Circular Economy and Sustainability (2023) 3:2267–2283
https://doi.org/10.1007/s43615-023-00269-y

OPINION PAPER

Sustainable Water Use in Industry—Reasons, Challenges, Response of Kazakhstan

Ivan Radelyuk[1,2] · Jiří Jaromír Klemeš[3] · Kamshat Tussupova[2]

Received: 30 January 2023 / Accepted: 7 May 2023 / Published online: 17 May 2023

Abstract

Industrial development poses significant challenges to water resource management, both in terms of quality and quantity. In response to these challenges, the concept of sustainable water use has been proposed as a means of addressing these issues. However, this concept is not yet widely adopted in developing countries, particularly in Kazakhstan. This paper examines the extent to which water use is sustainable on the example of the oil refinery sector in Kazakhstan. The investigation revealed a two-fold problem: the discharge of contaminated wastewater into the environment, which poses a risk of contamination transport, and the irrational use of water within the refinery. These issues are rooted in low water fees, low penalties for pollution and the gaps in legislation that allow for high maximum allowable concentrations of pollutants in discharges. As a result, toxic contaminants, such as petroleum hydrocarbons, are present in high concentrations exceeding permissible limits in groundwater up to 6 km away from the point of wastewater discharge. Based on the findings of the environmental impact assessments carried out in the sector, the authors propose a response that involves revising and implementing suitable legislative standards with requirements for transparent practices for environmental impact assessment and new efficient environmental monitoring programs to prevent water pollution. These measures have been adopted in the new Ecological Code and require proper control to ensure their effective implementation. However, the perspective of implementing efficient water-saving techniques and water integration is not yet widely visible and needs to be considered in order to achieve the sustainable water use in the industry.

Keywords Best available techniques · Circular economy · Environmental impact assessment · Industrial wastewater · Sustainable water use · Water integration

✉ Ivan Radelyuk
radelyuk.i@tou.edu.kz

[1] Department of Chemistry and Chemical Technologies, Toraighyrov University, Pavlodar 140000, Kazakhstan

[2] Department of Water Resources Engineering, Lund University, Box 118, 22100 Lund, Sweden

[3] Sustainable Process Integration Laboratory (SPIL), NETME CENTRE, Faculty of Mechanical Engineering, Brno University of Technology—VUT Brno, Technická, 2896/2, 616 69 Brno, Czech Republic

Introduction

Sustainable development, defined as 'allowing people to live in a healthy environment and improve social, economic and environmental conditions' [1], is an extremely important paradigm for humanity today. The establishment of such coherent reference point is essential in promoting responsible utilization of resources while simultaneously improving global living standards. With industrial sectors being the most prominent consumers of resources and leading sources of environmental pollution, a special emphasis must be placed on the harmonization of resource usage and economic growth in developing nations [2]. Water is considered by the United Nations (UN) to be a crucial component of sustainable development, playing a critical role in promoting socio-economic advancement, maintaining healthy ecosystems and enabling human survival [3]. Industrial development poses significant challenges to water resource management, both in terms of quality and quantity [4]. In response to these challenges, the concept of 'sustainable water use' (SWU) has been proposed as a means of addressing these issues [5]. The concept aims to assure three pillars of sustainability related to the water sector: social, environmental and economic. One of the first known definitions of the SWU was 'the use of water that supports the ability of human society to endure and flourish into the indefinite future without undermining the integrity of the hydrological cycle or the ecological systems that depend on it' [6]. Since then, particular focus has been paid to the importance of such aspects of the SWU as the volume of water consumption with the associated predictions of water scarcity [7], water pollution and its environmental consequences [8], technological aspects for providing available and safe water [9], corporate social responsibility [10] and water economy and its impact on water use [11]. Combination of such aspects for the application of the concept in the industry can be framed by the following factors (Fig. 1). Social factors include, firstly, public safety by consumption of available and safe drinking water and, secondly, relevant regulation assuring this right. Environmental factors consider the good ecological status of water bodies, where the water is supplied from and discharged to, including by industrial

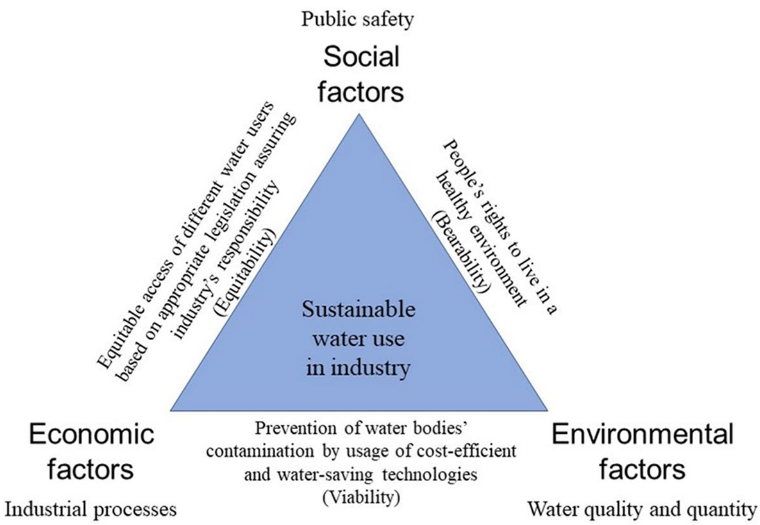

Fig. 1 The application of the Sustainable Water Use in industry

activities. Economic factors include efficient and fair pricing for water use, which considers the cost to obtain water, treat it and discharge or reuse it in a respective manner [12].

There is a lack of research on sustainable water management in industrial sectors in developing countries such as Kazakhstan, despite the increasing challenges in this field. For example, the search in the Scopus database using keywords 'TITLE-ABS-KEY (water AND circular AND economy AND Kazakhstan)' shows only one research paper written by the authors. Other relevant literature surveys have shown a limited focus on a maximum of two factors, which may hinder researchers and decision-makers from achieving the holistic and systematic approach to sustainable development [13, 14]. It is essential to address the challenges of ensuring viable, bearable and equitable water under conditions when most industrial enterprises do not have wastewater treatment facilities on their premises or do not carry out preliminary treatment with the direct discharge into rivers or urban sewerage systems [15]. These facts indicate that the principles of the SWU in industry are barely visible in Kazakhstan.

