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Oil refinery and water pollution in the context of sustainable development: Developing and developed countries

Ivan Radelyuk [a, b, *], Kamshat Tussupova [a, c], Jiří Jaromír Klemeš [d], Kenneth M. Persson [a]

[a] Department of Water Resources Engineering, Lund University, Box 118, SE-22100, Lund, Sweden
[b] Department of Chemistry and Chemical Technology, Pavlodar State University, Pavlodar, 140000, Kazakhstan
[c] Kazakh National Agrarian University, Almaty, 050010, Kazakhstan
[d] 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

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ABSTRACT

This paper is an attempt to evaluate the impact of the oil refinery industry on water resources worldwide from the point of view of sustainable development (SD). The local laws, reports from the industry and environmental agencies, conditions of the final disposal system were analysed. Key aspects, such as existing approaches for treatment systems, quality of treated wastewater, and ways to assure the safety of them were compared. The comparison between industrialised (represented by the USA and EU) and developing countries (Kazakhstan used as an example) shows that several obstacles, such as loopholes in legislation, historical contamination, and miscommunicating between stakeholders, exist, despite the formal promotion of the SD concept. That policy should be implemented based on the relevant scientific investigation through the possibility of integrating the respective technological development, an adequate system of environmental impact assessment, and fair operational monitoring.

1. Introduction

Sustainable Development (SD) has become an ideology, which builds a modern world. The 2030 Agenda for Sustainable Development calls all people, from individuals to crucial stakeholders, businesspersons and international organisations, to take actions for solving the current challenges formulated in Sustainable Development Goals (SDGs) (UN 2015). One of the common definitions of Sustainable Development is “Enhancing quality of life and thus allowing people to live in a healthy environment and improve social, economic and environmental conditions for present and future generations” (Ortiz et al., 2009). From a certain point of view, “Sustainable” means “Responsible”. Any current suggestion, decision, or action on any level should be based on the concept, which supports not only immediate benefits but to ensure equal rights of all types of benefits, including well-being and a healthy environment, for future generations.

Relationships between SD and industry have been complicated. It can be clearly presented within related Sustainable Development Goals (SDGs). When one of the elements does not work, it affects the success of the other goals. An example is presented in Fig. 1. Any type of industry is related to several SDGs (Appendix A). SDGs 8, 9, 12 and 13 are directly connected with the industrial processes. The processes should be innovative to achieve rational and efficient resource use (SDGs 8, 9, 12) and eliminate impact on the environment through sufficient treatment systems, which lead to the deceleration of climate change (SDG 13). The SDG 6 “Clean Water and Sanitation” requires: (i) to eliminate potential hazards of

* Corresponding author. Department of Water Resources Engineering, Lund University, Box 118, SE-22100, Lund, Sweden.
E-mail address: ivan.radelyuk@tvrl.lth.se (I. Radelyuk).

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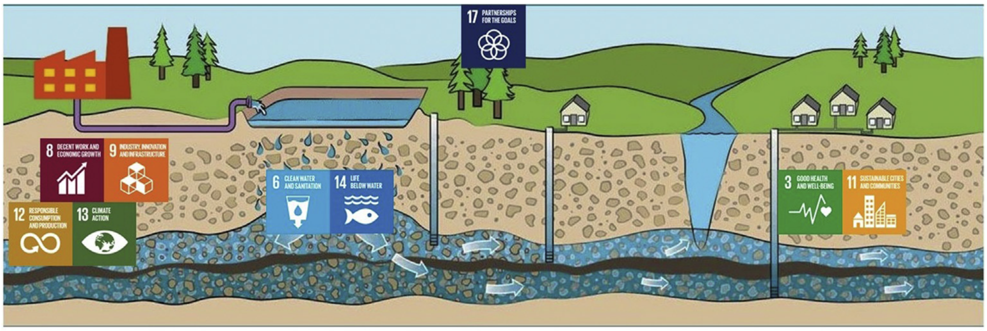

Fig. 1. SDGs related to the industry (Source: the authors).

disposal of effluents; (ii) to adopt water-saving techniques to reduce the consumption of fresh water to address water scarcity (Jia et al., 2020); and, (iii) protect water-related ecosystems, including rivers, lakes and aquifers. The SDG 14 "Life below Water" specifically focuses on the consequences of any kind of pollution for the aquatic world. Environment (water, soil and air) impacts the health of people, which belongs to SDGs 3 and 11. If the industry neglects principles of responsibility during the production process, it might lead to the crash of the "sustainability" system: deteriorated ecosystems and unhealthy people, locally or globally. The Agenda considers the involvement of all countries and their cooperation (SDG 17). UN has encouraged parliaments and lawmakers to implement SDGs as national ideas via suitable lawmaking, scientific and innovative technological approach, and suitable control (UNDP 2016).

The concept of "Sustainable water use" (SWU) brings several SDGs related to the water together. The SWU aims to assure three pillars of sustainability: social, environmental, and economical. Sustainable water use in the industrial context covers several factors of three dimensions of SD and their interactions, as shown in Fig. 2. Economic factors are represented by the processes inside the industry. The industry uses technologies to treat supplied and processed water and to utilise it in a safe manner. These technologies are associated with respective cost (Baleta et al., 2019). Environmental factors consider water quality in water sources and wastewater recipients. Interactions between economic and environmental factors are characterised by attempts to decrease the impact of industrial activities on water bodies and make water viable for following consumers by the usage of efficient technologies. Social factors are represented by ensuring public safety (e.g., health) and mainly regulated by the government. The governmental and civic authorities should ensure the availability of safe water by appropriate legislative and environmental tools (Hjorth and Madani 2014). Economic and social factors should be met by establishing the idea of equal rights for different water users. Appropriate legislation ensures the responsibility of the industry to apply related efficient and water-saving technologies.

Implementation of the SWU is important for two reasons. First, water consumption by industry ranges between 10% and 57% of total water consumption in different countries (Voulvoulis 2018). Second, industrial activities are recognised as one of the major sources of water pollution worldwide and can be quantified by environmental footprints (Čuček et al., 2012). The developing countries face challenges towards the implementation of the SWU. This type of countries is characterised by applying efforts to diversify the economy from just exporting resources to build

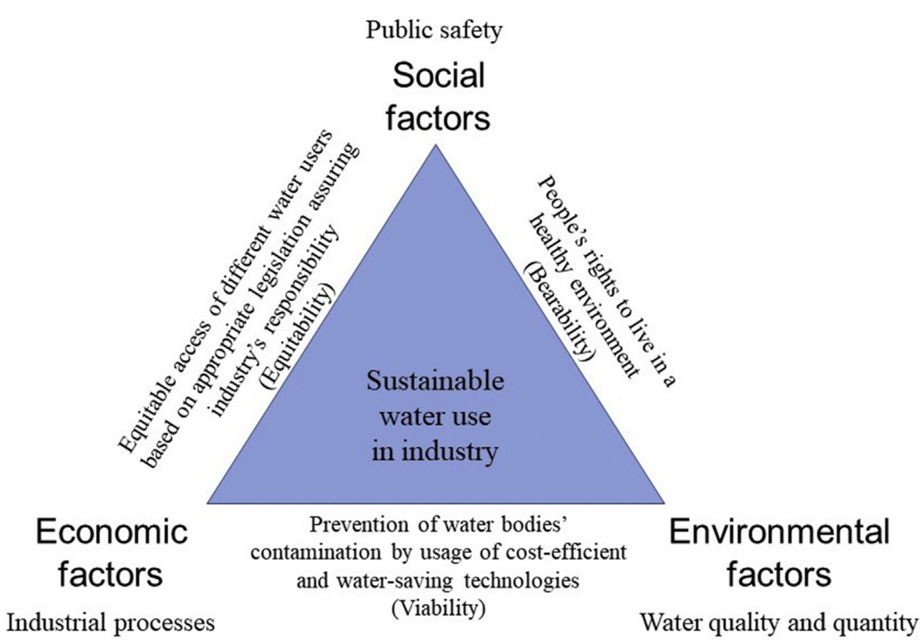

Fig. 2. The framework of Sustainable water use in industry (Source: the authors).

advanced technological infrastructure. This process includes accelerated industrialisation and growth of already existed manufacturing capacity, which increase the pressure on water resources in both an increase in water consumption and the needs for a decrease in water pollution (Naseri-Rad et al., 2020).

