MODERN WATER MANAGEMENT

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explores principles, best practices, and opportunities for recycling and reuse within water management for refineries and petrochemical plants.

The hydrocarbon industry – encompassing refineries, petrochemical plants, and upstream operations – is one of the most water-intensive sectors globally. Water is a critical component in nearly every facet of its operations, from cooling and steam generation to processing and purification. However, growing water scarcity, stringent environmental regulations, and increasing operational costs are driving a paradigm shift. The industry is moving from a linear model of 'take, use, and dispose' to a circular, integrated approach focused on water management, recycling, and reuse. This evolution is not just an environmental imperative but a strategic business necessity for ensuring security, efficiency, and a licence to operate.

This article explores key principles, best practices, and opportunities for recycling and reuse that are reshaping how the hydrocarbon industry approaches water.

The water-energy nexus: understanding demand

To appreciate the scale of the challenge, one must first understand the water use pattern within a typical refinery.

Water consumption in hydrocarbon industries is dominated by two primary processes:

- Cooling water: accounting for approximately 53% of total water use, cooling systems rely on massive volumes of water, with significant losses through evaporation and drift.
- Steam generation: representing about 42% of use, steam is essential for process heating, stripping, and power generation, leading to consumptive losses.

The remaining fraction is split between utility water (5%) and potable water (1%). Traditionally, the fate of this used water was disposal; approximately 41% was discharged as wastewater, with another 5% lost in sludge. This linear model is increasingly unsustainable.

The concept of a 'water balance' is fundamental. It is a comprehensive accounting of all water inputs – including raw water (surface, purchased, in crude), and even rainfall – against all outputs: product water, steam losses, evaporation, and discharge. The goal of modern water management is to minimise the input of fresh water and the output of wastewater by maximising the internal recycling and reuse of water, effectively closing the loop.

Principles of water management

Water stewardship and value recognition

The first principle is recognising water as a finite and valuable resource. Unlike hydrocarbons, water has no substitute. This recognition must extend beyond cost to include environmental, social, and reputational value.

Source protection and diversification

Ensuring sustainable withdrawal is crucial. Water sourcing should prioritise lower-stress basins and diversify across surface, groundwater, municipal, and alternative supplies (e.g. desalinated seawater or reclaimed wastewater).

Minimisation and efficiency

Before exploring advanced technologies, companies should adopt process optimisation to minimise water use per unit of production. Water-efficient technologies in cooling, steam generation, and process integration can reduce demand by 20 - 50%.

Circularity: recycle and reuse

A circular mind-set redefines wastewater not as waste but as a potential resource. Internal reuse (within the same process) and external recycling (between facilities or for community benefit) form the cornerstone of sustainable hydrocarbon water management.

Risk and resilience management

Water-related risks range from supply disruptions to regulatory penalties and community opposition. Resilience requires proactive monitoring, contingency planning, and adaptive water strategies aligned with climate projections.

Transparency and stakeholder engagement

Public trust hinges on transparency. Reporting water withdrawals, consumption, and discharge quality, along with engaging local communities, ensures accountability and social licence.

Key water management challenges

Upstream exploration and production

- Water-intensive hydraulic fracturing operations.
- Produced water (saline, hydrocarbon-laden) volumes often exceed hydrocarbon production in mature fields.
- Environmental risks of spills and improper disposal.

Midstream transport and processing

- Pipeline hydro-testing requires large water volumes.
- Terminal operations may involve contaminated storm water management.

Downstream refining and petrochemicals

- Refineries can require 1 - 2.5 bbl of water per bbl of crude processed.
- Cooling towers and boilers dominate water use.
- Wastewater often contains oil, grease, suspended solids, phenols, sulfides, ammonia, and heavy metals.

Regulatory and community pressure

- Operations in water-scarce regions face tighter scrutiny.
- Zero liquid discharge (ZLD) mandates are increasingly common in Asia and the Middle East.

The pillars of modern water management

An integrated water strategy in the hydrocarbon industry is built on three core pillars, each addressing a critical challenge:

Ensuring water security and process reliability

Water is a lifeline for continuous operation. A shutdown due to water shortage or quality issues can result in monumental financial losses. Integrated water management mitigates this risk by diversifying water sources. Instead of relying solely on finite freshwater resources or unpredictable municipal supplies, facilities can treat and reuse their own wastewater, creating a reliable, on-site source.

Due to a water shortage, Mangalore Refinery and Petrochemicals Ltd (MRPL) in India was forced to partially shut down its plant, resulting in lower production. To avoid such scenarios in the future, MRPL opted for sea water desalination to supply water and thereby improve the water availability. The plant was planned with a modular approach, so that the development can be done in a phased manner to meet the future expansion requirements.

Maximising cost efficiency and operational optimisation

Water procurement, treatment, and disposal represent significant operational expenditures. By recycling water, plants dramatically reduce their intake of expensive fresh water and simultaneously cut the volume of wastewater requiring costly treatment before discharge. Furthermore, advanced treatment processes can recover valuable resources. The Dahej PTA effluent recycling plant, India, is a prime example, where the anaerobic treatment process generates 34 000 m^3/d of biogas, leading to savings in operational energy costs. This transforms a cost centre into a value-generating unit.