This paper represents the first known attempt to investigate water usage in the industry from the perspective of sustainable water use (SWU) in Kazakhstan. The study encompasses the technological, environmental, socio-economic and political aspects of the current industrial water use system, with the oil refinery sector being used as a case study. The *general aim* of this case study was to understand to what extent water use in the oil refinery industry in Kazakhstan is sustainable. Respectively, three objectives related to interactions between dimensions of the SWU were identified for related investigation: *Objective A* aimed to investigate water and wastewater management practices at oil refinery factories in Kazakhstan in accordance with respective national and international legislation. *Objective B* aimed to assess groundwater safety affected by the current system of wastewater treatment in one of the refineries and its impact on environment and society. *Objective C* aimed to define possible solutions for industrial water and wastewater management system in Kazakhstan to ensure the SWU principles are met.

Case Study

While Kazakhstan is a water-rich country, there are known mismanagement problems in the water sector. The country already faces risks of water scarcity in future, experiences significant water losses due to the obsolete infrastructure of water facilities and faces damaging pollution of natural water sources [16]. Moreover, the impact of climate change, increase in water demand, weakness of institutional approach and uncontrolled use of water resources by upstream neighbourhoods only jeopardize the situation. It has been estimated that the mismanagement of freshwater resources would lead to a national water deficit by 2030 [16]. Kazakhstan accepted the national program for a transition towards a 'green economy' with the adaptation of the circular economy (CE) principles in 2013 [17]. Water issues have been accepted as the priority direction in the implementation of the CE in the respective national program [18]. The expected outcomes of implementation include, firstly, alleviation of the stress on freshwater supply by water reuse and adaptation of water-saving technologies and, secondly, elimination of associated water and energy losses due to ineffective water delivery systems [19].

Refining enterprises give a significant contribution to the structure of industrial development. The petroleum industry is the major actor and accounted for about 10% of the GDP in the country [20]. The sector is represented by three large enterprises and associated clusters in the north-east, south and west regions of the country. The refinery throughput in Kazakhstan is 339 thousand barrels daily, a number that is growing by 4.6% every year. The refinery capacity is estimated to be 350,000 barrels daily [21].

Water is a very important reagent in petroleum and petrochemical production processes. Distillation, extraction, preparation of solutions, cooling systems and washing processes are some examples of industrial water use, leading to large consumption in the current fuel and electricity production [22]. The total water consumption for those purposes is projected to increase by 55% between 2000 and 2055 globally [23].

The oil refinery industry in Kazakhstan consumed 77.8 mln m^3 of water in 2016, while only 3.5 mln m^3 of it has been re-used, and the rest has been discharged into the environment. According to the Environmental Performance Review for Kazakhstan [15], three oil refinery factories in Kazakhstan are one of the biggest sources of water contamination, despite attempts to control the pollution by both the government and the industry. Mitigating such risks is a challenge, which requires not only optimization during the treatment, but a research-based approach for the whole system of water and wastewater management in the industry [24, 25].

Methods

The investigation of the case study used the DPSIR (*Drivers-Pressures-State-Impact-Response*) framework to investigate existing *pressure* on water resources by the oil refinery sector in Kazakhstan [26]. The hypothesis was that the *pressure* is caused by improper wastewater treatment. Thus, legislation in this sphere, the treatment methods, the discharge process and the effect on the environment were evaluated following international and national regulations [27]. The related second step was to evaluate the resulting *state*, as an indicator of the *pressure*, by assessing the quantitative and qualitative parameters of the contaminated wastewater discharged by the oil refinery sector.

The next step was to evaluate potential *impact*, which may differ, including deteriorated or destroyed ecosystems, unsafe drinking water or the waste of water in the regions where water scarcity exists. Multivariate statistical technique is a widely used approach, which supported in the assessment of the behaviour of contamination from point sources [28]. For the particular case study, the potentially affected territories by the spreading of the contamination plume in space were identified based on historical observations. Furthermore, the assessment of the potential hazard from spreading the contamination under potential scenarios of varying loading of the contaminants was done. For this purpose, a two-step modelling procedure was developed and used [29]. The first step included the numerical groundwater model using MODFLOW to define the groundwater flow direction, as it is a necessary prerequisite to any contaminant transport modelling undertaken as part of the analysis of the pollution pressures on that body. In the second step, a semi-analytical contamination transport model was applied for the general investigation of plume development in the aquifer. As a result, the potential fate of contaminants can be assessed under the consideration of different scenarios, depending on local conditions [30].

As a final step of the DPSIR, the related *response* might be proposed to mitigate identified challenges. The main criteria for the *response* should be the efficiency of proposed solutions to handle roots of the problem, which lay in industrial water and wastewater management systems [31]. Figure 2 represents the structure of this study under the DPSIR framework.

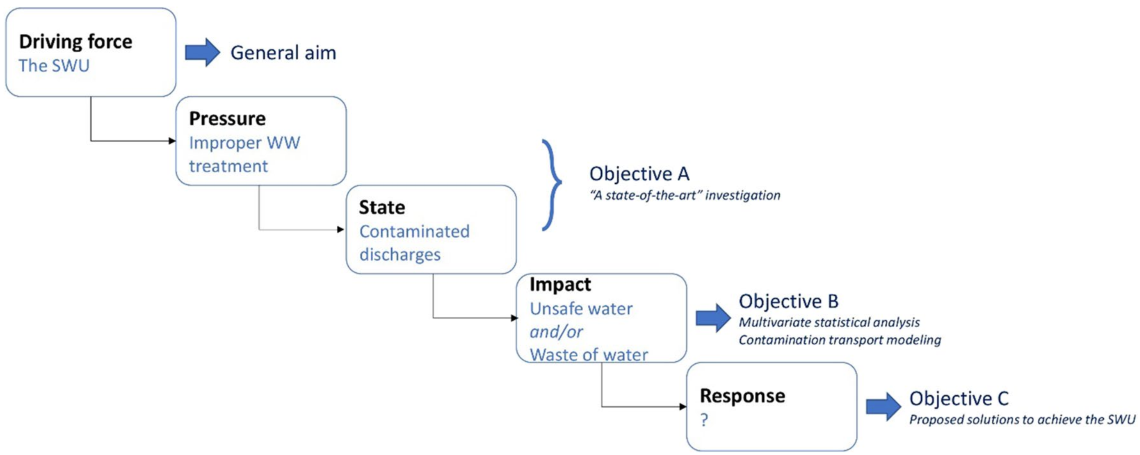

Fig. 2 The DPSIR framework used for assessing the shift towards the SWU in the oil refinery sector in Kazakhstan. The *italic* represents methods used in this study to solve the established objectives