This research aims to compare strategies and efficiency of the implementation of the SWU system in industry between developed (represented by the EU and the USA) and developing (Kazakhstan used as an example) countries. Specific type of industry – the oil refinery sector was chosen as a case study. According to the BP Statistical Review, the USA and EU hold the maximal capacity of oil refining units worldwide (BP, 2019). The western world has a reputation as drivers and promoters of sustainable development. SDG 8.4 clearly states that the developed countries are aimed to lead and transfer their experience in "global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation". According to a UN "World Economic Situation and Prospects 2019" book, Kazakhstan has been rated as a fuel-exporting country with transitional from developing to the developed economy (UN 2019). According to the Environmental Performance Review for Kazakhstan (UNECE 2019), the oil refinery cluster in Kazakhstan is one of the biggest sources of water contamination. Thus, the authors are interested in looking at how refinery companies deal with Sustainable Water Use. This paper discusses the engagement of all key stakeholders, such as government, industry, and academy, into a dialogue towards SD.

While the previous publication aimed to investigate the experience of the legislation of different countries and applied wastewater treatment techniques (Radelyuk et al., 2019); this paper mostly focuses on the interrelations and synergies between the oil refinery industry and water pollution with the focus on the problems of potential fate on affected water bodies in the context of SD.

2. Methodology

The DPSIR (Drivers-Pressures-State-Impact-Response) framework has been proposed by a Guidance document from the EU to analyse the existing pressures and their impacts on water resources (EU 2002). Accordingly, this study implements the DPSIR concept, as is shown in Fig. 3. Principles of the SWU have become the drivers to meet socio-environmental awareness and to decrease the *pressure* on water resources. The hypothesis is that *pressure* is caused by improper wastewater treatment. The resulting *state* or indicator of the *pressure* (which is usually measurable, according to the DPSIR approach) can show high concentrations of the contaminants in the wastewater, and consequently, in the recipient. The *impact* may differ, including deteriorated or destroyed ecosystems, unsafe drinking water, or the waste of water in the regions where water scarcity exists. The measures are taken to improve the *state*, and the *response* has to address the identified pressures.

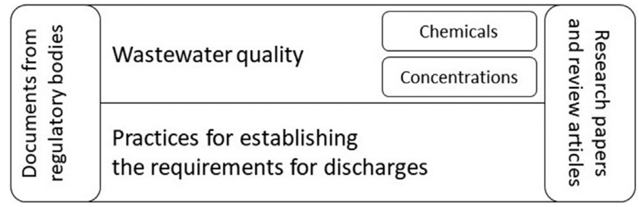

Fig. 4. Searching methodology: a conceptual framework (Source: the authors).

The structure of the performed assessment is presented in Fig. 4. The authors aimed to analyse available "first-hand" information about the *state* and the *impact* of governmental bodies. This information included legislative documents, such as laws, orders, reports, and standards; documents and reports from responsible authorities, such as Environmental Protection Agencies and oil refinery operators, and statistical datasets. The limitations for consideration of the *state and impact* information as relevant were 1) existing effluents conditions, including a description of the contaminants and their concentrations, and 2) description of characteristics of wastewater recipients. Also, the authors aimed to identify the pros and cons of the applied *response* for the establishing of current criteria. An extended literature review was carried out, despite the analysis of official information. The authors also attempted to overview the relevant experience of the SWU implementation (as *drivers*) in relevant scientific publications. The above criteria were used for consideration of the relevance of the reviewed literature. Highly cited papers in peer-reviewed journals were examined with the following "snowball sampling" review using the Scopus database. A combination of keywords (refinery AND (effluents OR wastewater OR waste AND water)) resulted in 1148 publications. 36 publications were chosen as sound examples of the respective research-supported solutions for decision-makers toward the SWU in the oil refinery sector. Consideration did not include the publications about treatment methods, as the previous publication from the authors already investigated the issue.

This paper consists of the Results, Discussion, and Conclusions sections. The Results section consists of three sub-sections, where

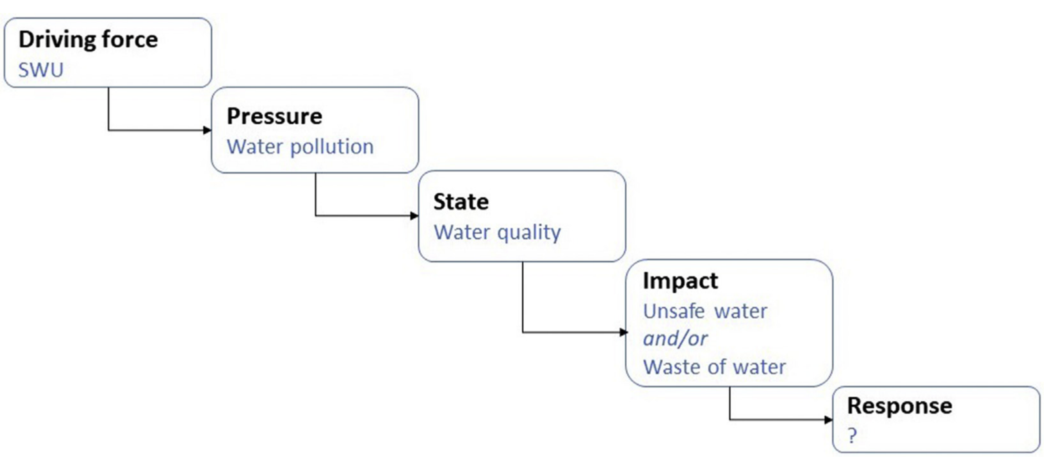

Fig. 3. The DPSIR framework for this study (Source: the authors).

the findings for the USA, the EU, and Kazakhstan are presented. The structure of the sub-section is as following:

(i) Description of historical background in legislative standards and oil refinery industry.
(ii) Description of current industry conditions with particular attention on wastewater treatment units.
(iii) Description of wastewater characteristics.
(iv) Description of wastewater recipients and potential consequences for the environment.

3. Resulting observations

The authors identified strategies from three selected regions, which have a goal to achieve a sustainable and safe environment via establishing the criteria for maximum allowable concentrations of contaminants in wastewater. The USA applies the National Pollutant Discharge Elimination System (NPDES), the EU uses the system of Whole Effluent Assessment (WEA), and Kazakhstan uses the Environmental Impact Assessment (EIA). The authors firstly investigated those approaches in each region – which actions are considered under the decision-making systems; and secondly, discussed their strengths and weaknesses (Fig. 5).

