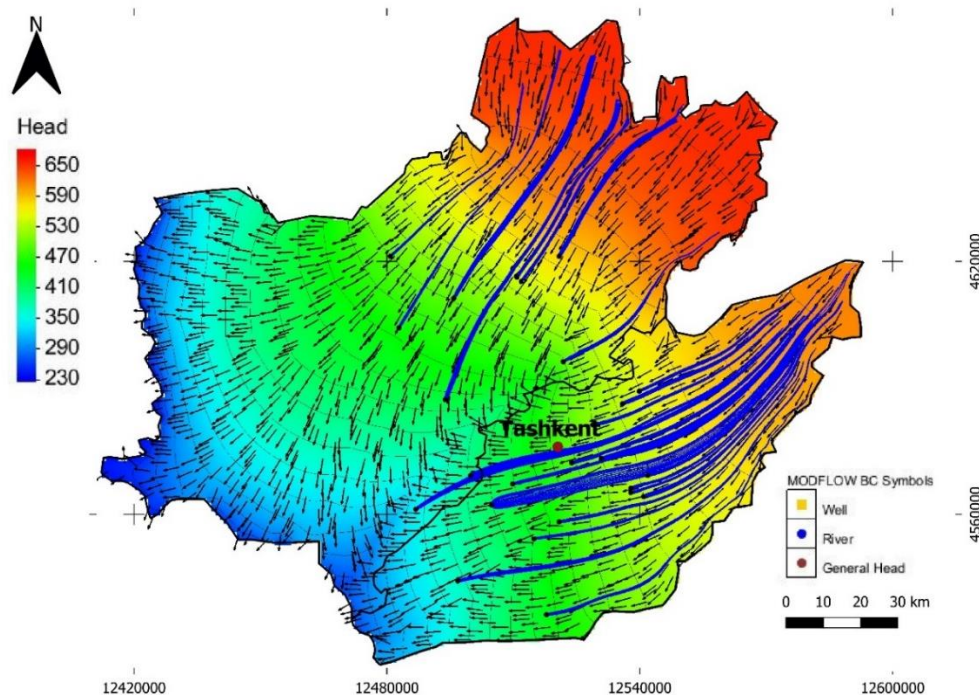
Figure 5.1.1 Head, vector velocity and flow direction to the wells of the PTBA

Side view of the PTBA groundwater system indicates the flow from two aquitards downwards to aquifers, from Layer 2 and 4 to Layers 3 and 5, *Figure 5.1.2*.
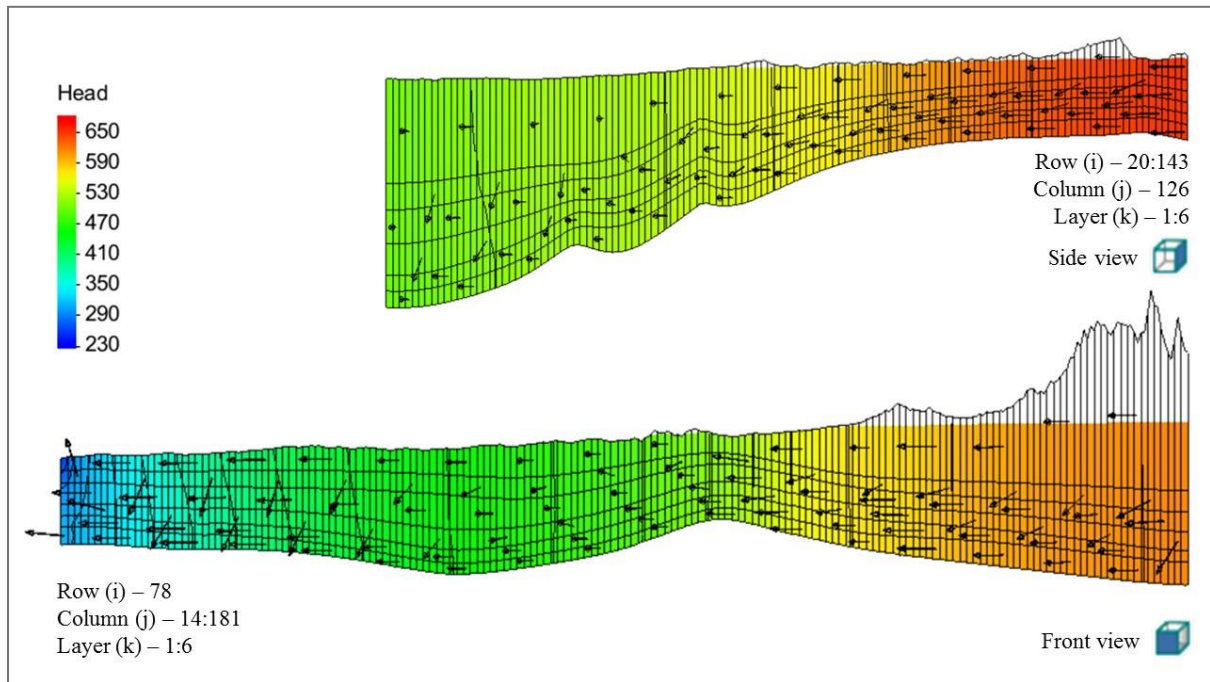
Figure 5.1.2 Side and front view of the PTBA system with velocity vectors

However, the groundwater flow in the system is not always downgradient. In the discharge zones it goes from bottom layers to the top, *Figure 5.1.3*. The highest velocities can be observed in the middle part of the aquifer, mostly on the territory of Kazakhstan, *Figure 5.1.3* where dark blue colour vectors indicate higher velocities. On the territory of Uzbekistan, most of the vectors are light blue (almost white) showing the intensity of the groundwater speed. In the discharge zone of Keles River, upgradient groundwater flow has lower velocities than horizontal flow within a layer.
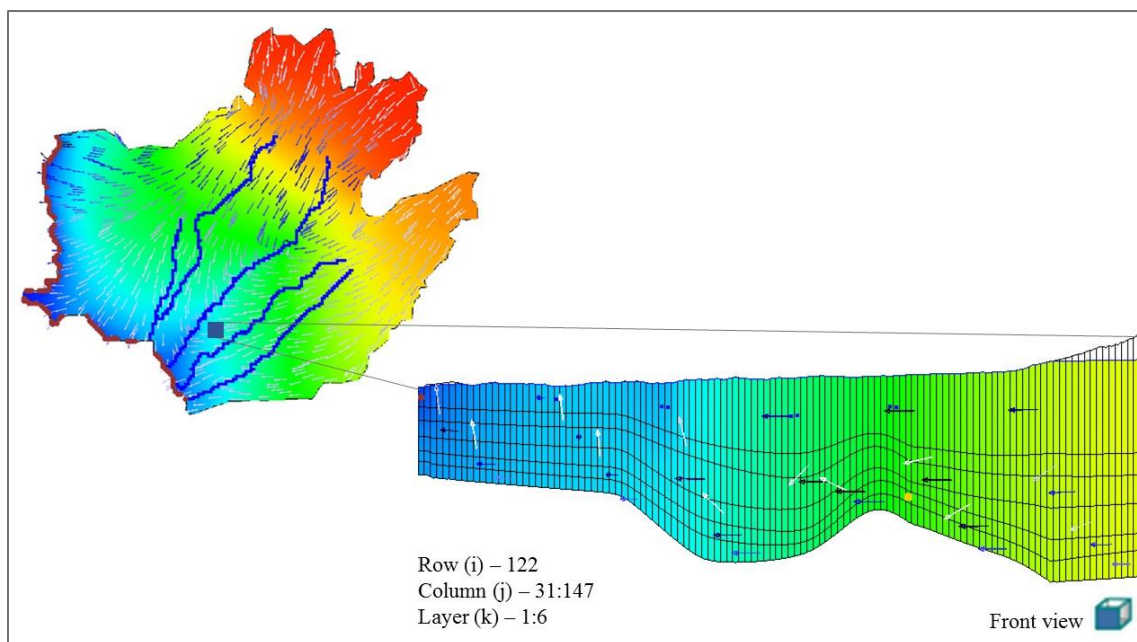
Figure 5.1.3 Front view of velocity vectors in the vicinity to Keles River

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Overall, the general direction of the flow is from higher to lower elevations discharging into Syrdarya and Keles rivers and Chardara reservoir. The circulation pattern varies depending on the top and bottom elevations of the layers directing the flow in vertical direction up- and downwards.

5.2 Groundwater budget

In the results section the test model with increased conductance in the discharge boundary was used, from 1 m^2/day to 10 m^2/day, and it was assigned only to the top layer. The other change was done to river conductance, where minimum values from the test of hydrogeological parameters were used. It is essential to note that the test model does not replicate the field conditions of the PTBA.

The groundwater budget of the Pretashkent Transboundary system consists of river leakage, head dependant boundary (Syrdarya river and Chardara reservoir) and recharge for inflow components and abstraction wells, river leakage and head dependant boundary for the outflow.

The test model provides the flow budget where the total amount of groundwater inflow in the system is 1,849,949.9 m^3/day, and outflow is 1,849,950.3 m^3/day. The change in storage is -0.37 m^3/day, *Table 5.2.1*.

Table 5.2.1 Groundwater budget for the PTBA system

Inflow:	m^3/day
River leakage	37820.1
Boundary inflow	9040.0
Recharge	1803089.9
Total inflow	**1849949.9**
Outflow:	m^3/day
Wells	41904.6
River leakage	1129255.0
Boundary outflow	678790.6
Total outflow	**1849950.3**

Recharge in the inflow and river leakage in the outflow are the major influencing terms in the budget, 97.5% and 61.0% accordingly, *Figure 5.2.1*. 36.7% of groundwater discharges through Boundary outflow. Presented values are estimated based on assumed model parameters. The sensitivity analysis showed the components are affected by the change of recharge and hydraulic conductivity values.
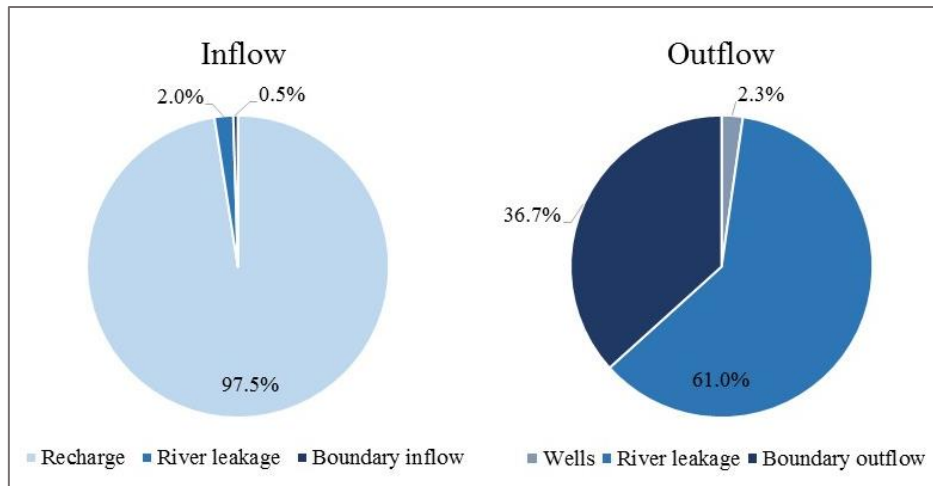
Figure 5.2.1 Groundwater budget for the PTBA system

Moreover, to compare the amount of water that is received by every country the model was divided into two zones for Kazakhstan (KZ) and Uzbekistan (UZB) for all layers, *Table 5.2.2*. The source of inflow to the aquifer system in Uzbekistan are rivers, and the head dependant boundary in the west contributes to the inflow in Kazakhstan. More recharge is available on the territory of Kazakhstan, 1,072,690.0 m^3/day comparing to 730,399.9 m^3/day in Uzbekistan. 662,119.4 m^3/day flows from Uzbekistan to Kazakhstan, and 249,554.0 m^3/day from Kazakhstan to Uzbekistan.

Abstracted groundwater in Uzbekistan is more than two times higher compared to the abstraction in Kazakhstan. River leakage as an outflow component is more significant from Kazakhstan, 906,424.0 m^3/day to 222,831.0 m^3/day from Uzbekistan. Through the outflow boundary the amount of water leaving the system from Kazakhstan is five times higher than from Uzbekistan, 575,284.1 m^3/day to 103,506.6 m^3/day accordingly.

Such differences can be explained by the area of the PTBA, 68% is located on the territory of Kazakhstan and 32% in Uzbekistan.