Results

The results addressed the established objectives, as follows:

Objective A

This study identified the imperfections of the existing framework for water use in the sector in Kazakhstan. It was found that there is no incentive by current law in Kazakhstan to shift towards the SWU, as there is in developed countries where enforcement of legislation was the first step towards the SWU. Formally, environmental regulation in Kazakhstan promotes the polluter pays principle and follows the World Health Organization (WHO) recommendations for ensuring drinking water quality, including groundwater. Simultaneously, the weakness of legislation was identified by lacking unified and transparent standards for treatment processes and wastewater quality [32]. Additionally, corruption might decrease the stringency of environmental regulations and might accordingly lead to higher emission levels according to Nugumanova and Frey [33]. Loopholes in the local law have allowed the discharge of improperly treated industrial wastewater into artificial or natural ponds, which potentially causes fate for the environment and society. One example is that permission has been based on the requirement that the initial concentration of pollutants in a recipient of wastewater is exceeded. Historically, there has been a time gap between when the discharge started and when the monitoring of the recipient started. Thus, the industry receives a legal permit for environmental pollution and does not have any motivation to invest in the improvement of treatment approaches or in the modernization of already obsolete treatment equipment [27]. Low water fees, low penalties for pollution and the possibility to establish maximum allowable concentrations (MAC) of the pollutants in wastewater equal to the background concentration of the pollutant in an already polluted recipient allow the situation to remain unchanged. Thus, Kazakhstani standards are not sufficiently adapted for international guidelines, which causes the release of potentially toxic substances together with wastewater into environmental media, where those substances migrate into another, e.g. groundwater [34], with the following threats for public health and connected ecosystems. It can be clearly seen from Table 1, where the MACs and the real concentrations of the contaminants in wastewater from one particular oil refinery and

Table 1 Content of wastewater released into the environment by the studied refinery in Kazakhstan (adapted from Radelyuk et al. [27])

Parameter	Unit	$MAC_{refinery}$	$MAC_{domestic}$	$C_{average}$	C_{median}
Ammonia (NH_4^+)	mg/L	55.18	2.00	49.26	52.36
Total petroleum hydrocarbons (TPH)	mg/L	3.02	0.10	1.30	1.23
Biochemical oxygen demand (BOD)	mgO_2/L	17.8	3.0	10.6	10.6
Sulphates (SO_4^{2-})	mg/L	643.0	500.0	449.0	469.5
Chlorides (Cl^-)	mg/L	169.8	350.0	82.5	70.6
Nitrates (NO_3^-)	mg/L	19.2	45.0	12.5	13.2
Nitrites (NO_2^-)	mg/L	7.7	3.0	0.1	0.4
Phenol's index	mg/L	0.25	0.25	0.02	0.02
Suspended solids	mg/L	20.98	25.00	7.29	7.69
Surfactants	mg/L	0.52	0.50	0.34	0.36

domestic wastewater plant are presented and compared. The maximal allowable concentrations of total petroleum hydrocarbons are 30 times higher, ammonia 25 times higher, and BOD are 6 times higher than those in the domestic wastewater. Also, the observations show that the industry prefers to keep the concentrations near the top possible level, as it is officially permitted. The situation remains similar for all refineries in Kazakhstan [27].

Thus, the investigation of the studied refinery has identified a two-fold problem: consisting of the discharge of contaminated wastewater into the environment, which poses a risk of contamination transport, and the irrational use of water within the refinery. It is likely that other oil refineries and industries in Kazakhstan face a similar situation.

Objective B

This study identified that groundwater surrounding the wastewater recipient pond had been affected and contained a high level of some chemicals, such as total petroleum hydrocarbons, total hardness, total dissolved solids and sodium. These pollutants are likely spreading towards areas with substantial groundwater use [35]. Multivariate statistical analysis showed that there is the two-fold origin of pollution in the studied area: anthropogenic and natural [36]. Even though anthropogenic load might be controlled by a respective decrease of contamination via effective wastewater treatment, this study showed that man-made chemicals with a high level of toxicity, such as TPH, exist in concentrations exceeding permissible limits on the significant distance (1 km) from the recipient pond. This fact may reflect the quasi-steady-state conditions of the plume in the aquifer due to exposure of pollution for a long period of time [37]. The development of groundwater flow and contamination transport models is a viable part of the assessment of the pollution pressures on that body. This study focused on the potential impact of groundwater contamination by total petroleum hydrocarbons (TPH), as an indicative contaminant of the case study. The semi-analytical contamination transport model was developed to investigate the behaviour of the plume of TPH inside the aquifer and to give respective recommendations for environmental managers and local habitats [29]. The results, based on retrospective observations, showed that the risks for residents in the potentially affected rural area of Kazakhstan could be avoided, as the plume has not reached the villages considered to be within the risk zone. However, agricultural areas at 2–6 km downstream the source of pollution could be affected by contaminated water (Fig. 3). Moreover, future growth of the industrial capacity in the region, with an expected increase in industrial pollution, does not promise improvement of the groundwater status. As it is shown, the increase in initial concentration of TPH, caused by the high loading of TPH from the industry, significantly extends the affected area. Thus, the adverse effect of the possible contamination in connection with the poor monitoring system of such contamination might consider the careful usage of groundwater from the shallow aquifer for irrigation purposes in this area.

Objective C

In order to achieve the SWU, the system of industrial water and wastewater management relies on legislative and normative standards. In Kazakhstan, the system is weakened not only by gaps in legislation, but also by the absence of appropriate environmental tools (such as operational monitoring and environmental assessment). The defined criteria to ensure equitable access of different water users and viable mechanisms to achieve water safety include (1) implementation of the concept of circular

