DOI:10.5937/IIZS25118K

BEST AVAILABLE TECHNOLOGIES AND PRACTICES TO TREAT THE THERMAL SPA WASTEWATER

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Abstract: The reuse of treated thermal wastewater from spas offers an innovative and sustainable approach to the restoration of degraded soda pan ecosystems. These unique saline-alkaline habitats are highly sensitive to changes in hydrology, salinity, and temperature, and their conservation requires carefully tailored interventions. Advanced treatment technologies enable the purification of thermal wastewater to meet the specific ecological requirements of soda pans. Carefully integrated, the reuse of spa wastewater can improve habitat quality, support rare and endemic species, and contribute to the long-term resilience and conservation of soda pans. This approach represents a promising model for combining sustainable water management with biodiversity restoration in vulnerable ecosystems.

Key words: reuse, thermal, wastewater, treatment, soda pan

INTRODUCTION

Thermal wastewater originating from spas and related facilities represents both an environmental challenge and an underutilized resource. When discharged untreated, such effluents can disrupt local ecosystems due to elevated temperature, altered salinity, and imbalanced chemical composition. However, with the application of advanced treatment technologies, thermal wastewater can be transformed into a valuable input for ecological restoration projects, particularly for fragile saline-alkaline habitats such as soda pans.

Recent technological developments, most notably low-temperature desalination, membrane-based separation processes, and systems with integrated waste heat recovery, enable energy-efficient purification of thermal wastewater. By selectively managing salinity and pH, recovering useful minerals, and regulating discharge temperature, it is possible to tailor the treated water to meet the ecological requirements of degraded habitats.

Beyond the ecological benefits, such approaches contribute to broader sustainability goals by lowering freshwater demand, reducing greenhouse gas emissions, and minimizing operational costs in industrial and spa sectors. Furthermore, adaptive water management strategies, combined with habitat enhancement measures and continuous ecological monitoring, provide safeguards to ensure long-term success.

This paper explores the potential of reusing treated thermal wastewater for the restoration of degraded soda pan ecosystems, with a focus on aligning technological capabilities with ecological needs. Special attention is given to water quality optimization, temperature regulation, hydrological management, and biodiversity support, as well as the role of scientific partnerships and pilot-scale demonstrations in scaling up best practices.

MATERIAL AND METHODS

Desalination¶

Thermal Desalination Technologies for Reuse of Spa and Industrial Wastewater

Thermal wastewater from spas and industrial facilities can be treated and reused through advanced thermal desalination technologies, offering sustainable solutions for water scarcity and ecological restoration. Key methods include Multi-Stage Flash (MSF) distillation, Multi-Effect Distillation (MED), Mechanical Vapor Recompression (MVR), and Low-Temperature Thermal Desalination (LTTD). Each technology has unique advantages and limitations depending on energy availability, feedwater quality, and operational scale.

Multi-Stage Flash (MSF) Distillation

MSF involves heating saline water and flashing it into steam across multiple stages with progressively lower pressures. Each stage recovers heat from condensed vapor to preheat incoming feedwater, improving energy utilization. MSF systems are robust, capable of handling high-salinity water, and suitable for large-scale centralized plants, often integrated with cogeneration or waste heat systems [1,2]. However, MSF is energy-intensive, prone to scaling and corrosion, and requires significant pretreatment, making it less favorable for smaller spa facilities or mineral-rich thermal water.

Multi-Effect Distillation (MED)

MED improves on MSF by cascading vapor from one stage to the next, enhancing thermal efficiency and reducing scaling risks. Operating typically at lower top brine temperatures (60–70°C), MED is compatible with low-grade or waste heat and renewable energy sources [3]. It is suitable for medium to large-scale operations (5,000–30,000 m^3/day) and increasingly favored over MSF due to lower energy consumption, greater feedwater tolerance, and modular scalability. Pretreatment remains necessary for mineral-rich thermal waters to maintain efficiency.

Mechanical Vapor Recompression (MVR)

MVR recycles the latent heat of vapor by mechanically compressing the evaporated vapor and reusing it to heat incoming water, drastically reducing external energy needs. It can achieve desalination rates up to 99.66% and water recovery up to 85% [4]. MVR systems are compact, energy-efficient, and suitable for high-salinity or scaling-prone waters, making them relevant for closed-loop spa wastewater reuse and ecological restoration. Limitations include high capital costs, maintenance requirements, and sensitivity to water composition variations.

Low-Temperature Thermal Desalination (LTTD)

LTTD operates under near-vacuum conditions, allowing water to evaporate at ambient temperatures and condense using cold water sources, such as deep seawater or cooling systems. It is energy-efficient, environmentally sustainable, and has minimal scaling and corrosion issues [5,6]. LTTD is particularly suitable for small- to medium-scale applications, island communities, or remote areas where conventional methods are energy-intensive. Its main limitation is site specificity, requiring access to temperature gradients between warm surface water and cold deep water.