Figure 1. Sea water desalination plant at MRPL, India.

Meeting environmental standards and enabling sustainability

Regulatory pressures to reduce the environmental footprint are intensifying globally. Integrated systems are designed to meet the highest environmental standards for direct or indirect discharge. More importantly, they enable companies to become better environmental stewards by significantly reducing their extraction from local water bodies and minimising their polluting discharge. This proactive approach protects local ecosystems and contributes positively to the socio-economic development of the region, bolstering the company's social licence to operate.

The Dangote Refinery Complex in Nigeria arranged for such an integrated approach at the planning stage, tapping raw water from a nearby lagoon with multiple stages of treatment including biological treatment for occasional contamination. The wastewater streams are segregated and treated in specific zones for specific contaminant removal using various treatment technologies, and then, finally, the treated effluent from each stream is combined and tertiary treated in the reverse osmosis based treatment plant for reuse of the water in various applications, including cooling water makeup. The reject from both the treatment plants are also treated meeting the stringent guidelines as specified by International Finance Corp. (IFC).

Best practices for water management

Water audits and benchmarking

Conducting comprehensive water audits establishes a baseline of water use and losses. Benchmarking against industry peers or global standards can highlight opportunities for improvement.

Refinery wastewater treatment and reuse

For internal reuse, employing primary treatment, secondary biological treatment, and advance tertiary treatment methods wherein the treated effluent can supply cooling towers, boiler feedwater, or firewater systems, and even process water.

Digital water management

- Real-time monitoring: sensors for flow, quality, and temperature allow continuous tracking.
- Data analytics and AI: predict water demand, optimise chemical dosing, and detect anomalies in water systems.
- Digital twins: virtual replicas of water networks enable scenario modelling and proactive decision-making.

ZLD and brine management

- Evaporation and crystallisation: convert concentrated brine into solid salts for safe disposal or reuse.
- Hybrid ZLD systems: combine membrane and thermal technologies for cost optimisation.
- Resource recovery: extracting valuable by-products such as lithium, magnesium, or industrial salts from wastewater.

Stakeholder collaboration

Shared water challenges demand collective action. Examples include:

- Industrial water reuse parks, where multiple companies share a central treatment and recycling facility.
- Partnerships with municipalities to co-invest in wastewater reclamation plants.
- Community programmes to supply treated effluent for irrigation.

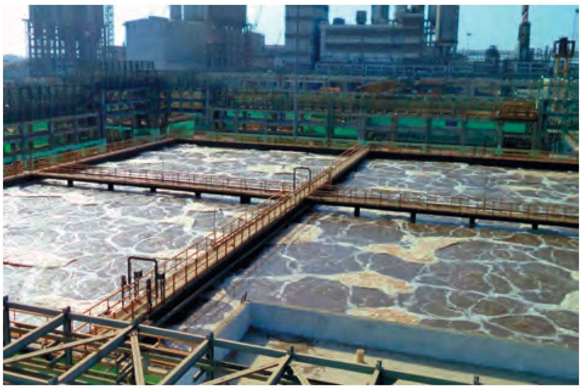

Figure 2. Effluent recycle plant at Reliance Dahej PTA complex, India.

The technological arsenal for treatment and recycling

Achieving a closed-loop water system requires a sophisticated combination of technologies, tailored to the specific quantity and quality requirements of each process stream. The following segment outlines a comprehensive suite of solutions:

Raw water treatment

The starting point is treating raw water from various sources (surface, ground, sea) to produce different quality streams: cooling water, boiler feed water, process water, and even ultrapure water.

Key technologies include:

- Clarification: clariflocculators, solids contact clarifiers, and lamella clarifiers remove suspended solids.
- Filtration: gravity and pressure media filters and more advanced membrane filtration (microfiltration [MF], ultrafiltration [UF]) provide finer solids removal.
- Desalination: for coastal plants or brackish sources, reverse osmosis and thermal desalination are critical for producing high-purity water.
- Polishing: demineralisation via ion exchange (IX) and condensate polishing are essential for high-pressure boiler feed water.

The Fajr Petrochemical project in Bandar Imam, Iran, stands as a testament to this capability, where a single integrated system provides five different water qualities – including boiler feed, cooling, service, drinking, and fire-fighting water – from one raw water source.

Raw water undergoes different levels of treatment to meet the requirements of the different qualities of water ranging from clarification, filtrations, demineralisation, and reverse osmosis technologies.