Table 5.2.2 Groundwater budget for the PTBA system in Uzbekistan and Kazakhstan

	KZ	UZB
Inflow:	m^3/day	m^3/day
River leakage		37820.1
Boundary inflow	9040.0	
Recharge	1072690.0	730399.9
Inflow from KZ		249554.0
Inflow from UZB	662119.4	
Total inflow	**1743849.0**	**1017774.0**
Outflow:	m^3/day	m^3/day
Wells	12586.0	29318.6
River leakage	906424.0	222831.0
Boundary outflow	575284.1	103506.6
Outflow from KZ		662119.4
Outflow from UZB	249554.0	
Total outflow	**1743848.0**	**1017776.0**

5.3 Transboundary flow

Groundwater transboundary flow in Layer 5 is likely to be present based on the results from the test model. Along the border, the flow crosses it several times in the north-east to the south-west direction not spreading far from the boundary area. In the south-west, the transboundary flow becomes more pronounced, crossing the boundary from Uzbekistan to Kazakhstan, *Figure 5.1.1* and *5.3.1*. Abstraction well 48(11tn) and 43(7tn) located in Kazakhstan are expected to pump groundwater in the PTBA from Uzbekistan.
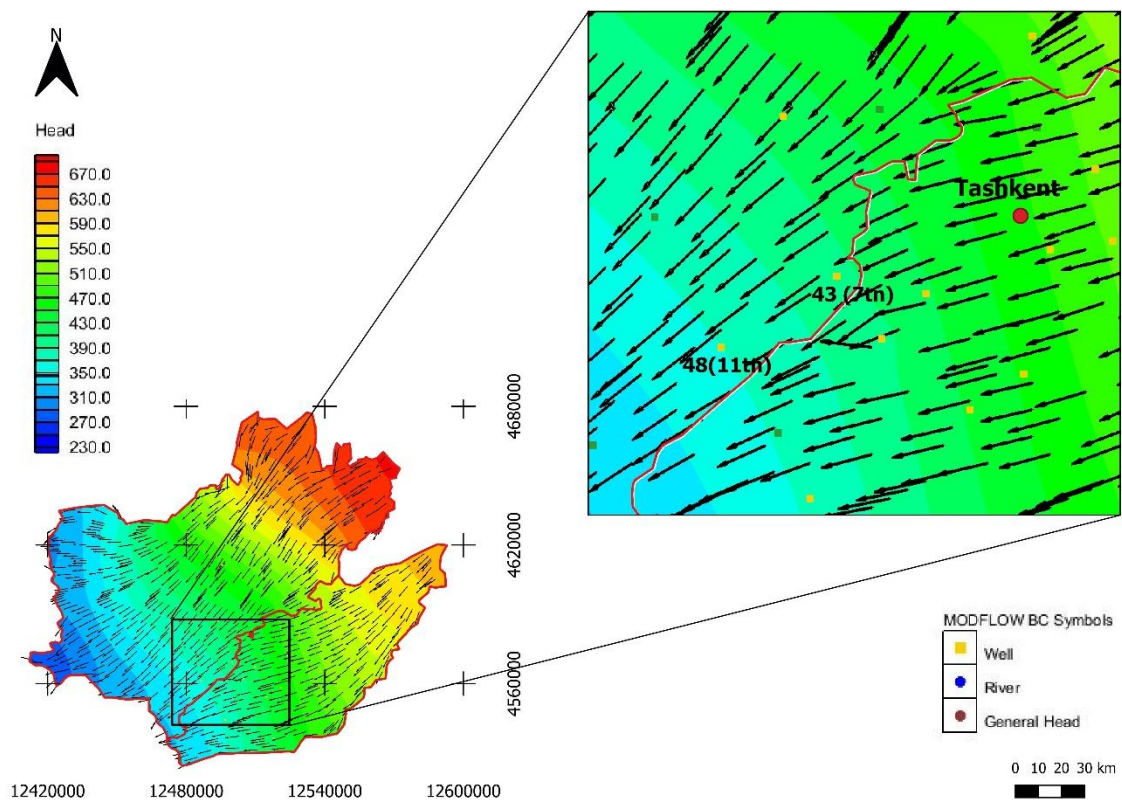
Figure 5.3.1 Velocity vectors in Layer 5

The Pretashkent Tranbsoundary aquifer was divided into two zones, located in Kazakhstan and Uzbekistan. The results of the flow budget show that more vertical leakage goes to the PTBA in Kazakhstan, 259,721.6 m^3/day compared to 161,040.8 m^3/day in Uzbekistan, *Table 5.3.1*. The same trend is observed in the outflow from the PTBA to the other layers, 273,788.9 m^3/day from the territory of Kazakhstan to 107,389.4 m^3/day from the territory of Uzbekistan. Transboundary groundwater flow from Kazakhstan to Uzbekistan is 55,534.0 m^3/day and 81,886.7 m^3/day from Uzbekistan to Kazakhstan. Net exchange is 26,352.7 m^3/day.

Table 5.3.1 Groundwater budget for the PTBA divided between Kazakhstan and Uzbekistan

	Other layers	PTBA in KZ	PTBA in UZB
Inflow:	m³/day	m³/day	m³/day
River leakage	37820.1	0.0	0.0
Boundary inflow	9040.0	0.0	0.0
Recharge	1803090.0	0.0	0.0
Vertical leakage from layers	0.0	259721.6	161040.8
From the PTBA in KZ	273788.9	0.0	55534.0
From the PTBA in UZB	107389.4	81886.7	0.0
Total inflow	2231128.0	341608.3	216574.8
Outflow:	m³/day	m³/day	m³/day
Wells	2313.9	12286.3	27304.5
River leakage	1129255.0	0.0	0.0
Boundary outflow	678790.6	0.0	0.0
Vertical leakage to layers	0.0	273788.9	107389.4
To the PTBA in KZ	259721.6	0.0	81886.7
To the PTBA in UZB	161040.8	55534.0	0.0
Total outflow	2231122.0	341609.2	216580.6

5.4 Potential saltwater leakage

The paleocene local aquifer is described as brackish or saline depending on the area of distribution, ranging from 3000 mg/l in the outskirts of Chulinsky uplift (outcrops of the PTBA) and 9000 mg/l in the depression (JSC Kurort, 2010). The lower aquifer complex of Turonian-Senonian formations is also specified as the aquifer with high salinity, around 6000 mg/l. In the conceptual model, they are divided between Layer 2 and 3, respectively. To model the possible impact of salinization for the PTBA, Cl constant concentration of 1000 mg/l was introduced in the third layer assigned to every cell. The scenario was simulated for 500 years. The result shows there is potential vertical leakage of saltwater to bottom and top layers. The river valleys are areas of future risk in the first two aquifers, *Figure 5.4.1*.

Layer 1   Layer 2
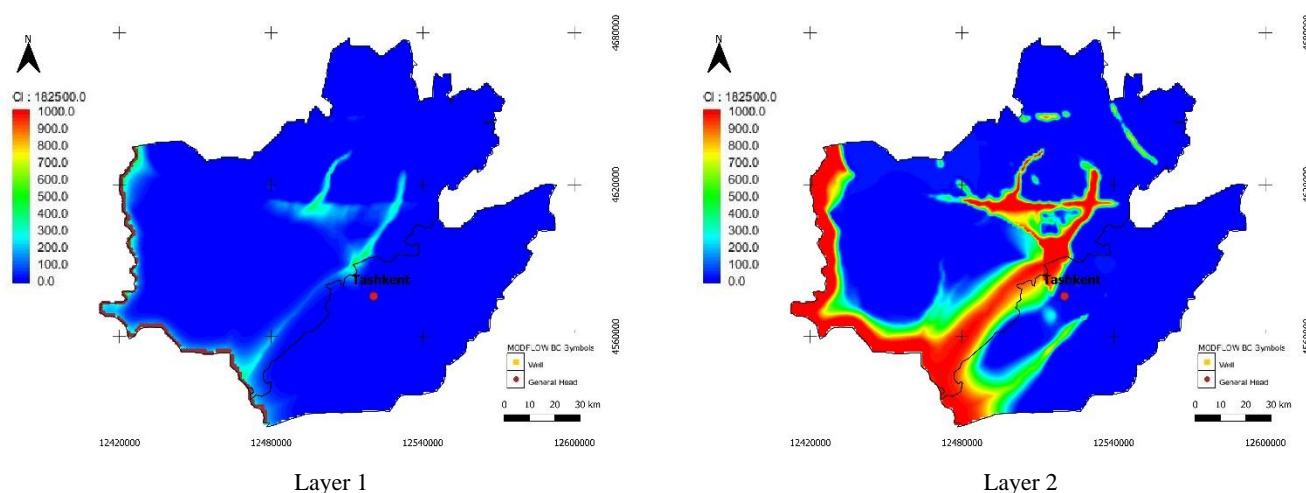
Figure 5.4.1 Saltwater leakage from Layer 3 to Layer 1 and 2

The thickness of Layer 4 as aquitard is not likely to protect the PTBA from salinisation. The lowest concentration of Cl can be detected along the river valleys, and the highest values appear in the north-east, *Figure 5.4.2*. The comparison of the salinisation effect between top layers and Layer 4 might indicate that the water from the third aquifer discharges into rivers, but not in the case of Layer 4. One reason for such sharp border between high and low concentration might be recharge zonation, especially the line to the south-east from Tashkent. Another reason is the groundwater flow upwards in lower parts of the aquifer where heads vary from 230 to 350 m. Profiles of groundwater flow circulation in the system show the direction of the flow from Layer 4 to Layer 3, *Figure 5.1.2* and *5.1.3*.
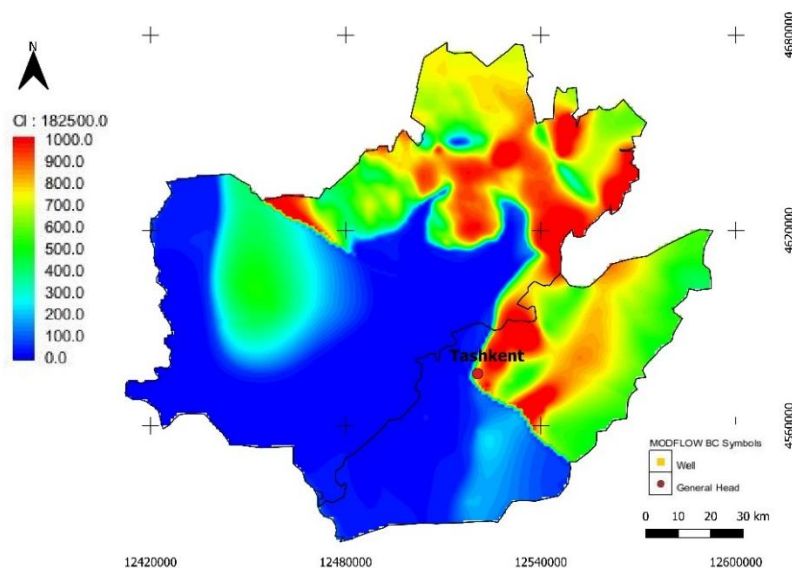
Figure 5.4.2 Saltwater leakage from Layer 3 to Layer 4

Main areas of saltwater leakage in the PTBA are in the north-east and middle parts of the aquifer, *Figure 5.4.3*. Due to pressure from abstraction in the Tashkent region, the salinity increases there till 400 mg/l. In 488 years, groundwater quality might change in the PTBA, reaching Cl concentration of 300 mg/l around Tashkent, *Figure 5.4.4*.
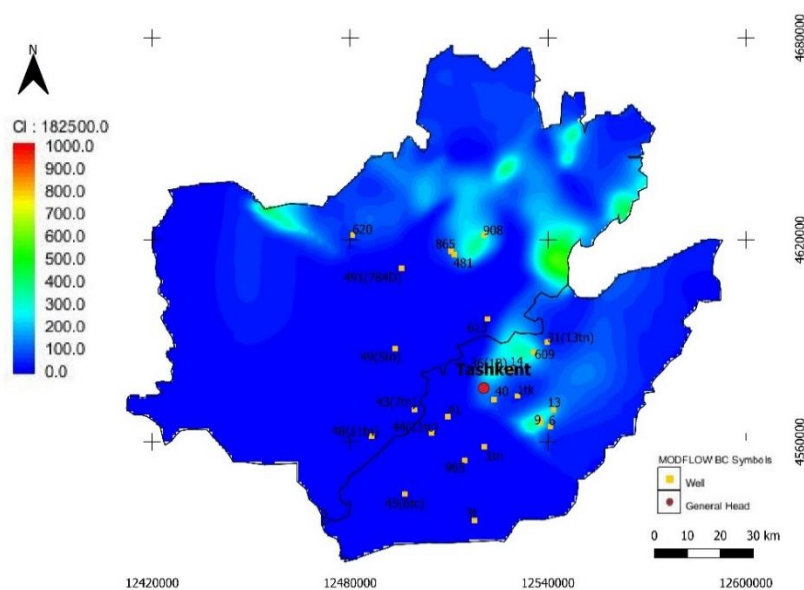
Figure 5.4.3 Saltwater leakage from Layer 3 to Layer 5
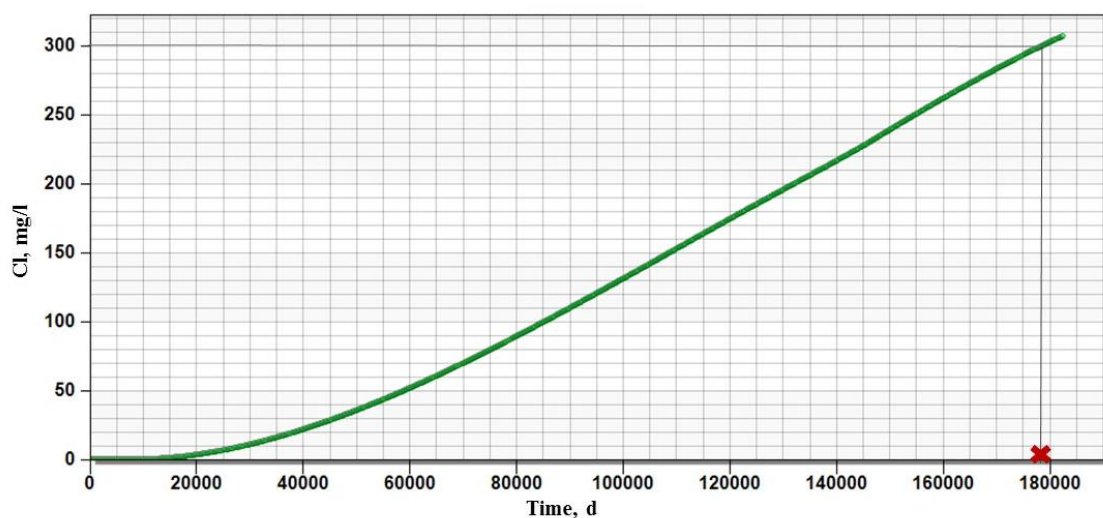
Figure 5.4.4 Time series of Cl concentration in Well 609, Layer 5