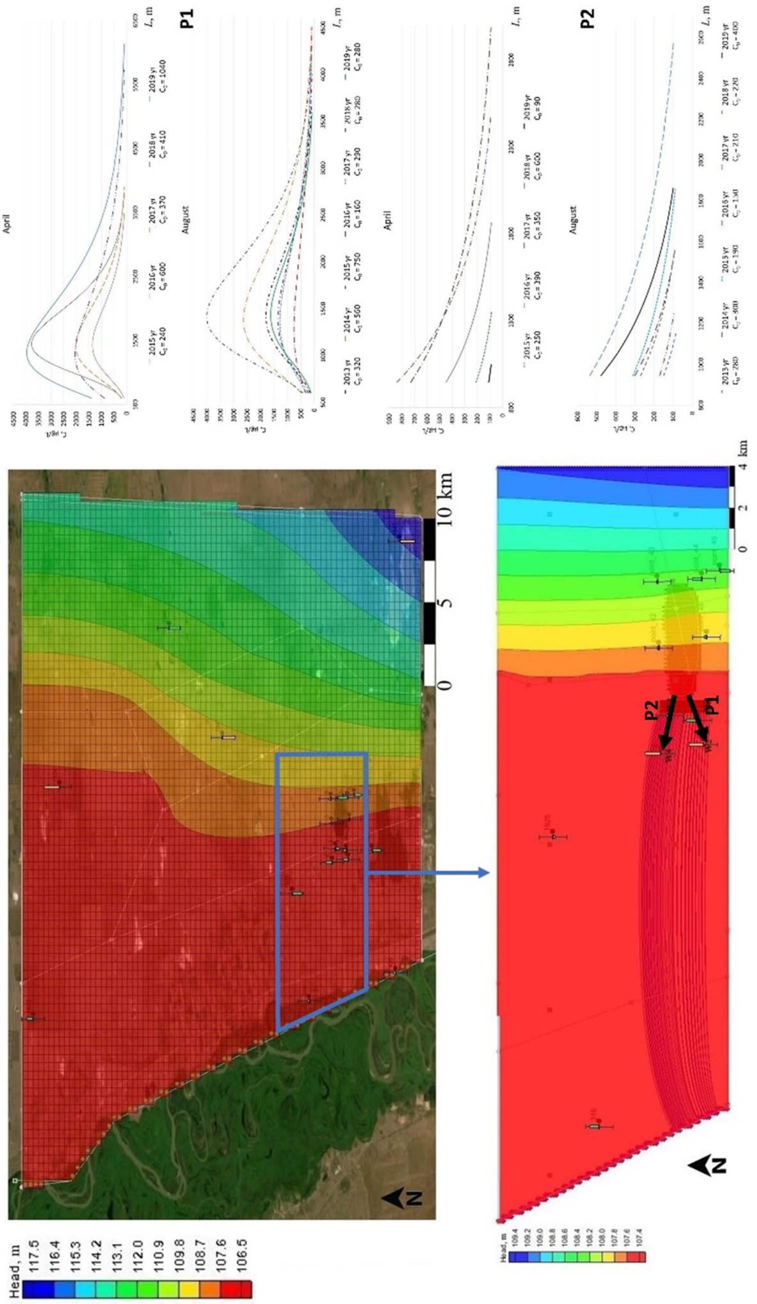

Fig. 3 The result of the semi-analytical contamination transport modelling (adapted from Radelyuk et al. [29])

economy (CE), via implementation of best available techniques (BAT) and water integration; (2) improvement of the current system of environmental impact assessment; and (3) improvement of the existing scheme of operational monitoring for wastewater quality. The suggested potential solutions should follow the requirement to control the amount of contamination inside the technological processes before final discharge. The performed investigations showed that decision-makers in Kazakhstan, unlike developed countries, do not follow scientifically approved techniques and mechanisms to prevent pollution, which guarantee a ‘good’ status of receiving water bodies [5]. The current trend is a transition towards ‘closed-loop’ systems—choosing sufficient treatment methods specifically for each factory, considering environmental conditions, facility size, age of facility, equipment etc. [38]. Refineries in Kazakhstan do not strive to reuse water despite the risk of water scarcity in the region. It is recommended to use an ‘in-plant control’ technique, i.e. installation of extra regeneration units for processing water before the final (or ‘end-of-pipe’) treatment system to supply regenerated water for secondary use within industrial processes. The results are two-fold: decreasing freshwater consumption and enhancing the efficiency of the final treatment. It was also found that the current wastewater treatment scheme at oil refineries does not use efficient advanced techniques at each step, including pre-, secondary and post- (or polishing) treatment. Thus, it is highly emphasized to improve the wastewater treatment systems via the implementation of the BAT.

The current scheme of environmental impact assessment in Kazakhstan is weakened due to a legislative loophole [15]. The adjusted new unconditional requirements for effluent safety assessment, such as a detailed investigation of effluent characteristics using, e.g. parameter-specific approach, whole effluent toxicity (WET) approach or bioassessment approach toxicity tests, have shown high efficiency worldwide [39]. The ban on potential transfer of toxic substances from one environmental media to another (for example, from surface water to groundwater) in many countries has contributed to environmental improvements and promoted both the governments and the industries to follow the SWU [40].

Kazakhstani oil refineries monitor only the sum of TPH, without detailed investigation of the resulting effect on the environment, while the developed countries identified certain indicators and a detailed list of pollutants, including toxic ones such as PAHs (in total and individual compounds), benzene, toluene, ethylbenzene, xylenes (BTEX) and PFAS, for better estimation of the toxic effect of their existence in wastewater. Still, the mentioned petroleum compounds are not degradable, which might cause risks even at low concentrations. Continuous update of the list of substances for operational control during wastewater treatment and environmental monitoring in many countries ensures environmental safety and follows the sustainable development principles positively affecting the monitoring system. Unconditional requirements for effluent safety, continuous update of the list of the potential pollutants and implementing BAT are the current requirements for the industrial management to follow the SWU.

Figure 4 represents the existing scheme of water use in the oil refinery sector in Kazakhstan and proposed by the authors’ available mechanisms to achieve the SWU, based on the results above.