3.1. The USA observation

The history of regulatory relationships between the USA Environmental Protection Agency (EPA) and oil refinery effluents systems started in 1974 with the promulgation of effluent limitations guidelines and standards (ELGs). This document was applied to establish pretreatment standards for existing and new sources of pollution with the permissible concentrations of few pollutants, such as ammonia, oil and grease, biochemical oxygen demand (BOD), phenolic compounds, sulfides and chromium in the effluents (USEPA 1974). The guidelines had been constantly revised, with the final document accepted in 1985. This resulted in more strict criteria for treatment standards and application of innovative Best Available Technologies Economically Achievable (BAT) (USEPA 1985). The permanent monitoring of available enhancements in technological and scientific progress enabled to enhance the efficiency of the law through the following amendments.

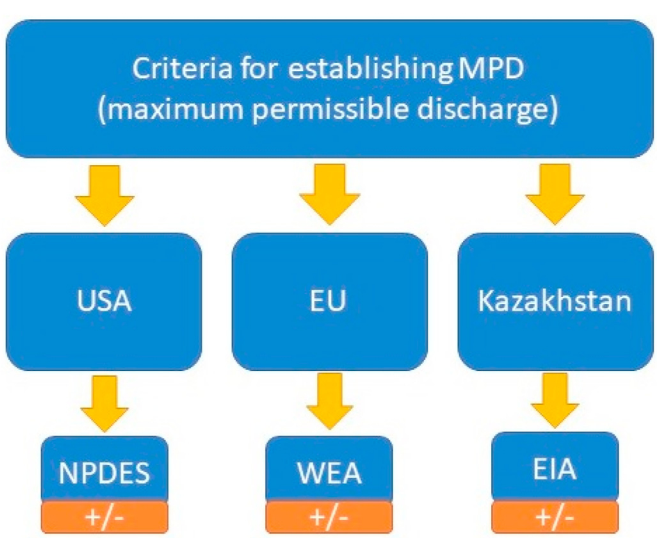

Fig. 5. Conceptual framework of performed observations (Source: the authors).

Implementation of BAT became one of the leading factors, which makes this guideline efficient to protect the environment towards the elimination of the discharge of all pollutants (in the USA) (U.S.Code). The principle of BAT is to find the most efficient and cheapest way to meet the requirements for local ecosphere safety by reduction or elimination of pollution. The idea of implementation of BAT is to invest in the prevention of contamination instead of pollution and consequent remediation actions.

One more of the special characteristics of the guidelines is using “in-plant” and “end-of-pipe” technologies. “In-plant” system controls the amount of pollutants in processing water after each technological unit through preliminary treatment methods, such as separation of stormwater and processed water; sour water strippers; or through re-using water, e.g. for using lightly contaminated water in water cooling towers. This approach reduces the burden on the final (or “end-of-pipe”) treatment system and enhances the efficiency of it. “End-of-pipe” technology assumes deep wastewater treatment and aims to eliminate or significantly reduce the concentration of pollutants in final effluents. Advanced treatment techniques for the oil refinery industry were described in detail in the previous publication from the authors (Radelyuk et al., 2019). They can include, e.g.:

(i) Combination of different pretreatment units (electrocoagulation-flocculation, dissolved air flotation (DAF), oil traps, etc.)
(ii) Enhanced common secondary treatment methods (e.g. activated sludge coupled with oxidation ponds, trickling filters, moving bed biofilm reactors (MBBR), etc.).
(iii) Polishing approached (wetlands, advanced oxidation processes, membrane technologies).

Under the regulation of principles of BAT and “end-of-pipe” and “in-plant” technologies, the EPA establishes production-based mass limitations for the pollutants included in the ELG. The main source of pollution is the desalination unit of the refinery, coupled with the atmospheric distillation unit. Crude oil contains a high level of sulfur, salts and metals. The desalination unit removes a major amount of salts by emulsifiers and generates 3–10 vol% on a crude charge into wastewater flow (Alva-Argaez et al., 2007). A significant amount of sulfides, ammonia, phenols, oil, chlorides and mercaptans comes after the distillation process. These chemicals are included in the list of priority pollutants for the refinery industry with the main focus on crude oil, or it is called “petroleum hydrocarbons”. While thousands of hydrocarbons exist, only very a few of them are investigated in detail (WHO 2008). Hydrocarbons are assumed as toxic substances, while the hazard level ranges between different groups of them. There is no unified way for associated terminology of the hydrocarbons related to industrial wastewater discharges yet. Depending on the focus contaminants, phase conditions, type of analysis, etc., the petroleum hydrocarbons in different regions are called TPH (total petroleum hydrocarbons), Oil in Water (OiW), or Oil and Grease.

The EPA regularly conducts a study of wastewater discharges from petroleum refineries to assess the situation in the sector. The evaluation includes 1) study visits, 2)questionnaire of the petroleum refineries to request information about their water use processes, crude processed, production rates, unit operations, wastewater characteristics, pollution prevention, and wastewater management, treatment, and discharge, and 3) data extraction from the national systems of Discharge Monitoring Report (DMR) and Toxics Release Inventory (TRI).

Recent reviews of 2011 and 2014 concluded that the regulations should be changed due to new information, such as reported discharges of toxic compounds, such as dioxin and dioxin-like compounds, polycyclic aromatic compounds (PACs) and increase of refineries reporting metals discharges, instead of only chromium included in the current guideline (USEPA 2019).

The system of establishing the requirements for each case of pollution, titled National Pollutant Discharge Elimination System (NPDES), includes several investigations (USEPA 2010). Firstly, limitations are based on the capabilities of the technologies available to control those discharges. Industrial processes and raw materials, facility size, geographical location, and age of facility and equipment are considered. Secondly, water quality-based effluent limitations are calculated. The conditions of the water body, which receives the discharges, are assessed for background contamination. Parameter-Specific Approach, Whole Effluent Toxicity (WET) Approach, and Bioassessment Approach are used in this step. Parameter-specific involves a site-specific assessment of the proposed discharge and its potential effect on the receiving water. The WET test is used to establish the frameworks of permits. This test measures the exposure of the contamination to the conditions of living of the selected organisms, which serve as “indicators” of their ability to live with the level of the contamination. The criteria approach is used to assess the overall biological integrity of an aquatic community. The idea is to finally establish the level to the extent when nature can utilise the hazard in its own functions.

The authors used the latest study report (USEPA 2019) as a basement for the following investigation. This report has presented information about 143 refineries in the USA. The authors focused on the category of refineries, which discharge their effluents directly into the environment to evaluate the consequent potential effect.

Table 1 shows that only 20 of 143 refineries send their pretreated effluents into the municipal wastewater collection systems. Twelve refineries are defined as unknown and excluded from consideration. Two refineries (Evanston Refinery and Sinclair Refinery) are defined with the “Zero Discharge” status. It means they achieved the possibility of near-zero liquid discharge through the full water reuse (Koppol et al., 2004), which seems to be an ideal case for the elimination of risks.