Layer 6 doesn't show any change due to vertical leakage for 500 simulated years. Generally, the simulation with saltwater leakage demonstrates that the first two layers are mostly affected along river valleys, and Layer 4 and 5 are influenced in the north-east of the aquifer. The simulation for 215 years illustrates that the quality of groundwater in the PTBA might not be affected by the vertical leakage of saline water, *Figure 5.4.5*.
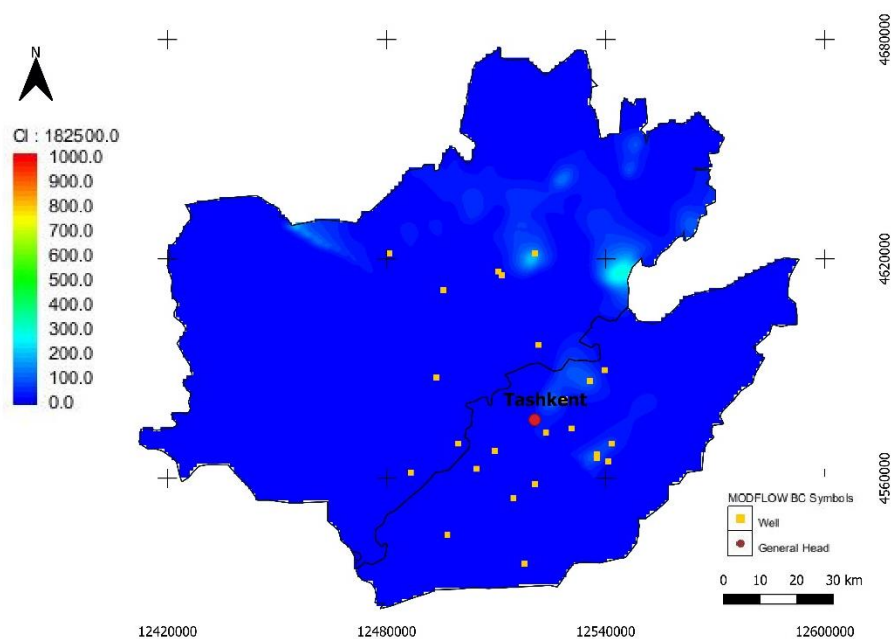
Figure 5.4.5 Saltwater leakage from Layer 3 to Layer 5, simulated period – 215 years

Chapter 6   Discussions

6.1 Data limitations and model uncertainties

6.1.1   The process of data collection and its availability

Access to data and information on transboundary groundwater resources is a crucial component for successful management and conflicts resolution between aquifer sharing states (Gerlak et al., 2014). There is no present transboundary legal and institutional framework indicating data and information sharing in the Pretashkent Transboundary Aquifer. However, both Kazakhstan and Uzbekistan mention ambiguously in their regulations monitoring of groundwater and the importance of information exchange but only between the owner of the well and the government. During the research no publicly available data portal was found on a local or regional level.

The GGRETA Project, during its first phase, contributed to establishing information exchange through conducting joint assessment of the aquifer. Nevertheless, only from 6 to 10 indicators are available for the PTBA territory in Kazakhstan and from 1 to 5 indicators in Uzbekistan on the Transboundary Waters Assessment Programme (TWAP) Groundwater Information System portal. The indicators don't include information on aquifer recharge, buffering capacity, vulnerability to climate change or its human dependency for various purposes. Furthermore, the boundary of the PTBA is assumed from the Uzbekistani part. Provided cross-section of the vertical cut V-V is the same attached to the Internal Report used for the study.

One of the challenges of this research is the lack of accessible and reliable data. The main sources used for data collection are dated by 1971, 2010 and 2016. The research was also restricted by internationally available scientific papers on groundwater in the region. To fill the gap, the literature in Russian was used. Newly established connections during the training organized by the IGRAC on groundwater modelling for participants from Kazakhstan and Uzbekistan contributed into receiving the Internal report from the Committee of geology and hydrogeology of Kazakhstan, that partly contained information on the PTBA area in Uzbekistan. The provided Internal report included some of the required hydrogeological data but its format, inconsistency and inaccuracy between text and visual representation made the process of data harmonisation with other sources challenging.

6.1.2   Data limitation

From hydrogeological data, no recharge estimations and discharge measurements were obtained. The aquifer thickness was collected by measuring the elevation from images of cross-sections and converting them into absolute values with the scale. There were cases when the indicated number of elevation did not coincide with the visualised measured depth of the well. Groundwater level measurements were not detected from observation wells but abstraction. Time series were limited by number of years from 1954 till 2009 for Kazakhstan and until 1981 for Uzbekistan with long gaps. The value was also only the average annual reading. Abstraction rates were small, so they were multiplied by five for the model input.

Meteorological data was fully obtained through open source where 21 stations around the area of interest were found with precipitation and temperature data with gaps in the time series.

Surface data was absolutely absent in the study, no publicly available river and reservoir water levels and cross-sections were found. River discharges were obtained from 4 stations on the Global Runoff Data Centre portal but their location was out of the PTBA boundary. Aquifer and aquitard parameters were also unavailable leading to the application of assumed values as input for the model.

6.1.3 Model uncertainty

Uncertainty in modelling starts from selecting a code where assumptions are made with indicating the importance of hydrologic processes in the system. Uncertainty related to the model itself (assumptions in the conceptual model, inaccurate observation data, simplifications) and details of future conditions are two key reasons for ambiguity (Anderson et al., 2015). For the current model the parameters of hydrologic processes were assumed based on geology, topography and climate.

Anderson et al. (2015) also states the more precise is the approximation of a conceptual model to the field site, the more reasonable would be the outputs of a numerical model. In this regard, the very first uncertainty is related to the boundary of the Pretashkent Transboundary aquifer. Two not scientific sources (internal reports) from the GGRETA project and Hydrogeology of the USSR (1972) present the boundary in Uzbekistan much extended to the south covering the valley of Akhangaran river, Appendix V.

Stratigraphical uncertainty

The information on the depth of the layers was collected from cross-sections and the number of wells was limited not representing the whole perimeter of the aquifer. Another simplification was made to the actual folding character of the system. The layers were approximated and fixed in GMS to avoid the difficulties in conversion from a conceptual model into numerical.

Hydraulic conductivity and recharge uncertainty

Not only the zonation but also values for hydrogeological parameters such as hydraulic conductivity and recharge rates were roughly assumed based on geology and topography as a consequence of data availability. The previous research estimated 3,598.6 m^3/day as recharge from the outcrops, river leakage and vertical leakage from top aquifers on the area of 301.8 km^2 and 760.3 m^3/day as recharge from faults on the territory of Kazakhstan. The values were provided without the identification of the exact zones location. The model estimated vertical leakage to the PTBA in Kazakhstan 259,721.6 m^3/day from area of 10,840 km^2 and 161,040.8 m^3/day from area of 6,160 km^2. The comparison of recharge on a Kazakhstani part between the previous model and the current results in a difference of 130,467.7 m^3/day less. Among the techniques for recharge estimation classified by Gee and Hillel (1988) the application of water budget is questioned in arid and semi-arid regions. The recharge through outcrops can be potentially measured using lysimeters since the rainfall values in that part of the PTBA are above 400 mm/year, the only restriction for this method would be the cost (Atiaa et al., 2004). The study of Death Valley Regional Ground-Water Flow System Transient Flow Model calculated recharge using a set of methods: empirical, water balance, chloride mass balance and distributed-parameter method. The distributed parameter was applied to approximate the

distribution of recharge through net infiltration model INFILv3. The uncertainty of its results increases when the thickness of unsaturated zone increases. This method can be applied only for the lower part of the PTBA where unsaturated zone is not deep, and the data on base flow of rivers and stream-channel characteristics is available for calibration (San Juan et al., 2004). Overall, the application of one method results in uncertainties; it is better to use a combination of methods (Scanlon et al., 2002). For the regional recharge it is suggested to use isotope dating, chloride mass-balance calculations, tracer mixing-cell modelling, Darcian flow modelling, and direct measurements of spring discharge or stream base-flow method (Gee and Hillel, 1988). Specifically for the arid and semi-arid regions in saturated zones, tracer methods and numerical modelling are applied (Scanlon et al., 2002).

Hydraulic conductivity values can be obtained through pumping tests. Pumping tests provide the estimation of transmissivity. Since the thickness of layers is a known parameter, it would be possible to calculate hydraulic conductivity as transmissivity divided by the thickness of an aquifer or aquitard. Pumping tests were conducted for 33 wells of the PTBA in 2009 but received datasets with the Internal report did not include the values of transmissivity.

Abstraction rates uncertainty

Historical data of 27 abstraction wells was available with inconsistent time series from 1954 till 2009. Only 9 wells contained observations from 1996 till 2009. The primary dataset covered the period from 1969 till 1985. For the steady-state model the long-term average was used that gave relatively small values. For the model they were multiplied by five to make the scenario more realistic.

Test of hydrogeological parameters

Calibration was not conducted due to the absence of observation data. The comparison of existing observed and simulated heads showed acceptable correlation.

Modelled hydraulic heads

Modelled hydraulic heads are almost the same as modelled by JSC "Kurort" for 2009 and presented in their Internal Report. There are two differences: the heads in the north-east in higher elevations are 150-200 m higher in the Internal report, and the second difference is related to their sequence. They are located further from each other in the Internal report and do not specify the dominance of Keles river but highlight the abstraction in the vicinity to Tashkent.

Modelled groundwater flow budget

Transient model built by JSC "Kurort" provides the values of flow budget in the Internal Report without any units. The comparison might be possible only with the assumption that the units are in 10^4 m^3/day. In this case, the average for the total inflow from the Internal Report for the period 1960 till 2010 is 2,129,000 m^3/day, and it is 279,050.1 m^3/day higher than the result of the output from the test model. Total averaged outflow for the same period is 2,163,000 m^3/day in the Internal Report comparing to 1,849,950.3 m^3/day, resulting in 313,049.7 m^3/day of difference between transient model from JCS "Kurort" and test steady-state model of this study.

6.2 Development of transboundary groundwater resources

Data, information and knowledge are significant factors for sustainable use and development of transboundary groundwater resources and their management (Gun, 2018). Cooperative work between aquifer sharing states is another aspect contributing to the beneficial use of it (Puri and Aureli, 2005). The attempts to establish transboundary cooperation between Kazakhstan and Uzbekistan started with the first effort made in 2009-2010 by JCS "Kurort" and continued with the GGRETA Project in 2013.

The importance to conduct the assessment of available groundwater resources in the Pretashkent Transboundary aquifer was already noted in 2000 in Kazakhstan. In 2001 Shymkent Hydrogeological Expedition drafted a project "Creation of the Pretashkent groundwater polygon of Cretaceous sediments and assessment of their resources". The project was approved in the Committee of geology and environment protection of the Ministry of energy and mineral resources of Kazakhstan (current name – the Ministry of Energy of the Republic of Kazakhstan). Due to limited funding, only the work on hydrogeological profiles was completed. JSC "Kurort", for its work on the regional assessment of available groundwater resources of the Pretashkent Transboundary aquifer, contacted colleagues from Uzbekistan who showed their interest to work together. For the official permission to exchange data between countries, JCS "Kurort" sent a letter to the State Committee of Geology of Uzbekistan (Goskomgeologiya), but an answer was not received (JSC Kurort, 2010). During the first phase of the GGRETA Project assessment information of the PTBA from Uzbekistani side was not publicly available. The request for cooperation during this research with the Institute of hydrogeology and engineering geology of Uzbekistan resulted in a positive reply to support the study. Nevertheless, it was received 3 months later, and due to time limitations it was not possible to get additional information. Overall, along these attempts it can be noticed that establishment of collaboration including the exchange of data in the region is a long process. Babow (2018) argues that hydrological data is politicized in the Syrdarya River Basin, and governments shape it in a direct way through collection, processing and share.