Based on the investigated case study, the authors suggested the following actions to decrease environmental pollution, to assure a healthy and productive environment and, consequently, to achieve the SWU:

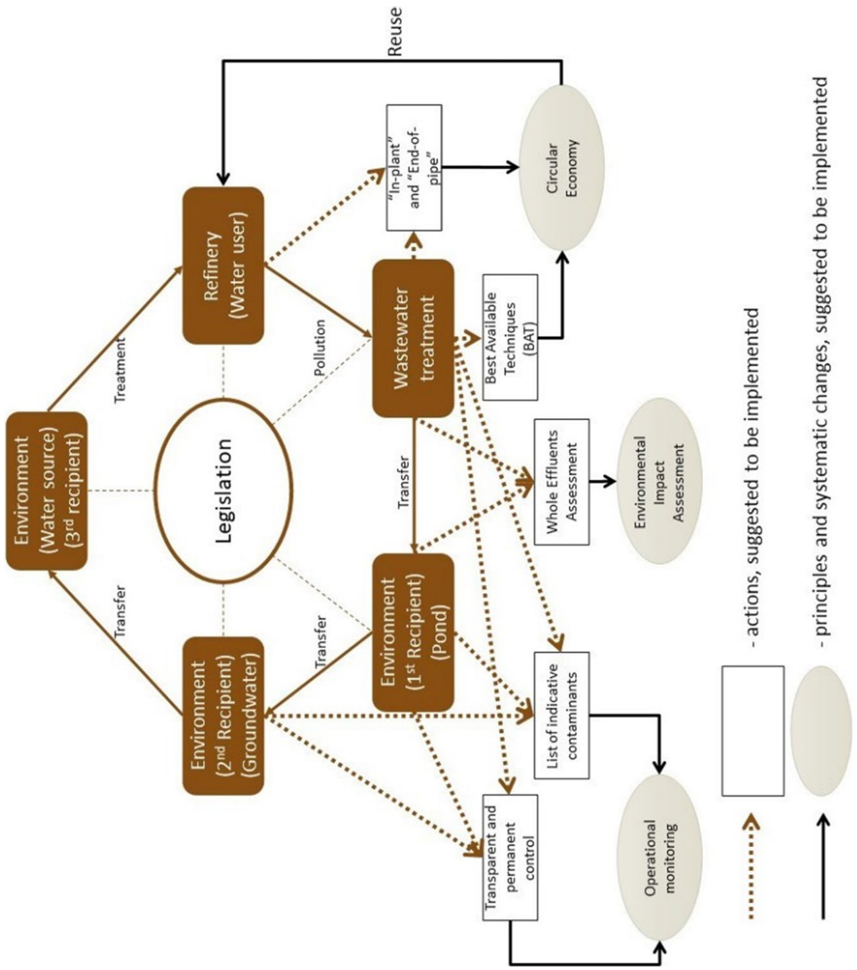

Fig. 4 An existing framework for water use in oil refineries in Kazakhstan with proposed improvements

a) This study identified a severe status of the contaminated recipient pond for wastewater from the studied refinery and related extended groundwater pollution, which likely will exist for decades and spread out on a kilometre scale. The main action from the government should be to acknowledge the problem and take necessary actions to address it.
b) Legislative loopholes in the methodology for establishing the requirements for effluents from the refineries are one of the major contributors to the resulting pollution. The government should take a leading role in the development of sufficient requirements for industrial wastewater treatment and disposal systems. The core action is the development of unified, transparent and fair regulatory standards for the procedure of the environmental impact assessment.
c) The lack of integration of a science-based approach weakens water management practices both at the governmental and industry levels. Detailed investigation of wastewater characteristics, and the application of new tools for environmental monitoring, such as developing groundwater and contamination transport models, will assist the environmental agencies in assessing and controlling industrial impact and related risks.
d) The implementation of the principles of circular economy, particularly 'water integration' (WI) and 'best available techniques', can contribute to preventive activities and reduce the risks for the environment and society.

Discussion

The most recent research advances highlight different aspects to perform efficient transition towards the SWU in industry with the number of successful implementations. These solutions were the responses to the challenges in each particular region. For instance, the implementation of efficient nature-based treatment techniques for oily wastewater reuse has been driven by water scarcity in Oman [41]; to conserve water and preserve watersheds according to corporate sustainability projects by the refinery of Dow Benelux BV company using advanced wastewater treatment techniques of the industrial and municipal wastewater with its following 'triple reuse'—water, associated energy and chemical savings [42]; unnamed industry with the application of advanced wastewater techniques to produce recycled water with the emphasis of cost benefits [43]; efficient management of wastewater resources with the focus on renewable energy production [44]; quantitative environmental and cost assessment of benefits for multi-water resources integration into the region's water supply to decrease freshwater withdrawal in China [45]; investing in treatment systems to reduce wastewater pollution to comply with environmental requirements established by international client companies [46]; high demand of recycled water by various users which can be covered by local industries [47]; production of regenerated water for its distribution along eco-industrial parks [48]; and technological possibilities to optimize the water allocation by water integration approach [49]; etc. Thus, it is important to identify the pros and cons of the situation in Kazakhstan towards sustainable water use in industry and compare the applicability of the known strategies in the local context or to suggest a unique approach.

This study has identified the state-of-the-art of industrial water use in Kazakhstan before the implementation of the new version of the Ecological Code instead of a previous one dated 2007 [50]. It was found that the current '*status-quo*' includes formal approval for polluting activities by the industry, which causes risks to the environment and public safety. This situation violates the principles of equitability and bearability of the SWU.

The latest version of the Ecological Code incorporates some of the recommendations described above. The updated version includes provisions for involving society and science in the decision-making process according to the Aarhus Convention during the entire environmental impact assessment. The previous version of the Law had already included the 'polluter pays' principle. However, it was assumed that only penalties would be charged to the government revenue if a violation was detected. The current version of the law states that polluters have two obligations: remediation and prevention. The first obligation is remediation, which means that polluters must restore the contaminated site to its original condition before the accident. The initial conditions should be obtained from permanent monitoring stations, which is also a new part of the Ecological Code. Enterprises are obligated to maintain automated 'real-time' monitoring systems for emissions and discharges of pollutants at the sources of contamination. The data about emissions are supposed to be recorded and transmitted directly to a governmental regulatory body [51]. This action aims to minimize the bureaucracy when industrial inspections were supposed to be conducted once per 6 months with the preliminary notification of at least 30 calendar days before the inspection [52].

Another function of the revised usage of the 'polluter pays' principle is the preventive function. The idea is to establish extremely high payments for environmental emissions in case the enterprise does not implement BAT. The core change in the Code is that emission permits will be based on the possibilities of achieving safe concentrations of contaminants in discharges using BAT, while the historical background of these concentrations has been used in the previous version. The new procedure of the environmental impact assessment, together with obtaining the complex environmental permits, has also been linked to the existence of BAT in the enterprise. The implementation of the BAT aims to achieve the CE within a long-term perspective, while the current situation prioritizes urgent solutions for already existing pollution problems. The version of the Code states that new rules will be put in place in 2025 to give the enterprises time to adopt new requirements. The idea to base main regulatory decisions on the usage of the BAT raises two types of concerns in the Kazakhstani context. Firstly, how the tariffs for environmental emissions will be calculated and will they be efficient? Secondly, new BAT Guidelines will be developed for every sector of the industry in Kazakhstan. The developers should ensure that the guidelines will contain the list of the most advanced treatment techniques. As a result, high standards for ensuring the safety of discharged wastewater must be followed.