90 refineries with direct discharges, coupled with nine refineries with both types of discharges, are subjects of investigation for this study (Table 2). Wastewater treatment of more than half of refineries is characterised by “Biological treatment”. It means that they commonly use primary and secondary oil/water separation units, coupled with one of the types of biological treatment techniques. The type of biological treatment varies widely, from the basic activated sludge to advanced, such as MBBR, membrane bioreactor (MBR), ADVENT integral biological system, etc. Refineries, categorised as “Current BAT technologies” (23 of 99), use an extra unit after a step of biological treatment to achieve the final requirements of the NPDES. Generally (16 of 23), it is a filtration implementation whenever the other refineries use settling ponds, extra aeration, and chemical oxidation. Five refineries use the most advanced wastewater treatment techniques and implemented more than one extra unit for polishing. Ion exchange, selenium reduction plant, and Filtration and Polishing identify those technologies as “Beyond BAT technologies”.

Table 1
US refineries by discharge status (USEPA 2019).

Discharge Status	Number of Refineries
Direct	90
Indirect	30
Direct & Indirect	9
Zero Discharge	2
Unknown	12
Total	**143**

Table 2
Categorisation by treatment methodology (USEPA 2019).

Categorisation by treatment approaches	Number of refineries
Biological treatment	56
Current BAT technologies	23
Beyond BAT technologies	5
Treatment other than Biological Treatment	7
No data/No information available	8
Total	**99**

The EPA identified 26 primary pollutants for monitoring in the refinery effluents. The reasons for the inclusion of the chosen substances were their presence in the untreated refining process wastewater and their rate of toxicity. Appendix B presents annual mean concentrations and estimated loadings of contaminants included in the list of pollutants. The EPA has tried to estimate the amount of the pollutants of interest in the discharges as average concentrations and their annual loading. The criteria for inclusion was the refineries, which directly discharge the treated wastewater into the surface water. That estimation has a limitation of data availability. For example, only three refineries provided data about BTEX (benzene, toluene, ethylbenzene, xylene) in their wastewater, or there is no reported data for polycyclic aromatic hydrocarbons (PAHs).

While the reported amounts of pollutants seem to be a significant contribution to water pollution, the averaged and simplified estimation does not show a detailed picture. The authors investigated the characteristics of the refineries wastewater at Top-20 refineries by their operating capacity, which practice direct discharges. Appendix C represents the searching methodology used by the authors. The authors used available DMR and TRI data from the online Water Pollutant Loading Tool. The data of monitoring for the year 2019 were used to assess the available data for the whole year in detail.

Appendix D contains the results of the investigation. All refineries are categorised under the control of effluent limits. 5 of 20 refineries use “Current BAT Technologies” for wastewater treatment, 12 of 20 use “Biological Treatment” techniques, and 3 of them use “other than Biological Treatment techniques”. All refineries discharge their effluents into the surface water, which are categorised with having flow, such as channels, bayou, rivers. 19 of 20 recipients contain the Endangered Species Act (ESA)-listed aquatic species – organisms, which live in the water and are characterised under the protection as vanishing. Half of those water bodies are used for different purposes, such as recreational use (9 of 20) and aquatic life use (11 of 20). 12 of 20 of those water bodies are listed for impairments by the EPA according to the Clean Water Act (USEPA 2015). It means that water quality has been already deteriorated by natural or anthropogenic factors. If the water body is already polluted, non-strict requirements can be applied for the belonged sources of the pollution. The substances, which cause the reason for impairment, include mostly organic matters, e.g. polychlorinated biphenyls (PCBs), pesticides, dioxins; the “total toxics”, including mercury; pathogens; nutrients; and oil and grease. These substances occur in water through anthropogenic invasion.

The next step was to look at the concentrations of substances, using the Pollutant Loading and Effluent Charts tools of DMR. These tools present data, which have been collected from regular monitoring. Appendix E shows the extracted data from the Pollutant Loading Report of USEPA about monitoring status for the Top-20 Refineries in 2019. There is a twofold opportunity to look at the existing data. Firstly, the report is formed for the whole year. According to the NPDES, the refineries get a license to discharge a certain amount of pollutants based on their designed flow. No one refinery have shown exceeding the permissible loading into the aquatic system per year. Secondly, the monitoring system works constantly, and if the violation is identified, the system indicates it. In this case, it is interesting to note that Garyville Refinery, BP Whiting Refinery, Corpus Christi East Refinery and Wood River Refinery perform the monitoring for not only the pollutants of interest but they have extended the list of contaminants significantly. The updated list includes, for example, derivatives of phenolic compounds, toxic metals, per- and polyfluoroalkyl substances, etc. Those substances match with the substances, which caused impairments for local water bodies. Simultaneously, those refineries provide advanced wastewater treatment systems, including the usage of BAT Technologies. The exceedance of permissible limits, at least once per year, have been identified in 5 of 20 refineries. The amount of total suspended solids (2 refineries), oil and grease (2 refineries), sulphide (2 refineries), total organic carbon (2 refineries), BOD and ammonia has been exceeded (Appendix F). For example, The Philadelphia Refinery discharged 0.12 t sulphides more than has been planned in October 2019. The Deer Park Refinery loaded 0.95 and 4.69 t of oil and grease and total organic carbon, more than has been planned in October and November 2019. The Valero - Corpus Christi East Refinery sent 1.9 t more ammonia into the drainage ditch in November 2019.

3.2. The EU observation

The EU also aimed to solve the potential problems with the gaps in legislation. The shifting to the control of hazardous pollutants started in the 1970s, with the first implementation of the BAT in the 1990s (CONCAWE, 2012). The recent understanding of the fact that water resources have limited capacity, despite a general improvement of water quality, has driven the European Commission to revise constantly the crucial law documents, such as Directives (e.g. the Urban Waste Water Treatment Directive, the Drinking Water Directive, the Water Framework Directive (WFD)), seriously (Werner and Collins 2012). The milestone in the European environmental legislation: The Water Framework Directive, aimed to achieve "good status for surface and groundwater", which means to avoid the deterioration of the quality and quantity of water bodies and related ecosystems (EU 2000). While the implementation of the Directive has safeguarded the water resources, there are still opportunities to improve the system by dealing with existent gaps and disadvantages of the current version of the legislation (Tsani et al., 2020). Those opportunities include, for example, improvement of the monitoring systems, more complex assessment of the status of water bodies, support of solution-oriented management, etc. (Brack et al., 2017).

The EU also promotes a preventive approach for industrial emissions to reduce and eliminate any pollution. Directive on industrial emission (EU 2010) requires the following key steps for implementation to achieve the goal: (i) the integrated approach states avoiding the transfer of pollutants from one environmental medium to another; (ii) the responsibility should be assigned to any operator who generates emissions; (iii) holding permission for the emissions means that the set of best available technologies (BAT) appropriate techniques must be applied to protect the environment. This approach ensures that the quality of the emissions is not allowed to elevate critical concentrations, dangerous for the people and the environment.