The results of this study show that the Pretashkent aquifer is transboundary with its crossing groundwater flow in the western part of the area. Well 48(11tn) and 43(7tn) on the territory of Kazakhstan is likely to pump groundwater from Uzbekistan. Tashkent region is potentially vulnerable to the quality deterioration as a consequence of probable leakage of brackish water from top aquifers to the PTBA. Under these conditions, the groundwater flow from Tashkent seems to reach wells in Kazakhstan, even though the leakage of brackish water on the part of Kazakhstan does not appear to be significant. Furthermore, the quantity of available groundwater resources of the PTBA as estimated with current model 558,183.1 m^3/day should be reconfirmed by an advanced transient model. The current steady-state model does not allow to assess the overexploitation of the aquifer. However, internal documents of the GGRETA project, namely the report prepared by Karimov and the presentation by Abdullaev mention the decrease of heads for 100 m in Uzbekistan (Karimov, 2013). The transient model from JSC "Kurort" indicates the same drop for 2009. It also suggests the abstraction limit of 7,107.7 m^3/day from the wells located on the territory of Kazakhstan in the PTBA. The future development plan on using PTBA's groundwater services might be established after simulating the transient model with current abstraction rates and mutually agreeing on limits between two aquifer sharing states.

6.3 Governance and management of transboundary groundwater resources

Water governance is an indispensable tool for supporting water security and addressing water scarcity (Villholth and Conti, 2018). Groundwater governance can be assessed through analysis of actors; legal, regulatory and institutional frameworks; policies and plans; information, knowledge and science (FAO, 2016). Groundwater management is responsible for the activities undertaken by actors within the governance framework (Villholth and Conti, 2018). In the study case of the PTBA, the Committee of geology and hydrogeology in Kazakhstan and the State Committee on geology and mineral resources in Uzbekistan could be highlighted as main governmental actors in the groundwater management. Other actors are companies producing bottled water, spa resorts, small businesses, water consumers and owners of private wells (FAO, 2016; UNESCO IHP, 2016). The comparison analysis of legal and regulatory frameworks of groundwater in two countries show that there is no major contradiction. However, it is not possible to assess their enforcement. Both states are accessors of the UNECE Water Convention. The Interstate Commission for Water Coordination (ICWC) is already established in the Syrdarya River Basin with the role to organize international water management including groundwater in Syrdarya River Basin (Rakhmatullaev et al., 2010). To address possible or already existing overexploitation of the aquifer, cooperative work should start from a management framework, *Figure 6.3.1*. On a technical level for the development of the model specialists from the Institute of hydrogeology and geoecology in Kazakhstan and specialists from the Institute of hydrogeology and engineering geology in Uzbekistan could be put in a working group for the development of the model. A strong communication should be established between two Institutions. Both entities are under direct management of Committees of geology and hydrogeology on an intermediate level. On a national level the governments are involved through the Ministries of Foreign Affairs and ministries in charge of the Committees' work. Since the role of ICWC in the region is already assigned as an entity for international water management, the process can be potentially synchronised by them including the coordination of work for the development of a bilateral agreement. Furthermore, its role might even strengthen as a controlling mechanism to manage the compliance of countries with treaty commitments and its compliance with the international water law.
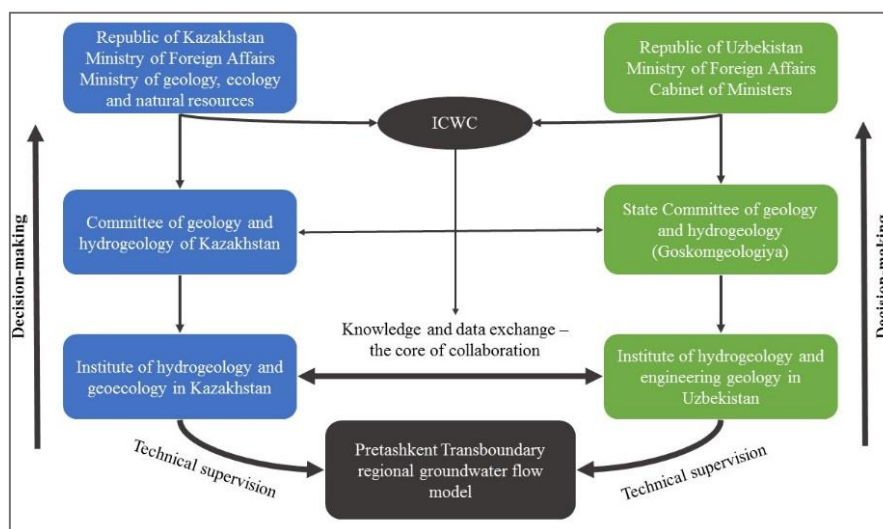
Figure 6.3.1 Possible structural management framework for the development of the PTBA model

Chapter 7   Conclusions and recommendations

7.1 Conclusions

The concern to build a test transboundary groundwater model was driven by the necessity to understand the cross border flow, the available amount of groundwater and address potential leakage of brackish/saline water from top aquifers to the deep-lying Pretashkent Transboundary aquifer located between the Republic of Kazakhstan and Uzbekistan.

A steady-state test groundwater model was built using Groundwater Modeling System (GMS). The available data was collected and harmonized for two aquifer sharing states. Such indicators as environmental, socio-economic, legal and policy aspects were assessed. First, the conceptual model was built and then transferred to a numerical. Test with the conductance of rivers and head dependant boundary helped to understand the potential behaviour of the aquifer. With increased conductance for rivers, their dominance reduces in the system, and the result can be detected assessing the pattern of contour lines. In the flow budget more water was involved in the surface-groundwater interactions. Incorporation of the General Head boundary to all layers result in lower heads along Syrdarya River since more water discharges through it. Sensitivity analysis was conducted to understand the change of model output based on the variations of hydraulic conductivity values in Layer 1 and Layer 5 and recharge rates. Three cases were indicated when total inflow increases. The scenarios are 1) increased hydraulic conductivity in Layer 1; 2) decreased hydraulic conductivity in Layer 5 and 3) increased recharge. The test model setup for the results and analysis included the head dependant boundary for Layer 1 and its conductance of 10 m^2/day, and reduced conductance for rivers. It is essential to note the test model does not represent field conditions and most of the input parameters are the result of assumptions.

Groundwater flow circulation of the whole system depends on assigned boundary conditions and hydrologic parameters. Thus, as output of current test model, the general trend of the groundwater flow between the layers is identified as downward leakage in higher elevations and upward vertical flow from aquitards to aquifers in lower elevations, especially in discharge zones to rivers. The results showed that the aquifer is likely to be transboundary with groundwater flow crossing the border from Uzbekistan to Kazakhstan in the western part of the aquifer. In the east and middle parts the exchange of groundwater flow might be minor, mostly parallel to the boundary or crossing it first from Kazakhstan to Uzbekistan and again entering the territory of Kazakhstan. Available test model allowed to estimate groundwater budget with inflow of 1,849,949.9 m^3/day and the outflow of 1,849,950.3 m^3/day. The potential risk of saltwater leakage from top aquifers to the PTBA might occur in 425 years in the vicinity to Tashkent with increasing salinity above 250 mg/l based on the output of the test model. In 488 years the test model shows the concentration of Cl might increase around 300 mg/l.

In conclusion, this test steady-state numerical model of the Pretashkent Transboundary aquifer can serve as an example of the model built with limited data. The regional groundwater flow and major processes of the test model were analysed without field representation. Such indicators as cross-border groundwater flow and risk of brackish/saline water leakage from top aquifers to the PTBA need to be taken into consideration for the development of the PTBA model and in decision making for strategical management of the region. In addition, the attention needs to be paid to field measurements and monitoring programs in two countries. Recharge and discharge processes should be closely studied as more groundwater inflow to the PTBA is most likely to be available on the territory of Kazakhstan and higher abstraction rates are possibly applied in Uzbekistan. The model might serve as an exercise in building a transboundary groundwater model with limited data. In future, an advanced model of the PTBA might indicate for the need to establish a cooperation between aquifer sharing states with further development of a bilateral legal framework on sustainable exploitation and risks prevention of the aquifer.

7.2 Recommendations

To increase the accuracy and applicability of the test model to the case study of the Pretashkent Transboundary Aquifer, a complete field investigations and groundwater monitoring are required.

Conceptual model

The revision of a conceptual model when updated information is available and the development of alternative versions are two ways of dealing with uncertainties in conceptual models (Anderson et al., 2015). Several advancements should be considered:

- The boundary of the PTBA on the territory of Uzbekistan is extended further to the south in Hydrogeology of the USSR (1972) and Internal report by Karimov (2013). The details on this aspect and deep research on the geological setting will help to advance the conceptualization of the transboundary aquifer.
- The availability of a land-use map with the exact delineation of agricultural fields, cities, bare land and pastures will improve the understanding of hydrologic processes.
- The information on recently drilled abstraction wells on the territory of Kazakhstan was received during personal communication with the director of the Republican State organization "South Kazakhstan Interregional Department of Geology and Subsoil Use" of the Committee of Geology and Subsoil Use of Kazakhstan ("Yuzhkaznedr") but without their location and abstraction rates. This fact should be incorporated into the conceptualization.
- The accuracy of recharge processes should be identified on a stage of building a conceptual model and such factors as landscape contributing to recharge, the change of these areas with time, control mechanisms, lateral redistribution of runoff and the flow downgradient should be studied (Sophocleous M, 2004).
- The presence of springs as discharge zones, faults as recharge zones is available in the final report of the GGRETA project, the information on their location and discharge and recharge measurements will enable to better understand hydrogeological processes of the aquifer. Hydrogeology of the USSR (1972) states that outcrops of the PTBA are present not only on the territory of Kazakhstan but also there are small patches along

the left bank of Chirchik River. After the confirmation, these terms will add to the understanding of recharge processes in the conceptual model and provide more details on the confinement of the aquifer.

- Charvak reservoir and irrigation channels on the territory of Uzbekistan should be included as an element of surface water in the system.

Numerical model

After the improvement of a conceptual model further steps should be taken to decrease the uncertainties of a numerical model:

- Calibration should be conducted with the data from observation wells. The availability of these datasets should be checked in the Institutes of hydrogeology in Kazakhstan and Uzbekistan.
- If the data is not available, the improvement of hydraulic conductivity values, recharge rates and conductance of rivers should be addressed by reviewing existing regional groundwater flow models in arid and semi-arid regions with similar hydrogeological characteristics. The study of Scanlon et al. (2002) could be a good starting point in finding the set of methods for recharge estimation. It is known that the pumping tests were conducted in 2009 on the wells located in Kazakhstan to get the values of hydraulic conductivities. The same should be checked with the Institute of hydrogeology in Uzbekistan. If the tests have not been run in Uzbekistan and the data is not available from two countries, the method to determine this parameter should be identified (empirical or experimental).
- Since arid regions are often characterised by losing surface-water bodies due to their separation with groundwater systems, the data on surface waters will allow the simulation of the interaction of surface and groundwater and the understanding of localized recharge sources (Scanlon et al., 2002). The data on surface water will also contribute to identifying the best option for a recharge estimation method.
- Agriculture is well developed in the Tashkent region. Drain package could be incorporated into the model. The data on the amount of water used for irrigation will add to analyse the recharge.
- Set a transient model with abstraction rates to assess the exploitation of the aquifer.

Transboundary water management

Overall, further development of a model is dependent on the availability of data. To address this challenge, cooperation processes and trust building should be settled between two countries. Data and information exchange is an important aspect for the secure management of a transboundary aquifer. ICWC as an existing regional organization for water cooperation could act as an implementing body of such processes.