According to the authors' opinion, the following steps need to be taken for continuation and enhancement of the transition to the SWU. The major goal of the abovementioned actions is in line with the aim of the respective national program to achieve alleviation of the stress on freshwater supply and elimination of associated water and energy losses. The authors believe that this goal might be considered from the perspective of the water-emissions-energy (WEE) nexus, with reference to the implementation of water integration (WI) and water footprints (WF). The WI is a concept that explains how to reduce freshwater consumption by sending wastewater of reasonable quality produced by one sector into another [53]. The WF concept represents the extent of water use concerning consumption and contamination in both monetary and volumetric values. The most recent extended versions of the WF aim to assess the sustainability of water use in a matter of establishing the current and future rates of water use on the environment and economic well-being of a certain area. All the processes in (waste)water management can be associated and assessed considering energy consumption for water supply and (waste)water treatment [54]. In the Kazakhstani context, the water supply and wastewater disposal systems for all sectors (residential, industrial, energy and agricultural) are centralized with one main shared source of water. The current conditions of the obsolete water network systems cause water losses, which are reflected in the respective energy losses [55]. There have been registered 15.7% water losses in the studied region in 2021 [56]. The combination of the selected approaches in the form of *Water-Energy Footprint Pinch Analysis* (WEFPA) can give a clear understanding to evaluate perspectives of circular water use and respective environmental and monetary benefits to decision-makers. This approach seems to be a challenge and an opportunity to fulfil the research gap for the system of water use, especially in the industry in Kazakhstan. A recently launched project titled 'Water-Emissions-Energy nexus – development of a tool to assess perspectives for water circularity in Kazakhstan' aims to analyse the ways to obtain the minimal possible water footprint (both qualitative and quantitative) by decreasing the emissions into the natural water sources and reducing freshwater abstraction for the industry in the region. As a novelty of this project, the applicants aim to develop and apply the assessment tool, which will implement also a parameter of energy into the WEFPA with the following investigations for reducing associated energy losses in the water sector [57], which is of the extremal relevance for Kazakhstan.

Conclusions

The findings of this study shed light on weaknesses in the system of industrial water use, using the oil refinery sector in Kazakhstan as an example. The study proposes ways to improve the system and highlights the need for the SWU approach to ensure efficiency. The current industrial water use system is not sustainable, as evidenced by the low rate of water reuse, poor wastewater treatment efficiency and release of potentially toxic contaminants into the environment. These issues violate the principle of equitability for safe water among different water users and the principle of bearability for people to live in a healthy environment. These problems stem from the weakness of the existing legislative framework, which lacks unified and transparent standards for treatment processes and wastewater quality. The following responses have been proposed to achieve sustainability in the sector: (i) implementation of suitable legislative standards with requirements for efficient water-saving techniques to promote the circular economy; (ii) transparent practices of the environmental impact assessment to evaluate the potential hazard of effluents fairly; and (iii) new efficient environmental monitoring programs to control and prevent water pollution. The newly updated version of the Ecological Code has responded to most of the recommendations with the usage of the BAT as the core driver to improve the environmental conditions in the mid-term perspective and to shift towards the resource use optimization in the long-term perspective. It is important to closely monitor the development of regulatory documents under the Code and ensure that industries are implementing them properly, as they are supposed to be vital documents in the shift towards the sustainable water use. While the adaptation of water-saving technologies has been claimed as the priority way to achieve 'green economy' in the country on the governmental level, the water integration approach is barely visible as the efficient tool to achieve the goal.

This study is subject to a potential limitation due to the choice of a single enterprise from a specific sector and the generalization of its results to the entire industrial sector of Kazakhstan. The application of a systemic approach was employed to conduct a comprehensive examination of the case study, incorporating a range of analytical instruments. It should be noted that this type of research is not currently prevalent in Kazakhstan, and consequently, the findings of this study are grounded primarily in available working papers, governmental and non-governmental reports. These sources indicate that the issues highlighted in this study are prevalent across all industries in Kazakhstan.

Acknowledgements The paper is dedicated to the memory of Prof. Dr-Habil Ing Jiří Jaromír Klemeš—the Head of Sustainable Process Integration Laboratory (SPIL)—who was the leading researcher in the area of process integration. He passed away in January 2023.

Author Contribution Ivan Radelyuk: conceptualization, methodology, investigation, formal analysis, writing—original draft, writing—review and editing. Jiří Jaromír Klemeš: conceptualization, supervision, writing—review and editing. Kamshat Tussupova: conceptualization, methodology, supervision, formal analysis, writing—review and editing.

Funding This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP14972725). Major outcomes of this paper come from a doctoral dissertation of Ivan Radelyuk titled 'Towards sustainable water use in industry: a case study of the oil refinery industry in Kazakhstan'. The authors also acknowledged the funding and support by the EU project Sustainable Process Integration Laboratory (SPIL), funded as project no. CZ.02.1.01/0.0/0.0/15_003/0000456, by Czech Republic Operational Programme Research and Development, Education, Priority 1: Strengthening capacity for quality research.

Data Availability Not applicable.

Declarations

Ethics Approval and Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing Interests The authors declare no competing interests.