The petrochemical industry in Europe is the main water-using industry within the manufacturing sector (Willet et al., 2019). Environmental issues caused by the oil refinery sector in Europe are managed by Concawe (an abbreviation of "CONservation of Clean Air and Water in Europe") – the organisation, which combines most oil companies operating in Europe. Their mission is to act in line with the concerns over environmental issues through the conductance of research programs to support cost-effective and safe decisions for the sector. Instead of the focus on the allowable concentrations of separated chemicals, the EU practices Whole Effluent Assessment (WEA) to test the response of local ecosystems to the mix of the discharged contaminants coupled with the operational monitoring of the status of the water bodies (CONCAWE 2012). The WEA approach is a tool, which aims to support the WFD in achieving the global aim of "good ecological status" for all European waters; and also to support in identification of BAT for the refinery industry under the Integrated Pollution Prevention & Control Directive (IPPC) for controlling pollution. The strategy of the assessment is based on the historical background, where the characteristics of receiving waters and effluents are already known for decades. Particular attention is paid to WET tests with the focus on the persistence, bioaccumulation or toxicity (PBT) properties of effluents or effluent constituents. The tests are carried out on living species, such as microorganisms, invertebrates and fish, to assess acute and chronic toxicity (CONCAWE 2004a). However, only 28 of 64 refineries reported their use of WEA with the most common method of short-term toxicity assessment, instead of the assessment of persistence and bioaccumulation (CONCAWE 2012). The Concawe perform both types of assessment of the influence of refinery effluents: they regularly carry out the surveys of effluent quality and water use at the refineries and, simultaneously, they analyse the application of the WEA by the refineries and produce their recommendations based on the results of the investigations.

The most recent report from the Concawe has been dated June 2020 (CONCAWE 2020a). 98 refineries have been called to share their statistics about water use issues, including the information of water consumption, discharge and related water quality data. 72 refineries provided the whole report, and results have been compared with the previous reports. The main appropriate outcomes from the report for this study are an assessment of the effluent discharge volume and the refinery effluent quality, coupled with the related trends. Most refineries clean their wastewater by themselves, and only a few of them (8.8%) send the wastewater to centralised urban treatment systems. More than half of the wastewater volume (51%) has been exposed to a three-stage wastewater treatment plant. 17% of wastewater has been treated by limited treatment techniques, such as physical and/or chemical only. That type of wastewater mostly belongs to lightly contaminated (e.g. rainwater water runoff).

The content of pollutants in the effluents from refineries in Europe shows a stable decrease since the 1970s (CONCAWE 2004b). The studies showed that there was significant damage to aquatic ecosystems by toxic substances, such as ammonia, sulfides, phenols and PAHs (Wake 2005). After the implementation of strict requirements and the stop of disposal of polluted effluents, there was hope for recovery.

Throughout the control of wastewater quality, the main focus is on hydrocarbons and related derivatives. Appendix G shows a summary of the reported values of the monitored contaminants. A detailed explanation of how much TPH/OiW, BTEX, phenols and PAHs have been discharged annually in different variations is presented. The amount of total TPH in effluents decreased from 44,000 t/y to 257 t/y during the period between 1969 and 2016. The reported mean annual concentration of TPH varied between 0.5 mg/L and 16 mg/L among the refineries, with an average concentration of 1.4 mg/L for all refineries. The same trend sounded for the phenol index with the descend from 179 t/y (0.41 g/t throughput in relative discharge) in the year 1993 to 29.6 t/y (0.058 g/t throughput in relative discharge) in 2016. However, there

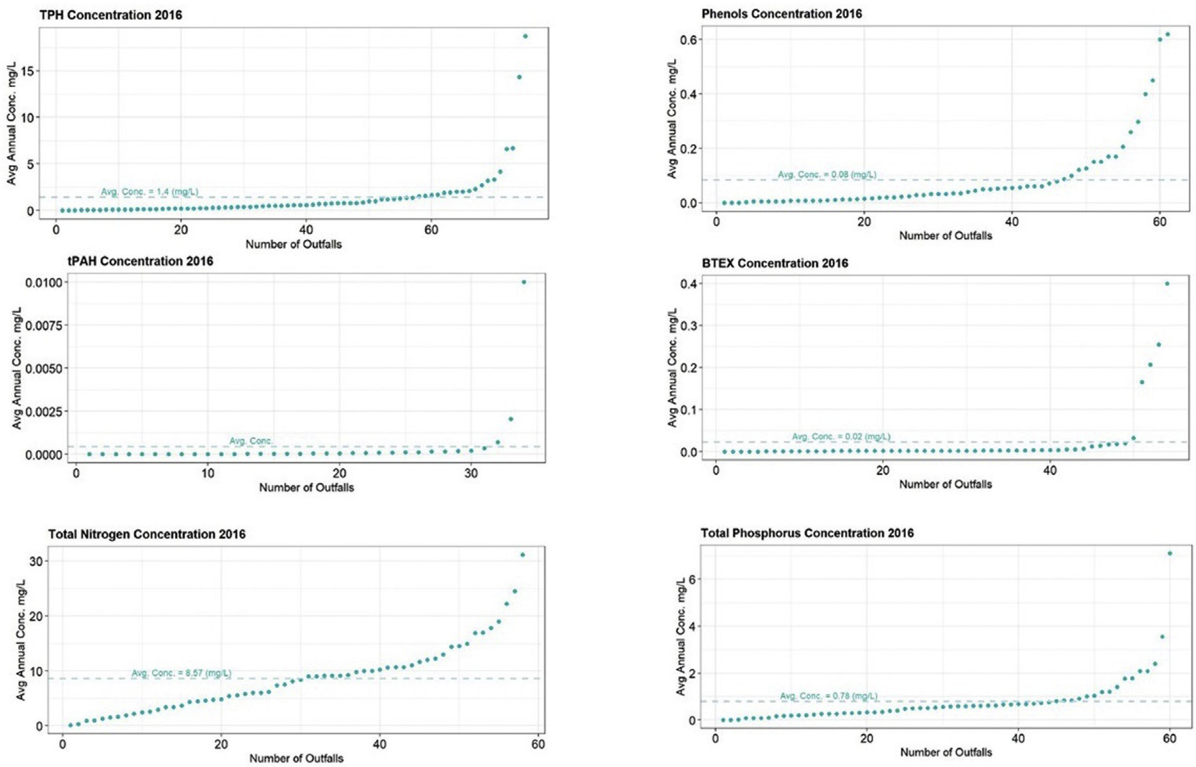

Fig. 6. The amount of key pollutants in the discharges from the refineries in the EU (CONCAWE 2020a).

is a light increase comparatively with 2013. Also, the average annual concentration of phenols ranged between 0 and 0.62 mg/L among different enterprises, with an average concentration of 0.08 mg/L (Fig. 6). The analysis of the presence of PAHs and BTEX in wastewater has been started relatively recently, and the data only for 2010–2016 have been presented in the report. The effect of loading of these chemicals is unclear because the cumulative sum has shown safe concentrations, while the concentrations of the separated hydrocarbons, such as anthracene and fluoranthene, exceeded the recommended values (CONCAWE 2018). The concentrations are relatively the same for the reports 2013 and 2016. The content of total nitrogen and phosphorus, as the potential sources of hazard for living microorganisms, has shown reasonable values. Fig. 6 shows the variations of concentrations of mentioned chemicals in the discharges at EU refineries. Most of the reported sites (around 70%) show the values below mean concentrations, while around 5–10% significantly higher than average.