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Appendices

Appendix I PTBA Cross-sections

V - V

VI - VI
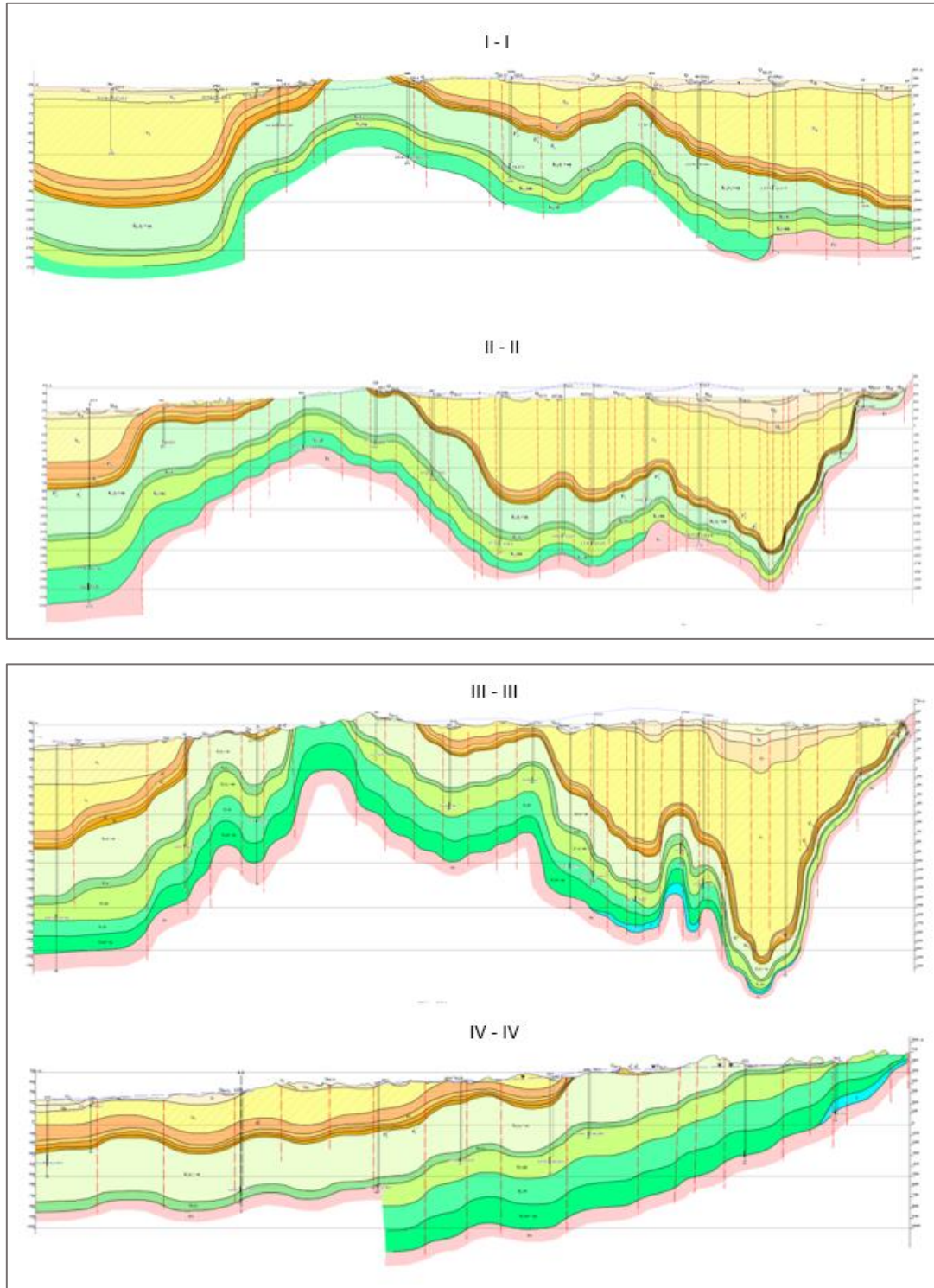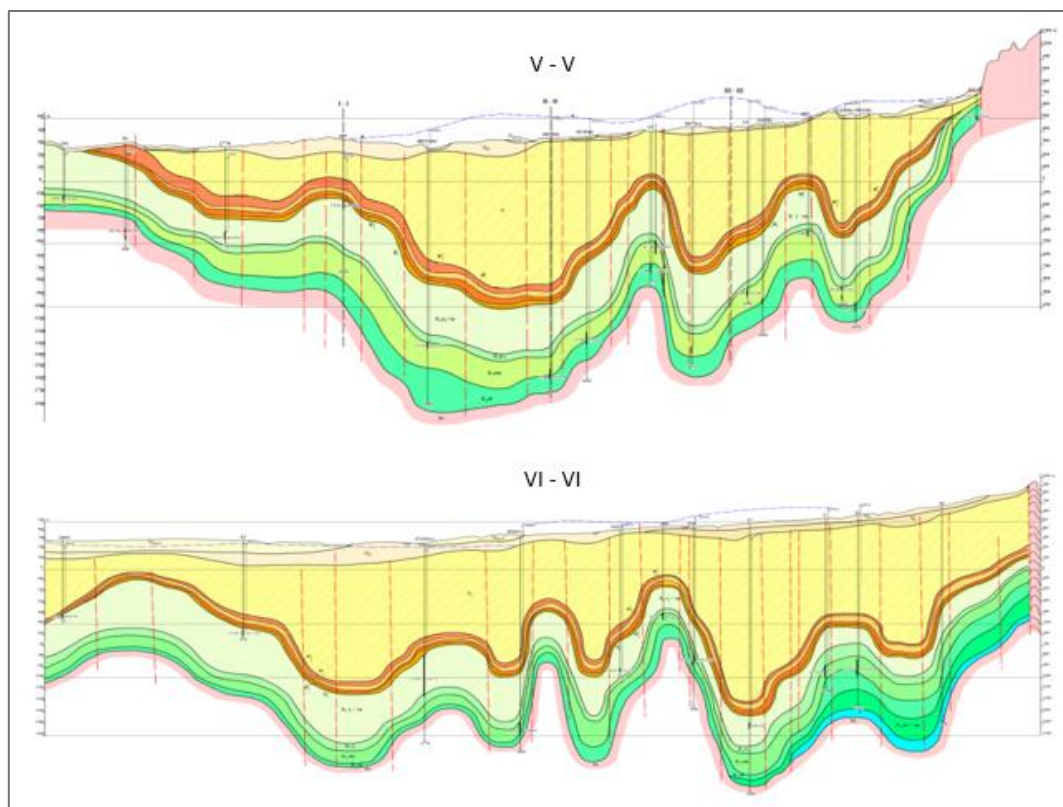
Source: JSC Kurort, 2010

Legend

Q_{III-IV}	Upper – Quaternary – Modern alluvial aquifer	P_2^2	Middle Eocene aquifer
Q_{III}	Upper – Quaternary alluvial – proluvial aquifer	$P_1^1 - P_2^1$	Paleocene – Lower Quaternary aquifer
Q_{II}	Middle – Quaternary alluvial – proluvial aquifer	P_2^1	Lower - Eocene aquitard
Q_I	Lower – Quaternary alluvial – proluvial aquifer	P_1	Paleocene formation, almost without water
N_2	Pliocene aquifer	K_2t_1	Lower – Turonian Upper – Cretaceous aquitard with outcrops
N_1	Miocene local aquifer	K_2t_2	Turonian platform Upper – Cretaceous aquifer
P_2^3	Upper Eocene aquitard	K_2t_2+sn	Upper Turonian and Senonian aquifer

K_2	Upper – Cretaceous aquifer
K_1	Lower – Cretaceous aquifer
K_2sm	Upper – Cretaceous Cenomanian aquifer
K_1al	Lower – Cretaceous Albian aquifer
K_1ne+ap	Lower – Cretaceous Neocomian – Aptian aquifer
J	Jurassic aquifer
Pz	Fractured Palaeozoic aquifer

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Appendix II Soil maps
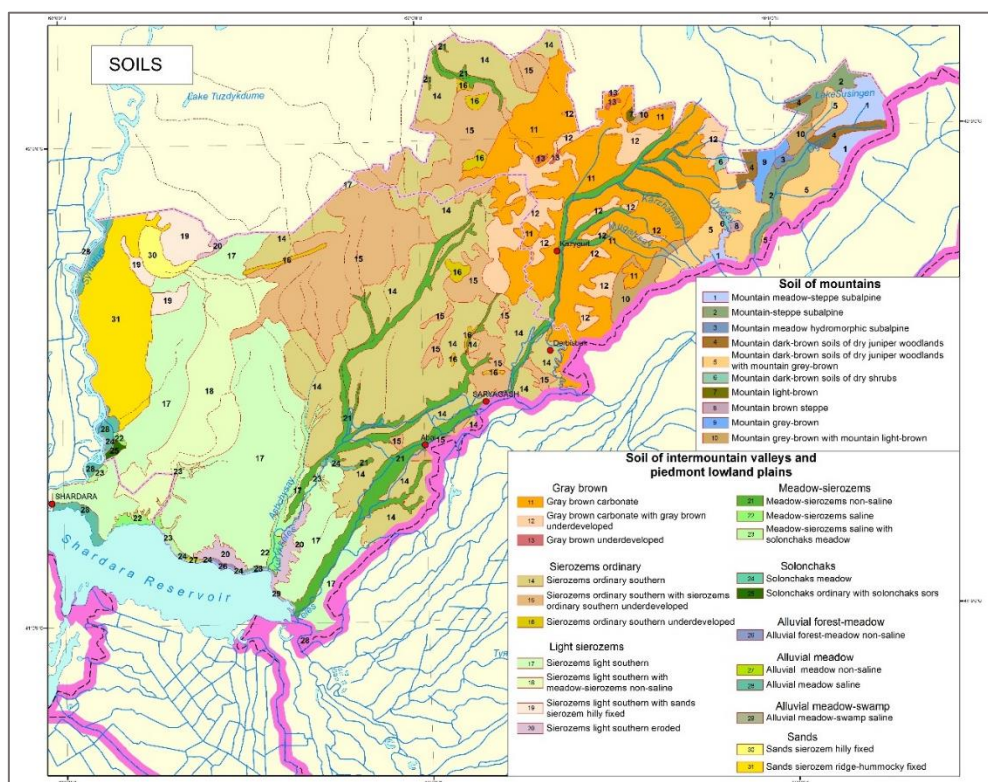
Soil map of the PTBA area in Kazakhstan. Source: UNESCO IHP, 2016
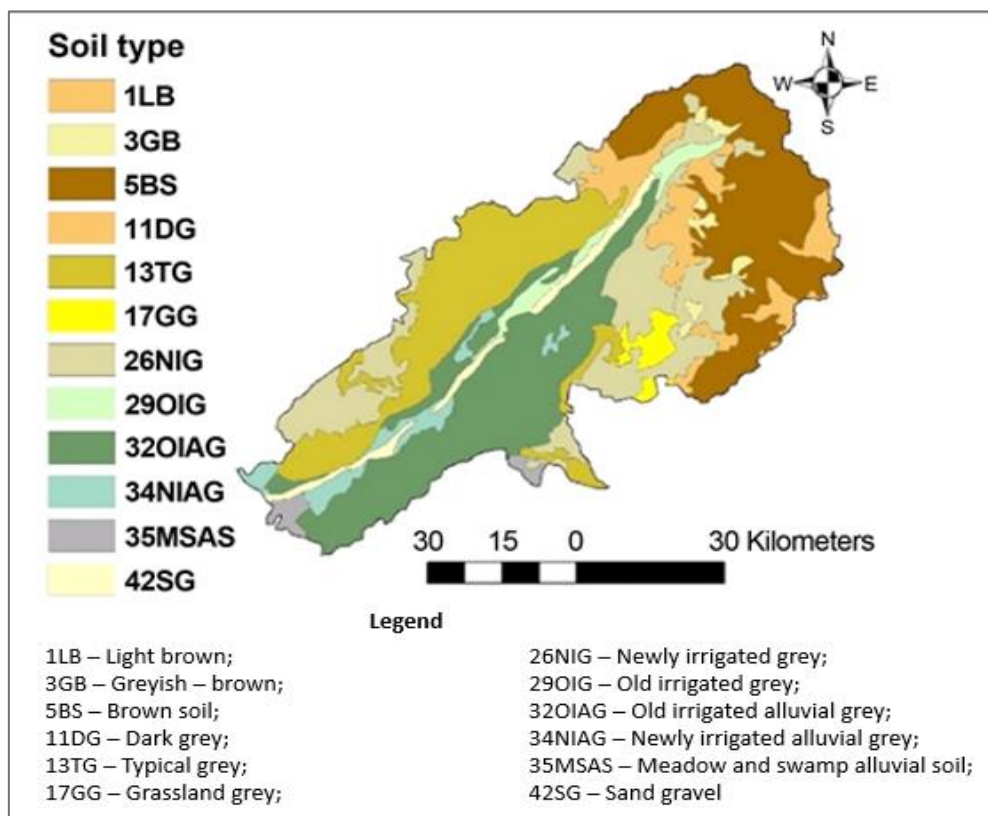
Soil map of the PTBA area in Uzbekistan. Source: Usmanov et al., 2016

Appendix III Transmissivity map
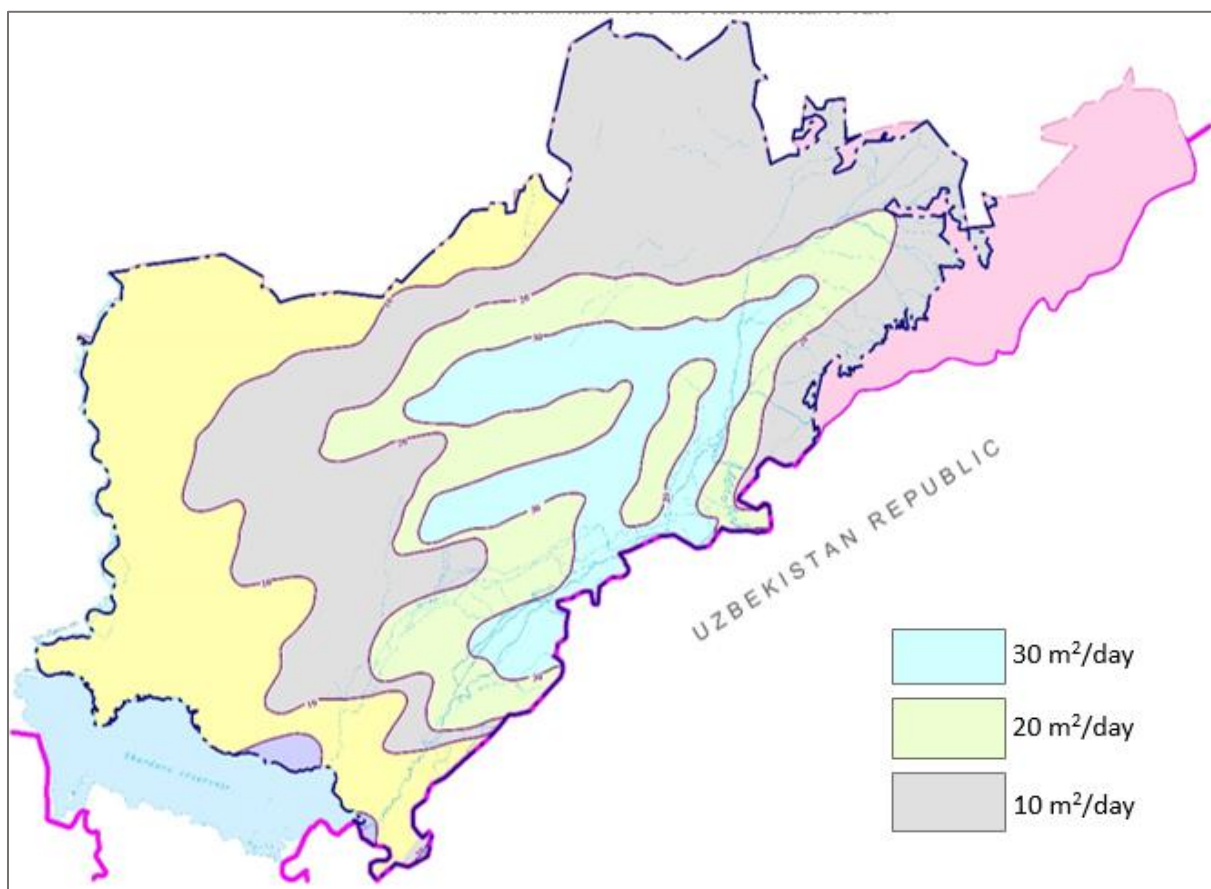
Transmissivity map of the PTBA in Kazakhstan. Source: UNESCO IHP, 2016