References

1. Ortiz O, Castells F, Sonnemann G (2009) Sustainability in the construction industry: a review of recent developments based on LCA. Constr Build Mater 23:28–39. https://doi.org/10.1016/j.conbuildmat.2007.11.012
2. Halog A, Anieke S (2021) A review of circular economy studies in developed countries and its potential adoption in developing countries. Circ Econ Sustain 1:209–230. https://doi.org/10.1007/s43615-021-00017-0
3. UN (2005) International decade for Action "Water for life" 2005–2015. UN DESA. https://www.un.org/waterforlifedecade/water_and_sustainable_development.shtml. Accessed 27 Mar 2023
4. OECD (2012) OECD environmental outlook. OECD Publishing, Paris
5. Radelyuk I, Tussupova K, Klemeš JJ, Persson KM (2021) Oil refinery and water pollution in the context of sustainable development: developing and developed countries. J Clean Prod 302:126987. https://doi.org/10.1016/j.jclepro.2021.126987
6. Gleick P, Loh P, Gomez S, Morrison J (1995) California water 2020: a sustainable vision. Pacific Institute Report, Oakland
7. Hoekstra AY (2014) Sustainable, efficient, and equitable water use: the three pillars under wise freshwater allocation. WIREs Water 1:31–40. https://doi.org/10.1002/wat2.1000
8. Van Fan Y, Lee CT, Lim JS, Klemeš JJ, Le PTK (2019) Cross-disciplinary approaches towards smart, resilient and sustainable circular economy. J Clean Prod 232:1482–1491. https://doi.org/10.1016/j.jclepro.2019.05.266
9. Ekwanzala MD, Budeli P, Momba M (2021) Sustainable solutions to the impact of industrial water pollution on the environment and community health. In: Davis CK, Rosenblum E (eds) Sustainable industrial water use: perspectives, incentives, and tools. IWA Publishing, pp 127–138. https://doi.org/10.2166/9781789060676_0127

10. Lambooy T (2011) Corporate social responsibility: sustainable water use. J Clean Prod 19:852–866. https://doi.org/10.1016/j.jclepro.2010.09.009
11. Wang W, Xie H, Zhang N, Xiang D (2018) Sustainable water use and water shadow price in China's urban industry. Resour Conserv Recycl 128:489–498. https://doi.org/10.1016/j.resconrec.2016.09.005
12. USEPA (2012) Planning for sustainability. A handbook for water and wastewater utilities. Ross & Associates Environmental Consulting, Seattle
13. Blum NU, Haupt M, Bening CR (2020) Why "Circular" doesn't always mean "Sustainable." Resources, Conservation and Recycling 162:105042. https://doi.org/10.1016/j.resconrec.2020.105042
14. Nika CE, Vasilaki V, Exposito A, Katsou E (2020) Water cycle and circular economy: developing a circularity assessment framework for complex water systems. Water Res 187:116423. https://doi.org/10.1016/j.watres.2020.116423
15. UNECE (2019) Environmental performance review for Kazakhstan. ECE/CEP/185. ECE Information Unit. Geneva. https://unece.org/environment-policy/publications/3rd-environmental-performance-review-kazakhstan. Accessed 11 Jan 2023
16. Karatayev M, Kapsalyamova Z, Spankulova L, Skakova A, Movkebayeva G, Kongyrbay A (2017) Priorities and challenges for a sustainable management of water resources in Kazakhstan. Sustain Water Quality Ecol 9–10:115–135. https://doi.org/10.1016/j.swaqe.2017.09.002
17. President (2013) About the Concept for the transition of the Republic of Kazakhstan to a "green economy" (in Russian). Decree № 577 of the President of the Republic of Kazakhstan dated May 30, 2013. https://adilet.zan.kz/rus/docs/U1300000577#z1. Accessed 12 Jan 2023
18. Government (2020) On approval of the Action Plan for the implementation of the Concept for the transition of the Republic of Kazakhstan to a "green economy" for 2021 – 2030 (in Russian). Resolution № 479 of the Government of the Republic of Kazakhstan dated July 29, 2020. https://adilet.zan.kz/rus/docs/P2000000479. Accessed 12 January 2023
19. Morseletto P, Mooren CE, Munaretto S (2022) Circular economy of water: definition, strategies and challenges. Circ Econ Sustain 2:1463–1477. https://doi.org/10.1007/s43615-022-00165-x
20. KASE (2017) Kazakhstan stock exchange. Oil and gas industry of the Republic of Kazakhstan. http://kase.kz/files/presentations/ru/Oil_gas_november_2017.pdf. Accessed 11 Jan 2023
21. BP (2019) BP Statistical review of world energy. 68th edition. London. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf. Accessed 11 Jan 2023
22. Walker ME, Lv Z, Masanet E (2013) Industrial steam systems and the energy-water nexus. Environ Sci Technol 47:13060–13067. https://doi.org/10.1021/es403715z
23. Wangt RR, Zimmerman J (2016) Hybrid analysis of blue water consumption and water scarcity implications at the global, national, and basin levels in an increasingly globalized world. Environ Sci Technol 50:5143–5153. https://doi.org/10.1021/acs.est.6b00571
24. Zhang L, Li A-H, Liu Z-Y (2019) Design of property-based water-using networks with the operator potential concept and a linear programming approach. Chem Eng Trans 76:1363–1368. https://doi.org/10.3303/CET1976228
25. Jasni AB, Kamyab H, Chelliapan S, Arumugam N, Krishnan S, Din MFM (2020) Treatment of wastewater using response surface methodology: a brief review. Chem Eng Trans 78:535–540. https://doi.org/10.3303/CET2078090
26. EU (2003) Common implementation strategy for water framework directive (2000/60/EC). Guidance document no. 3: Analysis of Pressures and Impacts. Office for Official Publications of the European Communities. Luxembourg
27. Radelyuk I, Tussupova K, Zhapargazinova K, Yelubay M, Persson M (2019) Pitfalls of Wastewater treatment in oil refinery enterprises in Kazakhstan-a system approach. Sustainability 11(6):1618. https://doi.org/10.3390/su11061618
28. Sarma R, Singh SK (2021) Simulating contaminant transport in unsaturated and saturated groundwater zones. Water Environ Res 93:1496–1509. https://doi.org/10.1002/wer.1555
29. Radelyuk I, Naseri-Rad M, Hashemi H, Persson M, Berndtsson R, Yelubay M, Tussupova K (2021) Assessing data-scarce contaminated groundwater sites surrounding petrochemical industries. Environ Earth Sci 80:351. https://doi.org/10.1007/s12665-021-09653-z
30. Naseri-Rad M, Berndtsson R, McKnight US, Persson M, Persson KM (2021) INSIDE-T: a groundwater contamination transport model for sustainability assessment in remediation practice. Sustainability 13(14):7596. https://doi.org/10.3390/su13147596
31. Davis C (2021) Sustainable water use by industry: what can we do? In: Davis CK, Rosenblum E (eds) Sustainable industrial water use: perspectives, incentives, and tools. IWA Publishing, pp 181–198. https://doi.org/10.2166/9781789060676_0181