3.3. *Kazakhstan observation*

The water sector in Kazakhstan faces severe problems. Climate change would affect the quality of water resources, coupled with the decline of their quantity (Salnikov et al., 2015). According to Karatayev et al. (2017), poor water infrastructure and water pollution are the main current weakness and challenges, while water-saving potential in Kazakhstan is ranked as one of the major opportunities in the water sector. Even when it seems that the representatives of the government are satisfied by the water legislation, the nongovernmental organisations, together with academia, define the problems in the water management sector. For example, the limited access to existing data for researchers, despite the ratified Aarhus Convention.

Multiple barriers, such as the perception of the industry of pricing and technological changes, exist in the oil refinery sector in Kazakhstan. Currently, the price of water is very low for the industry, as well as the penalties for the violation of the current version of the law. Kazakhstan deals with the implementation of suitable legislation. The government of Kazakhstan applies efforts to improve the situation through policy strengthening. A new ecological code has been announced for adoption. The law claims the implementation of BAT, increased penalties and investment of industry for environment protection (PrimeMinister 2019). The implementation of the law aims the transition to sustainable development and a “green economy”, with a focus not only on resource efficiency and waste prevention but on human well-being and ecosystem resilience as well (EEA 2015).

JSC NC “KazMunayGas” (KMG) is the national company in Kazakhstan, which operates all three refineries on the territory of Kazakhstan. The recent sustainability report claims to achieve and lead the initiatives of sustainable development, including the goals related to water-saving and efficiency (JSCNC“KazMunayGas”, 2020). The company confirms its commitment to efforts to deal with the efficient use of water and taking responsibility to reduce and minimise environmental impact. The report has listed the following issues as a top priority: liquidation of historical contamination, reduction in pollutant emissions and an increase in volume or recycled and reused water.

The procedure of giving permission for emissions into the environment in Kazakhstan is regulated by the procedure of Environmental Impact Assessment (EIA). This assessment considers the type of industry, the conditions of the effluents and recipients. The maximum permissible discharges (MPDs) are calculated based on the above characteristics under the methodology from an Order of Ministry of Environmental Protection of the Republic of Kazakhstan (2012). The MPDs are calculated for any recipient separately by the following formula:

$$C_{MPD} = C_0 + (C_{TLV} - C_0) \times k \quad (1)$$

Where C_{MPD} is a calculated and established concentrations of the pollutants in wastewater; C_0 is a background concentration of the pollutant in the recipient; C_{TLV} is a threshold limit value, which is established by law about sanitary and epidemiological requirements for water sources; and k is a coefficient, which characterises total assimilating, evaporating, filtering capacity of the recipient. Therefore, if the wastewater recipient is a closed type water body, which is not used for any purposes, such as a source of drinking, irrigation, recreation, or domestic water; the MPDs are equal to the actual discharge of pollutants after treatment facilities, or

$$C_{MPD} = C_0 \quad (2)$$

The historical background of water use in the oil refinery industry and related issues was described by Radelyuk et al. (2019). The loopholes in legislation let the refineries use already polluted storage sites as the recipients of effluents. The reason why the storage sites have been polluted is that refinery, and other industries sent their improperly treated or untreated wastewater into the recipients during the soviet and post-soviet era. The concentrations of the pollutants in discharges have been established based on the background concentrations of the chemicals in the recipients (Table 3). Not strict requirements have been applied for the quality of the effluent. Even those insufficient requirements have been violated by the industry, which has been discovered when unexpected commissions take place (KapitalKZ 2019). While the formal criteria are followed by the enterprises, the hazard for the environment and health of people still exists. A recent study (Radelyuk et al., 2020) shows that there is a direct impact on groundwater surrounding one of the recipients (Appendix H), where the average exceedance for total petroleum hydrocarbons was four times on the distance 1 km from the source of contamination. The direct discharge without any treatment for the first three years of the refinery work caused the source of contamination in the soviet period. The study shows that natural processes, coupled with anthropogenic deteriorate groundwater quality. The recipient pond is considered as the receiver for a higher amount of wastewater in future due to industrialisation of the region, whereas the quality of them cannot be assured safe. The recent investigations by the authors showed that a distance of contamination plume of petroleum hydrocarbons could spread out on a distance of 2–6 km depending on the initial concentrations until the concentration reaches the safe limit. It could affect the water quality using for irrigation (Radelyuk et al., 2021). Due to the drawbacks of the Kazakhstani management system, such as lack of data, lack of transparency, poor engagement of stakeholders into the collaborative work with academia, etc., there is still difficult to evaluate real conditions of the potential hazards. KMG plans to maintain the renovated equipment with advanced treatment techniques coupled with the program of recultivation of the recipient of Atyrau Refinery. However, the whole process would take place until 2023. The situation with the PKOP refinery, which is a part of the KMG group, seems better, as they use the long buffer channel with waterproofing bottom to send their effluents, firstly, to the evaporation pond, and after that to the local water body.

4. Discussion

This section analyses the results by, firstly, comparison between policies in different countries; secondly, comparison of differences in treatment and discharge techniques; and, thirdly, comparison of ways and progress towards the SWU in the sector, weaknesses and strengths on the local level, and possible ways to overcome obstacles towards the SWU. Table 4 summarises the results of the performed observations coupled with sound examples from a literature review.

This study identified that effective policy is an efficient *response* to achieve sustainable water use in the oil refinery sector in Kazakhstan. The best option to assure safe water is efficient water and wastewater management of water users, instead of post-factum attempts to clean already polluted sources (Fawell 2015). The effective management of industrial water use includes appropriate technology standards coupled with sufficient operational monitoring, which aims to prevent contamination. Thus, the *response* includes implementation of 1) the concept of circular economy (CE) (via 1a) water reuse and 1b) Best Available Techniques (BAT)); 2) Improved methodology for Environmental Impact Assessment (EIA), aiming to toughen the requirements for wastewater quality and characteristics of their recipients; and 3) Improved system of environmental monitoring.

4.1. Circular economy

Circular economy (CE) is a concept, which has relatively begun to be promoted in the western world and widely but slowly spreading through the other nations (Schroeder et al., 2019). The core of the concept is the transition from "linear model" of "linear economy" ("take-make-consume and dispose of") when the resources are transformed into the final product, which is consumed and subsequently wasted; to circular form, or even 10 Rs - "reduction and reuse, recycling and composting, and energy recovery" approach (Fan et al., 2020) when the waste, generated during the manufacturing process, are subject to 10Rs, and all

Table 3
Maximally permitted concentrations of different parameters in the effluents of three Kazakhstan oil refineries (Radelyuk et al., 2019).

Parameter	Units	Refinery X	Refinery Y	Refinery Z
Ammonia (NH_4^+)	mg/L	55.18	8.0	4.53
Total petroleum hydrocarbons (TPH)	mg/L	3.02	8.0	2.03
Biochemical consumption of Oxygen (BOD)	mgO_2/L	17.82	16.6	11.6
Nitrates (NO_3^-)	mg/L	19.2	7.8	8.96
Nitrites (NO_2^-)	mg/L	7.7	0.5	–
Sulphates (SO_4^{2-})	mg/L	643.05	500.0	471.1
Phenol's index	mg/L	0.25	0.05	0.182
Chlorides (Cl^-)	mg/L	169.8	350.0	678.8
Suspended solids	mg/L	20.98	25.75	6.05
Surfactants	mg/L	0.52	2.80	1.27
Phosphates (PO_4^{3-})	mg/L	1.05	2.0	6.89
Total Dissolved Solids (TDS)	mg/L	–	6000	–

"-"- not controlled.