Appendix IV Domestic legal and institutional frameworks in Kazakhstan and Uzbekistan

№	The Republic of Kazakhstan (RK)	The Republic of Uzbekistan (RU)
1	National legislation covering freshwater resources relevant to the PTBA area	
	- Decree (Act) №201 from 13.07.2013 issued by the Akimat[7] of South Kazakhstani region on establishing protection zones of surface waters (lost its force by the decree №354 from November 2015); - Decision of South Kazakhstani regional maslikhat[8] №47/388-V from 25.02.2016 on ratification of general water use rules in South Kazakhstani region.	- Provision №174 from 07.04.92 on the protection zones of artificial reservoirs and other ponds, rivers, channels, sources of drinking and industrial water supply, as well as waters for balneological and recreational purposes approved by the Cabinet of Ministers of Uzbekistan.
2	Applicability of the Water Code and the Water Law to groundwaters	
	Yes	Yes
3	Official policy documents complementing the national legislation	
	- Code on soil and subsoil use from 27.12.17 № 125-VI of the RK (with amendments and additions as of 04.02.19); - Environmental Code of the RK from 09.01.07 № 212- III ЗРК (with amendments and additions as of 04.11.19); - Land Code of the RK from 20.06.03 №442-II (with amendments and additions as of 03.04.19) - Resolution №93 of the Government of the RK from 23.01.02 on the industrial program "Drinking water" for 2002-2010, amended by the resolution № 956 from 16.10.2007; - Resolution №59 of the Government of the RK from 21.01.2004 on the special legal regime on regulating economic activities of state significance water bodies; - Decree of the Government of the RK from 21.12.04 №1344 on approval of the list of water facilities owned by the state;	- Land Code of the RU from 30.04.1998; - Decree №ПП-2954 from 04.05.17 on regulating the control of groundwaters rational use for 2017-2021; - Provision №273 from 23.08.16 on ratification of the environmental monitoring program in Uzbekistan for 2016-2020; - Resolution of the Cabinet Ministers of the RU from 03.02.10 №11 on additional measures to improve environmental protection in the system of communal services.

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[7] Municipal government in Kazakhstan

[8] Local representative bodies in Kazakhstan

	- Decree №113 from 13.03.2017 on approving the Action Plan for the implementation of the State program for the development of the agro-industrial complex of the RK for 2017-2021; - Decree of the Government of the RK from 31.12.03 №1378 on approval of the rules for maintaining the state water cadastre; - Law of the RK from 17.01.2002 №. 284-II on sailing trade; - Law of the RK from 23.10.2000 №94-II on the Accession of the Republic of Kazakhstan to the Convention on the Protection and Use of Transboundary Watercourses and International Lakes; - Law on ratification of the framework Convention for the Protection of the Marine Environment of the Caspian Sea from 13.12.05 № 97-III ЗРК.	
4	Ownership of groundwater	
	State - Code on soil and subsoil use from 27.12.17 № 125-VI of the RK (with amendments and additions as of 04.02.19).	State - Water Law of the Republic of Uzbekistan.
5	Ownership of groundwaters under the land by landowners	
	Yes Land Code of the RK. Chapter 5. Land as an object of property rights, land use rights and other real rights. Article 42. The limits of the right to land. The right to the land takes into account the use of surface soil, ponds, and vegetation. The granting of rights to extract common minerals and rights to use groundwater for landlords own needs is carried out simultaneously with the provision of land. Chapter 6 Rights and obligations of landowners and land users when using land. Article 64. Rights of landowners and land users to use land properties. The rights allow to independently manage the land, use available common minerals on the land property or in the subsoil,	Yes Land Code of the RU. Chapter 5. Rights and obligations of the landowner, land user, renter, and owner of the land. Article 39. Rights of a landowner, land user, renter, and owner of the land. The right allows to use of minerals, water bodies and exploit other useful properties of the soil following the established procedure for the needs of the farm. It is assumed that groundwaters fall under the term "other useful properties of the soil".

	plantations, surface and ground waters, as well as the exploitation of other useful properties of the land in the prescribed manner without the intention of the subsequent execution of transactions for the needs of their farm. If the main purpose of the land property is assigned for activities requiring licensing on subsoil use or agreements on subsoil use, the rights to use the land are granted after receiving permission, license or signing a contract on subsoil use.		
6	The provision by the legislation that groundwater is public property (or held by the State in trust for the public)		
	Yes, state property Water Code Article 8.	Yes, state property and nationwide wealth Water Law Article 3.	
7	Legislation providing for/mandate the preparation of water resources plans (master plan, catchment plan)		
	Yes Resolution of the Government of the RK from 8.04.16 №. 200 On approval of the General Scheme for the integrated use and protection of water resources.	No	
Groundwater resources abstraction and use			
8	Licensing of water abstraction and use		
	Yes, required Water Code of the RK, Article 66. Special water use. It determines the use of surface and ground waters with or without uptake from a water body to satisfy drinking and domestic needs of citizens as well as agricultural, industrial, energy, fishery, transport demands with the discharge of sewage waters, including water intake facilities equipped with pumping units and other water-lifting facilities for extracting groundwater. Special water use is carried out by individuals and legal entities based on a permit and must not violate the rights and legitimate interests of other persons and cause harm to the environment. The responsible authority for the issuance of the permit – Regional governmental authorities.	Yes, required Resolution of the President of the RU from 04.05.17 №. PP-2954 on Measures to regulate the control and accounting the rational use of groundwater reserves for 2017–2021. The responsible authority for the issuance of the permit - the subordinate hydrogeological organisations of the state committee of the RU on geology and mineral resources (Goskomgeologiya).	
9	Exceptions to licensing requirements		

	Water Code of the RK. Permission is not required when: - using the following water intake facilities: mine and tubular filter wells, as well as captive facilities, working without forced lowering of the level including water withdrawal in all cases not more than 50 m³/day from the first aquifer, not used for centralised water supply; - extraction (pumping) of groundwater (mine, quarry), collected during exploration and (or) mining of solid minerals. From the Code on soil and subsoil: - for a free-flowing wells.	Appendix №1 to the Resolution of the Cabinet of Ministers from 27.06.17 №430. Resolution on the procedure for issuing permits for drilling water wells. Permission is not required: - for individuals who drill wells with a depth of fewer than 25 meters, designed for the individual abstraction for their own needs not more than five m³/day; - for subordinate hydrogeological organisations of the Goskomgeologiya when drilling the wells for the development and reproduction of the mineral resource base within the annual state programs.
10	Duration of abstraction licensing	
	The period of permit validity for special water use is determined following Article 70 of the Water Code. Article 70 specifies water use into two types: constant and temporary. Constant water use means use without time limitations. Temporary water use can be long-term (from 5 to 49 years) and short-term (for five years). If needed the period of validity can be prolonged. The duration for the special water use depends on the potential of the resources and current ecological situation of a water body.	The period of validity of the permit is set for the period of drilling operations, but not more than one year.
11	Payment for licensing	
	Not specified	No The fee is not charged for the consideration of applications and issuance of permits.
12	Drilling of wells is a subject of a permit	
	Yes Water Code of the RK. Abstraction and use of groundwaters equipped with facilities and technical devices with limits higher than 50 m³/day are the subjects of permits.	Yes Resolution of the President of the RU from 04.05.17 №PP-2954 on Measures to regulate the control and accounting the rational use of groundwater reserves for 2017–2021. Chapter 4. Permit issuance procedure, point 22 states Goskomgeologiya decides on issuing, refusing or approving permits for drilling water wells for the construction of a group or single water uptake facilities.

13	Review and amendment of licenses	
	Yes Water Code of the RK. Article 66. Special water use specifies the case when the permission is terminated because of inaccurate information provided to the governmental authority or when violations of water and environmental legislation of the RK are identified, the renewal of the permit is possible after the elimination of provided information inaccuracies or revealed violations of the water and environmental legislation of the RK.	Yes Resolution of the President of the RU from 04.05.17 №PP-2954 on Measures to regulate the control and accounting the rational use of groundwater reserves for 2017–2021. Chapter 4 Permit issuance procedure includes points (26 and 27) on reconsideration of applications in case of preliminary refusal. When an applicant removes the reasons that served as the basis for the refusal, the documents shall be reconsidered within a week from the date of receipt of the application.
14	Termination and suspension of licensing (under the circumstances)	
	Water Code of the RK. Article 66. Special water use. The termination of the permission is considered in three cases: - when inaccurate information is detected while submitting it to the governmental authority to obtain permission; - when violations of the requirements of water and environmental legislation of the RK are detected; - restrictions on the right of water use provided for in Article 74 of the Water Code. Article 74 limits water use rights in accordance with the laws established by the RK to ensure the security and defense of the state, the protection of public health, the environment, historical and cultural heritage, the rights and legitimate interests of citizens, as well as during droughts, emergency situations of natural and anthropogenic characters. However, restriction of the right to use water should not worsen the condition for drinking and household water supply of the population. Article 75. Termination of special water use rights. It includes additional points when the rights are terminated: - the refusal of the water user from the right of water use; - the expiration of the water use period; - the death of the individual water user;	Resolution of the President of the RU from 04.05.17 №PP-2954 on Measures to regulate the control and accounting the rational use of groundwater reserves for 2017–2021. When a technical passport (includes information on the location, geographical coordinates, name of a drilling company, name of water user, purpose of the well, date of the permit issuance, daily abstraction rates, type of drilling, pumping test, water quality, etc) is not submitted to the appropriate territorial hydrogeological station of the Goskomgeologiya, it is the basis for the elimination of the drilled well to prevent pollution of groundwater.

 - liquidation of a water user legal entity; - natural or artificial disappearance of water bodies; - transfer of the right to use water bodies in the manner established by the laws of the RK to other individuals and legal entities. The right on special water use is also terminated under the circumstances: - non-use within one year of water resources intended for drinking water supply; - non-use of water resources for three years; - the need to use water resources for state needs; - failure to eliminate violations that were the reason for suspending the validity of permits for special water use.	

15	Water abstraction permits can be bought sold (traded)	
	No, not specified	No, not specified

16	EIA is required for proposed well drilling/water abstraction projects	
	Yes Water Code of the RK. Permits for special water use is given to individuals and legal entities when they have sanitary-epidemiological conclusion on the compliance with sanitary-epidemiological requirements for the collection of surface and/or groundwater for drinking water supply.	Yes Resolution of the President of the RU from 04.05.17 №PP-2954 on Measures to regulate the control and accounting the rational use of groundwater reserves for 2017–2021. Unconditional fulfilment of the state environmental inspection's conclusions is among the main authorisation requirements and conditions for issuing a permit.