32. Nugumanova L, Yemelina N, Yugay S, Frey M (2017) Environmental problems and policies in Kazakhstan: air pollution, waste and water. IOS Working Papers 366. Leibniz-Institut für Ost- und Südosteuropaforschung (IOS), Regensburg
33. Nugumanova L, Frey M (2017) Environmental governance and policy in Kazakhstan. IOS Working Papers 365. Leibniz-Institut für Ost- und Südosteuropaforschung (IOS), Regensburg
34. Schmoll O, Howard G, Chilton J, Chorus I (2006) WHO. Protecting groundwater for health: managing the quality of drinking-water sources. IWA Publishing, London
35. Radelyuk I, Tussupova K, Zhapargazinova K (2020) Impact of oily wastewater for public health in rural area: a case study of Kazakhstan. In: Proceedings of the EGU General Assembly Conference Abstracts, p 11235. https://doi.org/10.5194/egusphere-egu2020-11235
36. Radelyuk I, Tussupova K, Persson M, Zhapargazinova K, Yelubay M (2020) Assessment of groundwater safety surrounding contaminated water storage sites using multivariate statistical analysis and Heckman selection model: a case study of Kazakhstan. Environ Geochem Hlth 43:1029–1050. https://doi.org/10.1007/s10653-020-00685-1
37. Locatelli L, Binning PJ, Sanchez-Vila X, Sondergaard GL, Rosenberg L, Bjerg PL (2019) A simple contaminant fate and transport modelling tool for management and risk assessment of groundwater pollution from contaminated sites. J Contam Hydrol 221:35–49. https://doi.org/10.1016/j.jconhyd.2018.11.002
38. Morris JC, Georgiou I, Guenther E, Caucci S (2021) Barriers in implementation of wastewater reuse: identifying the way forward in closing the loop. Circ Econ Sustain 1:413–433. https://doi.org/10.1007/s43615-021-00018-z
39. Comber MHI, Girling A, den Haan KH, Whale G (2015) Oil refinery experience with the assessment of refinery effluents and receiving waters using biologically based methods. Integr Environ Asses 11:653–665. https://doi.org/10.1002/ieam.1639
40. Ali H, Khan E, Ilahi I (2019) Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation. J Chem:6730305. https://doi.org/10.1155/2019/6730305
41. Stefanakis AI, Prigent S, Breuer R (2018) Integrated produced water management in a desert oilfield using wetland technology and innovative reuse practices. In: Stefanakis A (ed) Constructed wetlands for industrial wastewater treatment, John Wiley & Sons, pp 23–42. https://doi.org/10.1002/9781119268376.ch1
42. Groot C (2021) Triple water reuse at Dow. In: Davis CK, Rosenblum E (eds) Sustainable industrial water use: perspectives, incentives, and tools. IWA Publishing, pp 89–96. https://doi.org/10.2166/9781789060676_0089
43. Rosenblum E, Moore B (2021) Implementing sustainable water use: a roadmap for industry. In: Davis CK, Rosenblum E (eds) Sustainable industrial water use: perspectives, incentives, and tools. IWA Publishing, pp 363–378. https://doi.org/10.2166/9781789060676_0363
44. Zarei M (2020) Wastewater resources management for energy recovery from circular economy perspective. Water-Energy Nexus 3:170–185. https://doi.org/10.1016/j.wen.2020.11.001
45. Li Y, Xiong W, Zhang W, Wang C, Wang P (2016) Life cycle assessment of water supply alternatives in water-receiving areas of the South-to-North Water Diversion Project in China. Water Res 89:9–19. https://doi.org/10.1016/j.watres.2015.11.030
46. Reghizzi OC (2021) Reducing pollution from industrial wastewater in developing and emerging countries. In: Davis CK, Rosenblum E (eds) Sustainable industrial water use: perspectives, incentives, and tools. IWA Publishing, pp 215–224. https://doi.org/10.2166/9781789060676_0215
47. Caldwell EJ (2021) Designer water: one utility's unique approach to industrial sustainability. In: Davis CK, Rosenblum E (eds) Sustainable industrial water use: perspectives, incentives, and tools. IWA Publishing, pp 255–260. https://doi.org/10.2166/9781789060676_0255
48. Somoza-Tornos A, Rives-Jiménez M, Espuña A, Graells MA (2019) Circular economy approach to the design of a water network targeting the use of regenerated water. Computer Aided Chemical Engineering 47:119–124. https://doi.org/10.1016/B978-0-12-818597-1.50020-5
49. Maheshwari A, Prasad V, Gudi RD, Biswas P (2019) Systems engineering based advanced optimization for sustainable water management in refineries. J Clean Prod 224:661–676. https://doi.org/10.1016/j.jclepro.2019.03.164
50. Kazakhstan (2021) Ecological Code of the Republic of Kazakhstan (in Russian). https://adilet.zan.kz/rus/docs/K2100000400#z4470. Accessed 29 March 2023
51. Ministry of Ecology, Geology and Natural Resources (2021) On approval of the rules for maintaining an automated system for monitoring emissions into the environment during industrial environmental control (in Russian). https://www.gov.kz/memleket/entities/ecogeo/documents/details/188579?directionId=14691&lang=ru. Accessed 29 Mar 2023

52. Kazakhstan (2015) Enterpreneurial Code (in Russian). https://adilet.zan.kz/rus/docs/K1500000375. Accessed 29 Mar 2023
53. Klemeš JJ (2012) Industrial water recycle/reuse. Curr Opin Chem Eng 1:238–245. https://doi.org/10.1016/j.coche.2012.03.010
54. Wan Alwi SR, Manan ZA (2007) Targeting multiple water utilities using composite curves. Ind Eng Chem Res 46:5968–5976. https://doi.org/10.1021/ie061238k
55. Rivotti P, Karatayev M, Mourão ZS, Shah N, Clarke ML, Dennis Konadu D (2019) Impact of future energy policy on water resources in Kazakhstan. Energ Strat Rev 24:261–267. https://doi.org/10.1016/j.esr.2019.04.009
56. Bureau of National Statistics (2021) About water supply and water discharge infrastructure in the Pavlodar region (in Russian). https://stat.gov.kz/region/263009/statistical_information/industry/55157. Accessed 29 Mar 2023
57. Kazakhstan (2022) An extract №1 from a protocol №8 of the decision of the National Scientific Committee "Rational use of water resources, flora and fauna, ecology" (in Russian). https://www.ncste.kz/en/raczionalnoe-ispolzovanie-vodnyix-resursov,-zhivotnogo-i-rastitelnogo-mira,-ekologiya-2022. Accessed 11 Jan 2023