Table 4
Main outcomes from the performed observations with sound examples from an extended literature review.

Principle	USA	EU	Kazakhstan	Determining publications	Application of the principle	Improvement of the principle and usage as a tool for transition to the SWU
Circular Economy	•“In plant” and “End-of-pipe” approaches	•Priority of the strategies and promotion on the federal level	•Formal promotion and willingness to improve the situation (PrimeMinister 2019; JSCNC“KazMunayGas”, 2020)	*Water rationalization*: Description (Wang and Smith 1994);	Application of Water Source Diagram (WSD) method (de Souza et al., 2009);	Constant water auditing to improve water conservation (Barrington et al., 2013);
	•BAT (USEPA 2015)	•BAT (EU 2014, 2020)		Review of conceptual and mathematical models (Bagajewicz 2000);	Proposed synthesis of water allocation and mass exchange network (Karthick et al., 2010);	Aiming zero liquid discharge and respective improvements of existing opyimization techniques (Maheshwari et al., 2019);
				Focus on multicomponent content of wastewater reused (Savelski and Bagajewicz 2003)	Proposal for use in Iranian refineries, considering different conditions of reused wastewater (Mohammadnejad et al. 2011, 2012);	Reuse of municipal wastewater at refineries (Johnson 2019)
				Environmental footprint: (Čuček et al., 2012)	Prospects for water rationalization practices in Brazilian refineries (Pombo et al., 2013)	
Environmental Impact Assessment	•NPDES with Assessment of the recipients	•Whole effluents assessment (CONCAWE 2012)	•Legislative loopholes (Kazakhstan 2012)	Assessment of pioneering toxicity testing of the effluents (Chapman et al., 1994);	Characterization of oil refinery effluents, specifically PAHs, PCBs, metals, and TOC in sediments and biota in the receiving river in the US (Hall and Burton 2005);	Discussion of the efficiency of conventional toxicity tests in the context of the new European water-related directives (Comber et al., 2015);
	•Whole effluents assessment (USEPA 2020)			Investigation of impact of effluents on aquatic species (Bleckmann et al., 1995)	Assessment of nuclear abnormalities in fishes affected by oil refinery effluents (Cavas and Ergene-Gozukara 2005);	Investigation of behaviors of naphthenic acids (Wang et al., 2015) and their derivatives (Wang et al., 2019);
					Examining the main and interaction effects among components in the effluents (Parvez et al., 2008); Comparison the combination of persistency, bioaccumulation, and toxicity tests to an approach using only toxicity tests (Leonards et al., 2011); Genotoxicity tests of effect of refinery effluents in India *in vitro* (Gupta et al., 2015) and *in vivo* in plant, animal and bacterial systems (Gupta and Ahmad 2012)	Discussion of efficiency of toxicity testing on certain parameters (Daflon et al., 2017)
Operational monitoring	•USEPA permanent monitoring and control	•Directives on industrial emission and integrated pollution prevention and control	•Limited indicators for monitoring	Identification of contaminants and their levels in the effluents and the recipients (Burks 1982; Snider and Manning 1982; Wake 2005)	Warning to monitor quality of the effluents and the reciving bodies after investigation of affected rivers (Vallieres et al., 2007; Hoshina et al., 2008), groundwater (Ripper and Fruchtenicht 1989; Hayat et al., 2002), sediments and living species in marine environment (Pettersen et al., 1997; Ruiz-Fernandez et al., 2016; Hara and Marin-Morales 2017)	Recommendations to revise parameters for monitoring after accidental discharge (Bandyopadhyay 2011);
	•Extended list of contaminants (USEPA 2019)	•CONCAWE control and guidance (CONCAWE 2018)	•Lacking permanent control (Radelyuk et al., 2019)			Development of remediation practices for monitored pollutants (Janbandhu and Fulekar 2011)

resources are re-used again as much as possible (Smol et al., 2020).

The industry is the place where the concepts of the SWU and CE meet and interconnect with each other (Fan et al., 2019). The “win-win-win” (economic-social-environmental) potential of the circular economy contributes to all three dimensions of SD (Korhonen et al., 2018). The application of both is important on any level, from small-sized companies to international consortiums (Lewandowski 2016) through shared research, demonstration projects, and policy cooperation (Baas and Baas 2005). Schroeder et al. (2019) have identified relationships between CE and SDGs and have highlighted that one of the strongest relationships and synergies are between CE practices and water-related goals, among others. Concerns about environmental pollution and resource conservation are met in the concept of CE the same as for sustainable water use. According to (Bocken et al., 2014), technological aspects are the key element in achieving SD and CE. The importance of wastewater reuse has been highly emphasised in the context of CE. Achieving sufficient water quality is impossible without appropriate treatment approaches, which is the core of the BAT approach (Voulvoulis 2018).

First schemes of water use rationalization were proposed in publications from the early 2000s (e.g., Bagajewicz 2000). This concept received considerable attention and began to be improved and incorporated into the water management systems in oil refineries worldwide (e.g., Pombo et al., 2013). Currently, a combination of water and environmental awareness addresses the aims of the SWU. For example, water auditing can be used to identify both the current weaknesses of site water management and the potential for technical and behavioural improvements, including through aligning corporate strategy with water management goals (e.g., Maheshwari et al., 2019).

In comparison with developed countries, refineries in Kazakhstan do not aim to re-use water. Achieving sufficient re-use water quality is impossible without appropriate treatment techniques, which is the core of the BAT approach. The principle of BAT is to find the most efficient and cheapest way to meet the requirements for safe or re-used water. While the industrial processes and content of generated WW are the same for refineries in the USA/EU and Kazakhstan, the significant difference between developed countries and Kazakhstan is the usage of the "in-plant control" principle and BAT. The basic biological treatment method (activated sludge), which is used by refineries in Kazakhstan, cannot efficiently treat for two reasons: firstly, the petroleum hydrocarbons are heavily degradable, and secondly, salinity and toxicity of wastewater inhibit the efficiency of biomass. It means that there are requirements not only for finally treated effluents but for the quality of generated WW after each technological unit either. It leads to additional preliminary treatment, which reduces the burden on the final (or "end-of-pipe") treatment system and enhances the efficiency of it. As the generated wastewater consists mainly of salty unprocessed heavy oil-water emulsions, and even after primary mechanical treatment, there is a challenge to remove hydrocarbons from wastewater (Bruno et al., 2020). The basic biological treatment method (activated sludge), which is used by refineries in Kazakhstan, cannot efficiently treat for two reasons: firstly, the petroleum hydrocarbons are heavily degradable, and secondly, salinity and toxicity of wastewater inhibit the efficiency of biomass. Refineries in other countries solve this issue by using advanced techniques on each step of treatment: pre-, secondary, and post- (or polishing) treatment.

The implementation of BAT became one of the leading factors towards the transition to a circular economy (Pinasseau et al., 2018). However, even developed countries have not met the requirements for their technical capacity to meet the criteria of CE practices yet (IWA 2016). It should also be all the time be kept in mind that a circular economy is a tool, but the ultimate target is to minimise environmental footprints (Čuček et al., 2012). This becomes even more evident when the world is going through the COVID-19 pandemic (Klemeš et al., 2020a) and with the rising challenges providing an opportunity for a substantial innovation step (Klemeš et al., 2020b).