17	Obligation to monitor report extractions/gw levels by users	
	Water Code of the RK. Article 72. Water User Responsibilities states that water users are obliged to timely submit to state authorities reliable and complete information on the use of a water body in the form established by the legislation of the RK. Article 120. The speciality of groundwater bodies protection underlines that individuals and legal entities whose production activities may harm the state of groundwater are required to monitor	Appendix №2 to the Resolution of the Cabinet of Ministers from 27.06.17 №430 Statute on state monitoring of groundwater. Chapter 4. The procedure for conducting state monitoring, point 14 indicates that industrial (local) monitoring covers single wells or group of wells located on the owned land experiencing anthropogenic impacts on groundwater, and it is carried out by legal entities or individuals at their own expense. The obligation is not clearly stated in the document.

groundwater and take timely measures to prevent pollution, depletion and harmful impacts of water resources.	
18	Sanctioning of illegal well drilling and water abstraction and the penalties
	Water Code of the RK. Article 75. Termination of special water use rights indicates that deprivation of special water use permit is carried out following the Code of the RK on Administrative Offenses from 5.07.14 No. 235-V (with amendments and additions as of 07/01/2019). Operation of wells with violation of the requirements established by the legislation (Code on soil and subsoil use of the RK) - entails a fine on small businesses in the amount of 150, on medium-sized businesses - in the amount of 300, on large businesses - 1000 monthly calculated indicators (2525[9] tenge for 2019). It is assumed that the extraction of groundwaters is in the definition of subsoil use.	Code of the RU on administrative liability, approved by the Law of the RU from 22.09.94 №2015-XII, enacted from 04.01.1995 following the Decree of the Supreme Council of the RU of 22.09.94 №2016-XII Article 72. Violation of rules for the protection of water resources includes penalties on citizens - in the amount from two to five, on officials - from five to seven minimum wages (223 000[10] som for 2019) for drilling water wells. Exceptions are drilling wells designed for individual selection of groundwater for individual needs including irrigation of household territory; destruction or damage of production and observation wells; failure to take measures to equip self-flowing wells by regulating devices; preservation or liquidation of wells unsuitable for exploitation; placement of industrial, agricultural and other objects in the formation zone of groundwater quality which may be the source of contamination or degradation of groundwater. If the incident repeats within a year after the application of the administrative penalty - the imposition of a fine on citizens from seven to ten, and on officials - from fifteen to twenty minimum wages shall entail.
	Control of groundwater pollution
19	Permission for wastewater discharges to water bodies or under the ground
Yes, required Water Code of the RK. Article 89. Use of surface water bodies for the discharge of sewage. Discharge of sewage into surface water bodies is allowed if there is a permit for special water use with the condition of their treatment to the	Water Law of the RU. Chapter XIX. The use of water bodies for discharging sewage water. Article 74 Conditions for the admissibility of wastewater discharge into water bodies. The discharge of wastewater into water bodies is allowed only if it does not lead to an increase in the concentration of

[9] https://online.zakon.kz/document/?doc_id=1026672
[10] https://www.gazeta.uz/ru/2019/07/12/wages/

	limits established by the authorised state body in the field of environmental protection and the authorised body in the field of sanitary and epidemiological welfare of the population. Within the definition of special water use the discharge of industrial, domestic and drainage sewage is considered into surface and ground waters. Additional regulation document - Order of the Minister of National Economy of the RK dated 20.07.15 №546 On approval of the rules for the reception of wastewater in the drainage system of settlements.	pollutants above the established norms and under the condition that wastewater is treated by the water user and the consumer till the limits established by the authorities of environmental protection and sanitary supervision. Article 75. The procedure and conditions for the use of water bodies for the discharge of wastewater state that procedures and conditions are established by law, not specifying the need for a permit. Additional regulation document - Resolution of the Cabinet Ministers of the RU from 03.02.2010 №11 on additional measures to improve environmental protection in the system of communal services.
20	Duration of permits	
	Duration of permits is the same as for the special water use: temporal and constant. See indicator №10.	No, not specified However, the validity period of the municipal environmental standard is set for five years, and it is valid for the period of preserving the water balance and the quantitative, qualitative composition of discharged industrial wastewater.
21	Standards of effluent quality	
	Water Code of the RK. Article 84. Standards of maximum acceptable harmful impacts on water bodies determine the definition of the standard and responsible authorities: authorised body in coordination with the authorised state body in the field of environmental protection, subsoil, sanitary and epidemiological welfare of the population and civil defence. Standards of maximum permissible harmful impacts on water bodies are established based on: 1) the maximum permissible value of the anthropogenic load, the long-term impact of which will not lead to a change in the environmental system of the water body; 2) the maximum permissible mass and concentration of harmful substances that can enter the water body and its catchment area.	Resolution of the Cabinet Ministers of the RU from 03.02.10 №11 on additional measures to improve environmental protection in the system of communal services is aimed to provide surface waters protection from industrial and domestic sewage waters and efficient work of wastewater treatment plants. It secures proper organisation of industrial wastewater reception into the communal network.

Additional regulation document - Order of the Minister of Agriculture of the RK from 15.05.15 №19-1 / 441 on approval of the rules for the development and approval of standards for maximum acceptable harmful impacts (MAHI) on water bodies. The authorised body in the field of use and protection of the water fund, water supply, and sanitation approves the maximum allowable flow of chemicals into the water body. It is calculated for each hydro-economic area of the water body using the formula: $Mass\ of\ influx = [SWQ_I^V * (Q_R - Q_U + Q_S) - (Q_R * C_F)] * 0.031$ Where, Mass of influx – the mass of maximum acceptable concentration of chemicals in a water body or hydro-economic territory (V) for the accounting period for every chemical substance (I) (tons/year); SWQ – the numerical value of water quality standards for each chemical substance (I) (g/m^3), determined by the Order of the Committee's on water resources under the Ministry of agriculture of the RK Chairman from 09.11.16 №151 "Unified system of water quality classification in water bodies." Q_R – average annual river discharge (m^3/s); Q_U – uptake by water users (m^3/s); Q_S – total discharge of sewage flowing into a river or hydro-economic area (m^3/s); C_F – factual concentration of polluting substances at the control point of a water body at the moment of assessment (g/m^3) 0.031 – transferring coefficient from g/s into tons/year.	
22	Ambient water quality standards provided for/in effect
Water Code of the RK. Section 7. Protection of water bodies and combating the harmful impacts of water. Chapter 23. Water conservation activities. Article 112. Protection of water bodies introduces actions under which water bodies should be protected and the prevention reasons such as violation	Norms of maximum acceptable concentrations: aniline – 2.57 mg/l; acetaldehyde - 8,58 mg/l; acetone - 17,16 mg/l; barium - 0,44 mg/l; benzoic acid - 5,43 mg/l;

| of the environmental sustainability of natural systems, deterioration of the hydrogeological and hydrological regime and others. | glycerin - 38,6 mg/l; vegetable and animal fats - 5,0 mg/l; caprolactam - 10,73 mg/l; xylene - 1,0 mg/l; sulphur-containing substance – 10.7 mg/l; molybdenum – 1 mg/l; metazine - 12,9 mg/l; methanol – 1 mg/l; methylstyrene – 0.1 mg/l; polyacrylimide – 2 mg/l; resorcin – 0.18 mg/l; bisulfide carbon - 5,0 mg/l; synthetic surface active substance - 20,0 mg/l; vinylbenzene – 0.56 mg/l; sulphide – 1 mg/l; stibic – 0.2 mg/l; thiurea - 0,13 mg/l; titanium - 0,1 mg/l; methyl benzene – 2.8 mg/l; cresyl phosphate - 0,03 mg/l; pH - 6,5-8,5; suspended particulate matters – 500 mg/l; dry residue – 2000; total nitrogen – 30 mg/l; nitrogen – 2.5 mg/l; nitrite – 3.3 mg/l; nitrate – 45 mg/l; ammonium - 2,5 mg/l; chlorides – 350 mg/l; phosphates - 2,5 mg/l; fluoride ion – 1.5 mg/l; chemical oxygen demand – 500 mg/l; |

		biochemical oxygen consumption 20 – 15-30 mg/l;
		biochemical oxygen consumption 5 - 11,3-22,6 mg/l;
		Toxic pollutants:
		aluminum - 0,75 mg/l;
		pentavalent vanadium - 0,1 mg/l;
		bismuth - 15,0 mg/l;
		iron (ion Fe^{++}) - 5,0 mg/l;
		ferrous sulfate iron - 0,5 mg/l;
		cadmium - 0,1 mg/l;
		cobalt - 0,1 mg/l;
		manganese - 30,0 mg/l;
		copper - 1,0 mg/l;
		arsenic - 0,1 mg/l;
		petroleum and its products – 1 mg/l;
		nickel – 0.5 mg/l;
		tin – 20 mg/l;
		mercury - 0,001 mg/l;
		plumbum - 0,1 mg/l;
		selenium - 0,01 mg/l;
		strontium - 18,0 mg/l;
		phenol - 0,05 mg/l;
		formaldehyde - 0,6 mg/l;
		trivalent chromium - 0,5 mg/l;
		chromium hexavalent - 0,1 mg/l;
		cyanides - 0,64 mg/l;
		zinc - 1,0 mg/l.
23	Wastewater discharge permits are the subject of payment	
	No, not specified	No
		Resolution of the Cabinet Ministers of the RU from 03.02.10 №11 on additional measures to improve environmental protection in the system of communal services. Chapter III. Order of issue of technical conditions to discharge industrial wastewater.

		Consideration and issuance of the technical condition are made free of charge within three days after receipt of the application. In the definition "technical condition" is equal to permit.
24	Review and amendment of permits by the government	
	The same as in criteria №13. The permit is for special water use that considers both the abstraction and discharge into surface and ground waters in the Water Code of the RK.	No, not specified
25	Termination or suspension of permits	
	The same as in criteria №14.	No, not specified
26	EIA is required for proposed waste/water discharge projects	
	Yes Same as in criteria №16, additionally supported by the Environmental Code of the RK, Chapter 33. Environmental requirements for water use, Article 225. Environmental requirements for sewage discharge.	Yes Resolution of the Cabinet Ministers of the RU from 03.02.10 №11 on additional measures to improve environmental protection in the system of communal services. Chapter III. Order of issue of technical conditions to discharge wastewater, point 19 states that coordination of construction and reconstruction project documentation of enterprises is carried out by water and sewage enterprises when the application and project documentation is submitted by the customer or by the general designer, including sections "Water supply and sewerage" and "Statement on environmental impact".
27	Monitoring and reporting of water quality is an obligation of discharges	
	Same as in criteria №17.	Yes Resolution of the Cabinet Ministers of the RU from 03.02.10 №11 on additional measures to improve environmental protection in the system of communal services. Chapter IV. Control over industrial wastewater discharge, point 23 highlights that customer is obliged to provide monthly reports on the volumes, qualitative and quantitative composition of industrial to the water supply and sewage enterprises. The deadlines for submission are determined by a bilateral agreement between the customer and the wastewater enterprise. The customer is responsible for the accuracy of the reported data.
28	Regulation of contamination from closed/disused wells	

	No, not specified	No, not specified
29	Use/control/disposal of hazardous substances regulation	
	Environmental Code of the RK. Chapter 33. Environmental requirements for water use. Article 224-1. Environmental requirements for the use of groundwaters. Article 225. Environmental requirements for the disposal of sewage.	Resolution of the Cabinet of the Ministers of the RU on the approval of a monitoring program for the environment in the Republic of Uzbekistan for 2016 – 2020.
30	Sanctions for illegal discharging of waste/water, penalties	
	Code of the RK on administrative offences. Article 326. Failure to comply with environmental conditions specified in the environmental permit. Failure to comply with environmental requirements specified in the environmental permit - entails a penalty on officials in the amount of 15, on small businesses - 30, on medium-sized businesses - 50, on large businesses - 200 of monthly calculation indicators. If the failure repeatedly committed within a year after the imposition or causing great damage to the environment with the threat to the safety of population life and health, penalties increase till 30 for officials, 60 - on small businesses, 100 - on medium-sized businesses, 500 - on large businesses of the monthly calculated indicators. Penalty for causing great damage to the environment includes termination of the permit. Non-elimination by individuals and legal entities of violations by the established deadline entails deprivation of the environmental permit. Environmental Code of the RK, Article 225. Environmental requirements for sewage discharge highlights the need for permits to discharge emissions into the environment.	Code of the RU on administrative liability, approved by the Law of the RU from 22.09.94 №2015-XII, enacted from 04.01.95 following the Decree of the Supreme Council of the RU from 22.09.94 №2016-XII. Article 72. Violation of rules for the protection of water resources Pollution or water pollution, violation of water protection regime at catchments shall entail the imposition of a fine on citizens from three to five, and on officials - from five to ten minimum wages. Setting into operation enterprises, utilities and other objects without structures and devices that prevent water pollution or their harmful effects, as well as the production of other actions that violate the natural state of water bodies -shall entail the imposition of a fine on officials from five to ten times the minimum wage. Committing the offence repeatedly within a year after the application of the administrative penalty - shall entail the imposition of a fine on citizens from seven to ten, and on officials - from fifteen to twenty minimum wages.
Other water protection measures		
31	Land cultivation practices regulated to avoid groundwater pollution	
	No specific identification of groundwaters. Land Code of the RK. Article 99. The use of irrigated lands with technical facilities states the responsibilities of landowners on the maintenance of crops changing scheme, conduct necessary	Land Code of the RU from 30.04.98 Chapter 1. General provisions show that one of the bases of the land legislation is insurance of protection, expansion and strictly purposed use of lands, especially in agriculture of irrigated lands.