Effluent and produced water treatment

Industrial wastewater and produced water from oilfields are complex streams containing hydrocarbons, chemicals, and dissolved solids. Treatment often involves a multi-stage approach:

- Preliminary treatment: API/CPI separators and dissolved air flotation (DAF) units are used for free oil and grease removal.
- Biological treatment: this is the core of organic pollutant removal. Technologies range from conventional activated sludge processes (ASP) and sequential batch reactors (SBRs) to more advanced systems like membrane bioreactors (MBR) and moving bed biofilm reactors (MBBR). Anaerobic processes like upflow anaerobic sludge blanket reactor (UASB) are employed for high-strength wastewaters, offering the benefit of biogas production. Often biological treatment is the combination of two or three processes to meet the desired quality of treated wastewater.
- Advanced treatment: for stubborn pollutants, chemical, and physical processes like wet air oxidation, chemical oxidation, and biofiltration are deployed.

The scale of this challenge is met by projects like the Petronas RAPID complex in Malaysia, one of Asia's largest integrated refinery and petrochemical effluent treatment plants, which effectively treats over 102 000 m^3/d of seven distinct effluent streams – from process wastewater to fire-fighting run-off – in a single, integrated facility.

This integrated wastewater treatment segregates different streams of wastewater based on level of contamination and undergoes different levels of treatment ranging from oil treatment units, conventional ASP, biotowers, depth filtration with media, and final surface filtration.

Water recycling and reuse

This is the culmination of the integrated strategy, where treated effluent is further purified to a standard suitable for re-entry into industrial processes. This requires advanced tertiary treatment:

- Tertiary filtration: dual media filters and self-cleaning filters remove residual suspended solids.
- Advanced membranes: UF acts as a perfect pre-treatment barrier for reverse osmosis, which removes dissolved salts and organics, producing high-quality reusable water.
- Polishing: activated carbon filtration (GAC) and ozonation (BIOZONE®) remove trace organics and ensure disinfections.

India has pioneered some of the largest refinery water reuse plants:

- Panipat Refinery (Indian Oil Corp. Ltd): 21 600 m^3/d, 90% recovery for boiler feed and process water.
- Dahej (Reliance Industries): 36 000 m^3/d PTA effluent recycling with combined aerobic-anaerobic treatment, producing biogas for heating.
- Paradip Refinery (Indian Oil Corp. Ltd): 54 000 m^3/d, 75% water recovery using multi-stream effluent treatment and reverse osmosis.

The road ahead

The integration of the water-energy nexus is driving innovation across the sector, with energy-efficient treatment technologies such as forward osmosis, membrane distillation, and anaerobic MBRs being deployed to lower operational costs.

In decentralised treatment units, modular and skid-mounted systems enable flexible water recycling at well pads, terminals, and satellite facilities.

Nature-based solutions, including constructed wetlands and biofiltration, are being tested for effluent polishing, enhancing biodiversity while reducing treatment costs.

Advances in material science – such as nanomaterials, graphene-based membranes, and biomimetic materials – offer higher selectivity and reduced fouling in desalination and water reuse systems.

Extending the circular economy beyond water, the integration of waste heat recovery, carbon capture, and resource recovery from wastewater supports net zero and broader sustainability goals.

Conclusion

The evolution of water management in the hydrocarbon industry is clear. Water is no longer a utility to be managed in isolation but a strategic resource integral to the entire production lifecycle. The principles of integrated water management – understanding the water balance, implementing a multi-barrier technological approach, and focusing on recycle and reuse – are delivering tangible benefits.

Companies that embrace this holistic approach are future-proofing their operations against water scarcity, realising significant cost savings through reduced consumption and resource recovery, and positioning themselves as leaders in corporate environmental responsibility.

As the case studies from Reliance Dahej, Panipat Refinery, and Dangote Refinery show, investing in complete water solutions is not merely an operational expense; it is an investment in resilience, efficiency, and long-term sustainability, truly enabling sustainable solutions. The technology and expertise exist; the imperative now is for wider adoption across the global hydrocarbon sector.

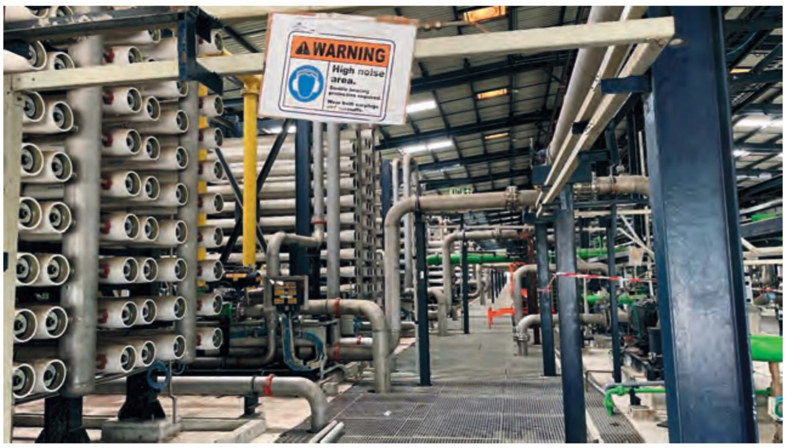

Figure 3. Effluent recycle plant at Dangote Refinery complex, Nigeria.