4.2. Environmental impact assessment

While there is a unified formal aim for all – to sustain the safe water system and eliminate the impact of wastes, there is no universal way to achieve and evaluate this goal. There are two general approaches – 1) to achieve safe concentrations for the ecosystem preliminary. And here is a potential bias depending on the decision-makers – how to calculate "safe concentrations" for a certain site. 2) to set the common rules for every player on the market.

There are different approaches in Kazakhstan and the EU/USA to make the process of implementation of the EIA efficient and transparent. Related decisions are taken by respective policy standards in both cases. However, both the USA and EU base their decisions and develop their strategies on the scientific approach (Zijp et al., 2016). The design of policy implementation for EIA in the EU has been based on the relevant scientific investigation through the possibility of integrating the respective technological development, well designed, clearly explained and regularly evaluated (Voulvoulis et al., 2017).

Toxicity testing (e.g., Chapman et al., 1994; Bleckmann et al., 1995) is historically acknowledged as the most efficient way to evaluate the safety of the effluents. There is a common practice when the results of investigations become publicly available and transparent. As examples can serve the detailed assessment of the effluents from refineries on aquatic ecosystems with a specific focus on PAHs, PCBs, metals, etc. (e.g., Gupta and Ahmad 2012). The process of effluents assessment continuously updated based on already existed knowledge, for example, assessment of new potentially bioaccumulative substances (PBS) (e.g., Comber et al., 2015), derivatives of naphthenic acids (e.g., Wang et al., 2019), or application of the toxicity tests to evaluate the efficiency of new treatment techniques specifically chosen for certain parameters (Daflon et al., 2017).

The current scheme of Environmental Impact Assessment in Kazakhstan is weakened by the respective legislative loophole. A Kazakhstani methodology (Equations (1) and (2)) is used to assess the environmental status of final effluent-water. There is a potential bias that maximum admissible concentrations have been set not in accordance with principles of sustainability and have used gaps in the legislation, which lets to discharge inappropriately treated wastewater. The whole methodology might be affected and represent the wrong score from the first step, which leads to environmental pollution. In contrast, the unconditional requirements for effluents safety assessment, such as a detailed investigation of effluents characteristics using, e.g., Parameter-Specific Approach, Whole Effluent Toxicity (WET) Approach, or Bioassessment Approach toxicity tests, have shown the high efficiency in the developed countries. The current conditions of discharges in the USA and the EU have shown a positive trend, as requirements for them are established based on reliable techniques of the EIA.

Also, that is a very unusual practice when the wastewater releases into the ponds with the affection on groundwater, like in the Kazakhstani case. And even if it is formally eligible, the unexpected commissions and complaints from the local habitats on the perception of groundwater quality shed light on the disadvantage of those pitfalls. In contrast, the EU directly forbids the transfer of pollutants from one environmental media to another. This ban has contributed to environmental improvements and promote both the governments and the industries to follow the SWU.

However, there is not full confidence in the "safety" of treated wastewater for two reasons. Firstly, the fate of hydrocarbons has not yet fully explored. For example, the recent study of PAHs degradation shows that the products of degradation are hazardous (CONCAWE 2020b). Secondly, several refineries still show high concentrations of contaminants, permanently or accidently, which requires additional investigations.

4.3. Operational monitoring

Overview of the improvements resulted in the identification of separated compounds supported with the future establishing criteria for effluents assessment since the early 1980s (e.g., Snider and Manning 1982). Identification of new substances in the effluents supported in the identification of hazardous substances, fractions and establishing their permissible levels. Wake (2005) published a substantial review of trends identified positive trends in Europe, concerned about already polluted sites. The potential fate for the environment and ecosystems from real case studies has been studied and presented for affected river and fish there (e.g., Hoshina et al., 2008), on groundwater (e.g., Ripper and Fruchtenicht 1989), on sediments and living species in a marine environment (e.g., Hara and Marin-Morales 2017). All these findings highlighted the necessity for adequate operational monitoring for both effluents and receiving water bodies. Operational monitoring is important as it helps to define the parameters needed to be revised as a result of the activities of the oil refineries (Bandyopadhyay 2011); or to develop respective remediation practices for monitored pollutants (Janbandhu and Fulekar 2011).

While the developed countries identified certain indicators, such as polycyclic aromatic hydrocarbons (PAH), naphthenic acids, PFAS, or benzene, toluene, ethylbenzene, xylene (BTEX), for better estimation of the toxic effect of their existence in wastewater; Kazakhstani oil refineries monitor only the sum of TPH, without detailed investigation of the resulted effect on the environment. Still, 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 the wastewater treatment and environmental monitoring in developed countries ensures environmental safety and follows the sustainable development principles positively affecting the monitoring system. E.g., US EPA carries out permanent control of the quality of wastewater and recipients to detect any accidental or other exceedance of permissible values for contaminants. In the EU, any operator of pollution monitors their emissions under the directives on industrial emission and integrated pollution prevention and control.

5. Conclusions

Delivery of SDGs requires a healthy and productive environment. The situation when the industry causes risks for the environment and public safety violates the principles of equitability and bearability of the SWU in Kazakhstan. This work was to compare the strategies of the implementation of the SWU system in the oil refinery industry between developed and developing countries. While the oil refinery industry discharges the effluents into the environment worldwide, the examples of chosen countries show that there are different approaches to ensure or not their safety. In order to achieve the SWU, the system of industrial water and wastewater management should rely on legislative and normative standards. The defined criteria should be implemented to ensure equitable access of different water users and viable mechanisms to achieve water safety are 1) implementation of the concept of Circular Economy (CE), via the implementation of Best Available Techniques (BAT) and water reuse, 2) an adequate and fair system of Environmental Impact Assessment, and 3) an adequate scheme of operational monitoring for wastewater quality. The considered principles should follow the requirement to control the amount of contamination inside the technological processes before final discharge.

It was found that the current "*status quo*" in Kazakhstan includes formal approval for polluting activities by the industry. The system is seriously weakened not only by gaps in legislation, rather by the not sufficient development of appropriate environmental tools (such as operational monitoring and preliminary and permanent environmental assessment). The performed investigations showed that decision-makers in Kazakhstan do not follow scientifically approved techniques and mechanisms to prevent pollution, which guarantees a good-status of receiving water bodies, comparatively with developed countries. The current trend in well-developed countries is a transition towards a "closed-loop" system. Comparatively, refineries in countries like Kazakhstan still need to implement the aim to re-use water, which does not reflect a risk of water scarcity in the region. Also, the current wastewater treatment scheme does not use efficient advanced techniques on each step, including pre-, secondary, and post- (or polishing) treatment. Thus, it is highly emphasised to improve the wastewater treatment systems via the implementation of the BAT.

Multiple barriers, such as the perception of the industry of pricing and technological changes, slow down the process of implementing the suggested *responses* in the oil refineries in Kazakhstan. The primary action should be the changing of the policy, which has not been updated for years.

CRediT authorship contribution statement

Ivan Radelyuk: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Kamshat Tussupova:** Conceptualization, Methodology, Supervision, Formal analysis, Writing – review & editing. **Jiří Jaromír Klemeš:** Conceptualization, Supervision, Writing – original draft, Writing – review & editing. **Kenneth M. Persson:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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