	reclamation and recovery work, including the maintenance of the irrigation and collector-drainage systems in a proper manner. Environmental Code of the RK. Article 203. Environmental requirements for the object operation in the industry, energy, transport, communication, agriculture, and melioration mentions that the activities should be carried out considering the established environmental requirements and the use of environmentally reasoned technologies, necessary treatment facilities, and sanitary protection zones that exclude environmental pollution. During the operation of these facilities, low-waste and non-waste technologies should be introduced that ensure environmental safety.	The legislation mentions the protection of lands and ground waters from the pollution; however, the exact measures are not indicated. Additionally, monitoring of pollution in the air, surface and ground waters, dangerous natural and anthropogenic processes, lands and surface ecosystems are described and regulated by the Resolution №111 from 03.04.02 by the Cabinet of Ministers of the RU on approval of the regulation on state monitoring of the environment in the RU.
32	Considering the impact of urban and land development projects on water resources in the context of land development permit procedures	
	No, not specified	No, not specified
Government and non-government water institutions		
33	Government institution at the national level responsible for the administration of the legislation analysed	
	Water Code of the RK, Article 36. Competence of the Government of the RK underlines the roles of governmental authorities. State administration in the field of use and protection of water resources, water supply, and sanitation is carried out by the President of the RK, the Government of the RK, the authorized body in the field of public utilities, local representative and executive bodies of regions (cities of republican significance, the capital) within their competence, established by the Constitution, this Code, other laws of the RK, acts of the President of the RK and the Government of the RK. The Government of the RK: - develops the main directions of the state policy in the field of use and protection of the water fund, water supply, and sanitation; - organises management of water facilities that are in the state's ownership; - approves the rules for regulating water relations between the regions of the Republic;	Water Law of the RU. Chapter II. Competences of governmental authorities and management in water relation regulations. Article 5-7. Several governmental institutions are responsible for the control and management of water legislations: - Oliy Majlis of the RU is responsible for the adoption of legislation on water and water use (including amendments and additions). It also determines the main directions of the state policy in water resources use and protection and adopts state strategic water management programs; - The Cabinet of Ministers of the RU pursuits policy on integrated and rational use, management and protection of water resources. The Cabinet is responsible for the coordination of the work among other government institutions involved in integrated and rational use, management and protection of water resources as well as prevention and elimination of the harmful impact of waters. It establishes the framework of creation and use of water

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	- cooperates in the manner established by the legislation of the RK with foreign states and international organisations on the use and protection of transboundary waters; - approves the general scheme of integrated use and protection of water resources; - determines the organisation for the modernisation and development of housing and communal services; - performs other functions assigned to it by the Constitution, laws of the RK and acts of the President of the RK.	fund, the procedures on approving norms for water use, consumption and withdrawal limits from a water body. The Cabinet supports state monitoring, control of usage and protection of waters and state water cadastre. It develops measures to prevent and liquidate major accidents, disasters, environmental crises and harmful impact of waters; takes part in establishing the process of pricing for the use of water resources, incentives for polluted and depleted water bodies, develops interstate relations; - Ministry of agriculture and water industry manages surface waters; - State Committee on geology and mineral resources is responsible for groundwaters. State Committee on ecology and environmental protection together with the state governmental institutions on a local level, the Inspection for the control of mining and geological activities under the State Committee of the Republic of Uzbekistan on geology and mineral resources, the Inspection for the control of the agro-industrial complex and food security at the General Prosecutor's Office of the RU, the Ministry of Health of the RU, the Ministry of Agriculture and Water Management of the RU are in charge of state control for the protection and use of water resources.
34	Intermediate level responsible government institution for the administration of the legislation	
	Water Code, Article 37. Competence of the authorised body. Authorised body participates in the development and implementation of state policy in the use and protection of water resources, water supply, and sanitation within its competence; coordinates and manages the local executive bodies; develops schemes for the integrated use and protection of water resources; develops and approves safety criteria; coordinates the specific norms of water consumption and drainage; develops and approves standard rules for general water use; approves water use limits in the context of basins and regions (cities of	Water Law of the Republic of Uzbekistan. Chapter III. Governance and control in the field of water use and protection. Article 8. State administration in the field of water use indicates that the State administration of water use is carried out also by specially authorised state administration bodies for the regulation of water use directly or through basin (territorial) administrations.

	republican significance, the capital); approves the method of calculating payments for the use of water resources of surface sources, established by the tax legislation of the RK; develops and approves the procedure for coordinating the location of enterprises and other structures; develops and approves the rules for navigation and production of economic, research, exploration and field work in the territorial waters (sea); determines the procedure for the development and approval of general and basin schemes for the integrated use and protection of water resources and water balances; supports state control in the field of use and protection of the water fund.	
35	Responsibility of local level government institutions for the administration of the legislation		
	Water Code of the RK. Article 38. Competence of local representative bodies of regions (cities of republican significance, the capital) in the field of use and protection of water resources, water supply, and sanitation indicates their roles: - establishing the rules for general water use taking into account the peculiarities of regional conditions; - establishing the procedure for use and withdrawal of municipal water utilities granting; - approving payment rates for using water resources from surface sources; - exercise other powers to ensure the rights and legitimate interests of citizens following the legislation of the RK. Article 39. Competence of local executive bodies of regions (cities of republican significance, the capital) in the field of use and protection of water resources, water supply, and sanitation includes: - management of communal owned water facilities, taking measures to protect them; - keeping records of water management facilities that are state-owned, when detecting ownerless water management facilities, carry out the procedures stipulated by the civil legislation of the RK;	Under the Water Law of the Republic of Uzbekistan, Chapter II. Competences of governmental authorities and management in water relations regulation, local government authorities are responsible for: - the determination of the main directions of use and protection of water resources on its territory; - ensuring law and the process of regulating the use and protection of water resources; - monitoring and assessment of the state of water bodies, control over the use and protection of water, compliance with the established limits on water uptake, water users' records of water use; - taking measures to preserve and improve the condition of water bodies, prevent and eliminate harmful impacts, as well as water pollution, restoration of objects damaged as a result of accidents, floods, mudflows, and natural disasters.	

	- implementation of the state policy in the use and protection of water resources, water supply, and sanitation; - establishment of water protection zones, lanes and zones of sanitary protection for drinking water sources in coordination with the basin water departments, the authorised body in the field of sanitary and epidemiological welfare of the population; - establishment of the regime and special conditions for the economical use of water protection zones and zones in agreement with the basin water management departments; - provision of water bodies for separate use or joint use on a competitive basis in the manner established by the Government of the RK; - participation in the work of basin councils and the basin agreement, proposals submission for rational use and protection of water bodies, water supply, water sanitation for consideration of basin councils; - insurance of the implementation of measures for the rational use and protection of water bodies, water supply, water sanitation of human settlements, including land reclamation; - informing the population about the state of water bodies, water supply, and wastewater systems located in the relevant territory; - development of payment rates for the use of water resources of surface sources; - the implementer of measures for subsidising the cost of water delivery services to agricultural producers and supplying drinking water from the particularly important group and local water supply systems; - distributor of water use limits among water users.
36	Provision of the WUO (water user organisations)

	Yes Water Code of the RK. Article 79. Non-state water management organisations illustrate legal actors who have rights to create non-state water organisations. They are individuals and legal entities, including foreign ones, to provide water delivery services, maintenance of water facilities and business activities in the use and protection of water resources, water supply, and sanitation. By business activities, the article covers withdrawal of water resources for the use, water treatment or delivery to water users; collection and treatment of sewage; improvement of water quality. Article 80. Requirements for the activities of water management organizations specify that these organizations are subjects of natural monopolies and operate in accordance with this Code, the legislation of the RK, the organization's charter and the treaties of the parties (Standard of rendering services to consumers by subjects of natural monopolies in the field of water supply and (or) water sanitation, Appendix 3 to the Order of the acting Ministry of National Economy of RK from 29.07.15 №573). Water organizations are obliged to ensure the proper technical condition of water management systems and facilities, as well as their safety; to provide water users with water in accordance with the contract; install water-measuring devices at points of separation in agreement with water users; to take measures to prevent pollution, clogging and depletion of water bodies and the harmful impacts of water;have a passport irrigation system, waterworks.	Yes Under the Water Law of the Republic of Uzbekistan, Chapter III. Governance and control in the field of water use and protection, Article 10. Participation of the association of water users, other non-governmental, non-profit organisations and individuals in taking measures on rational water use and protection indicates their role where associations, NGOs and individuals assist state bodies in the implementation of measures for the rational use and protection of water bodies. Chapter VI. Water users, consumers, and objects of their use. Article 18. Association of water users describes what principles should be considered for the creation of the association, such as hydrographical principle. Founders of the association could be farms, dekhkan farms with the formation of a legal entity, as well as other water consumers acting as legal entities. Farmers and dekhkan farms, self-governing body, as well as other water consumers can be members of water user associations. Water relations between the association of water consumers and its members are regulated on a contractual basis.
37	Existence of specialised water courts	
	No The subject is mentioned in the Water Code of the RK. Section 10. Water disputes and liability for violation of water legislation of the RK. Chapter 29. Resolution of Water Disputes mentions that disputes are resolved by negotiations of the parties, their consideration in the bodies created by water user associations, in local executive bodies of	No The subject is mentioned in the Water Law of the RU. Chapter XXIII. Settlement of disputes on water use and water consumption. Articles 85 – 96 cover regulations on the state, intermediate and local authorities competence related to resolving disputes; resolution of international disputes and general procedures.

	the region (the city of republican significance, the capital) and the authorised body or courts.	
38	Existence of informal groups (water users, conservation bodies, local government bodies)	
	Yes (Wegerich 2008, Zinzani 2015) Water Law of the RK. Terms are expressed in Article 63. Activities of public associations in the field of use and protection of water fund and Article 79. Non-state water management organisations	Yes (Hirsch, 2007, Veldwisch and Mollinga, 2013) The Cabinet Ministers' Decree №8 adopted on 5.01.02 on measures to reorganise agricultural entities into farming entities, Chapter II Organization of WUA acts as the main document marking legal aspects of WUA's establishment. Rules on access, use, storage and exchange of water, details on membership, decision-making and information sharing are not presented in the Decree №8. This specification is a matter of an agreement signed between a WUA and water users.
39	Accessibility of data on regulations related to groundwater monitoring, protection, and abstraction	
	Yes Through Legal information system of Regulatory Legal Acts of the Republic of Kazakhstan	Yes Through Legal information system of Regulatory Legal Acts of the Republic of Uzbekistan

Appendix V The boundary of the PTBA from Uzbek source
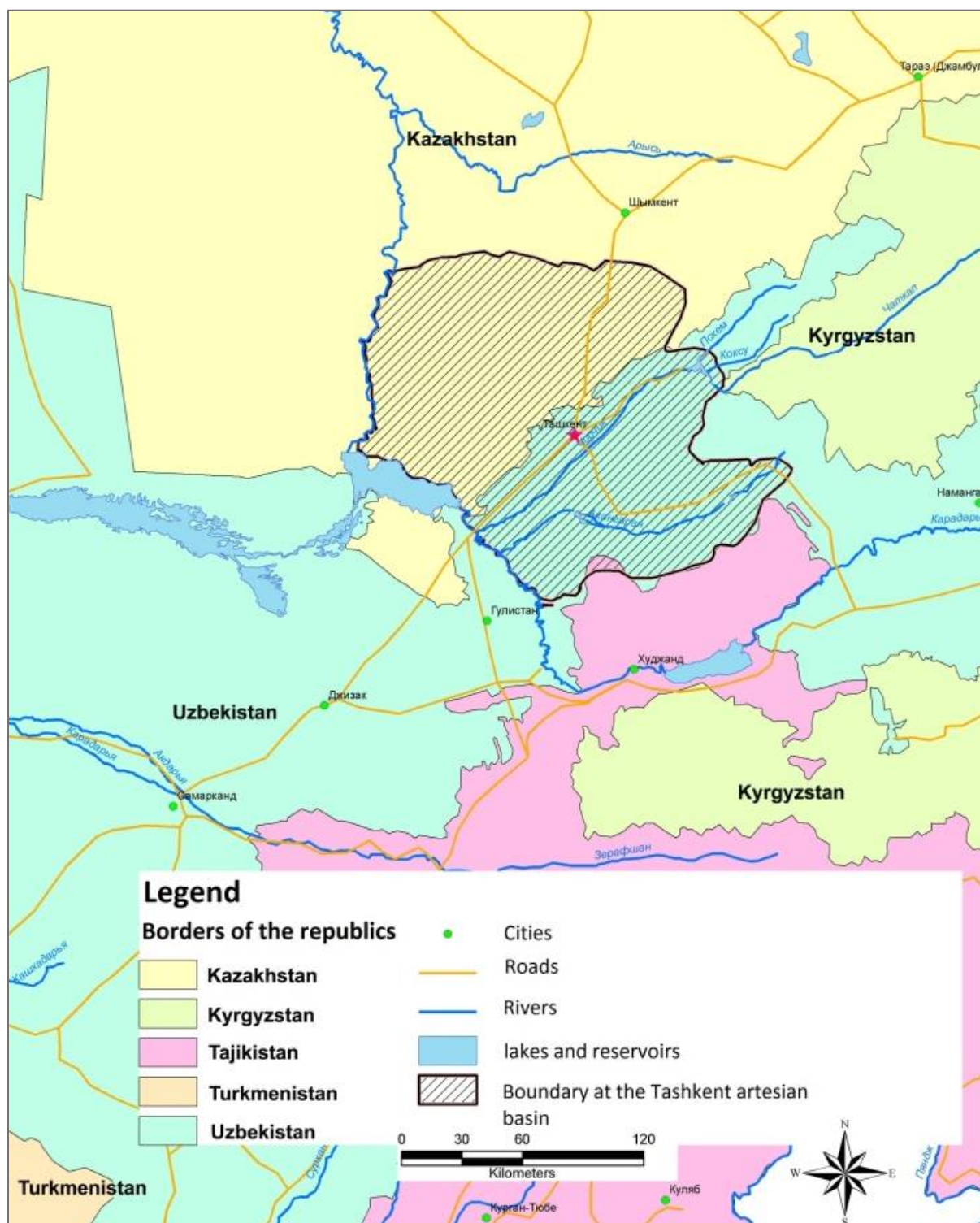
The boundary of the Pretashkent transboundary aquifer from the Internal report from Uzbekistan submitted within the GGRETA project. Source: Karimov, 2013