Selective Ion Management

Thermal Membrane Desalination for Spa and Industrial Wastewater Reuse

Thermal Membrane Distillation (TMD) combines thermal evaporation with membrane separation, allowing only water vapor to pass through a hydrophobic membrane while retaining salts and non-volatile contaminants. Operating at relatively low temperatures (40–80°C), TMD is energy-efficient and compatible with low-grade or residual heat, making it suitable for industrial wastewater, high-salinity brines, and spa effluents [7,8].

Four main TMD configurations are commonly used:

- Direct Contact Membrane Distillation (DCMD): Simple, feed and permeate directly contact the membrane.
- Air Gap Membrane Distillation (AGMD): Includes an air gap to reduce heat loss, increasing thermal efficiency.
- Vacuum Membrane Distillation (VMD): A vacuum on the permeate side enhances vapor transport and reduces temperature requirements.

Sweeping Gas Membrane Distillation (SGMD): Uses an inert gas to carry vapor to an external condenser. TMD achieves high rejection of salts, heavy metals, and organics (>99%), operates at low pressures, and has a modular design suitable for decentralized or industrial deployment. It is especially relevant for environmentally sensitive applications such as soda pan restoration, wetland revitalization, and industrial symbiosis. Limitations include relatively low water flux compared to reverse osmosis, requirement of thermal energy, and potential membrane fouling without pretreatment.

Vacuum Membrane Distillation (VMD)

VMD is a TMD variant where the permeate side is under vacuum, enhancing vapor transport and water flux. Water is heated to moderate temperatures (50–80 °C) and evaporates across a hydrophobic membrane, while salts and non-volatiles remain in the feed. Vapor is condensed externally, yielding high-purity water with salt rejection >99.9% [9].

Advantages of VMD include:

- High water flux due to strong vapor pressure gradients.
- Operation at low feed temperatures, enabling use of solar or waste heat.
- Compact and scalable systems suitable for modular deployment.
- Ideal for Zero Liquid Discharge (ZLD) and concentration of hypersaline brines.

Challenges include membrane wetting risk with surfactants or organics, the need for vacuum pumps and external condensers, and potential scaling or fouling from untreated feedwater. Despite these, VMD is effective for seawater and brackish water desalination, industrial brine treatment, high-salinity wastewater recovery, and integration into hybrid systems.

Temperature Adjustment

Soda pans are ecologically sensitive saline-alkaline wetlands, hosting unique microorganisms, crustaceans, and birds. Discharges of warm industrial or municipal wastewater can disrupt microbial communities, reduce oxygen solubility, and alter seasonal reproductive cycles, threatening biodiversity. Temperature regulation prior to discharge is therefore essential.

Passive Heat Exchangers

Passive systems transfer heat without mechanical energy, using ambient air, soil, or water. Common types include buried pipe systems, air-cooled radiators, and submerged coils [10].

Advantages of the systems include its energy efficiency, low maintenance requirements, environmental friendliness, cost-effectiveness for small to medium flow rates, and silent operation. However, the systems also present certain disadvantages, such as limited cooling capacity, variability in seasonal efficiency, substantial space requirements, slow cooling processes, and challenges associated with retrofitting [11].

Cooling Ponds and Constructed Wetlands

These nature-based solutions slow water flow, allowing heat dissipation via radiation, convection, and evaporation. Constructed wetlands additionally filter nutrients and improve water quality [12,13]. Advantages include low energy consumption, multifunctionality, enhancement of biodiversity, resilience, and long-term cost-effectiveness. However, the system also presents certain disadvantages, such as substantial land requirements, variability in performance due to seasonal changes, risks associated with mosquitoes and odors, sediment accumulation, and slow hydraulic throughput.

Mechanical Cooling Systems

Active systems, including cooling towers, chillers, and forced-circulation heat exchangers, provide precise temperature control for high-volume discharges. Advantages of the system include its high cooling efficiency, compact design, reliability, scalability, and automated operation. However, it also presents certain disadvantages, such as high energy and maintenance costs, noise generation, potential refrigerant leaks, and technical complexity.

Integration with Desalination and Hybrid Systems

Waste heat from industrial or power generation facilities can be used to drive thermal desalination (e.g., MED, TMD) to reduce freshwater demand and carbon footprint [11]. Hybrid systems combining Adsorption Desalination (AD) with MED enhance energy efficiency, freshwater output, and reduce environmental impact [14].

Cooling Tower Blowdown Treatment and Low-Temperature Distillation (LTD)

Blowdown water contains high salinity and impurities. Treating it with TMD, LTD, or MED allows reuse as makeup water, supporting Zero Liquid Discharge (ZLD) goals and water conservation. LTD operates under low pressure and temperature, using waste heat, achieving 80–95% water recovery with low scaling and fouling risks. Advantages include the utilization of waste heat, high water recovery rates, environmental sustainability, and the potential for modular and scalable implementation. However, the system is associated with several disadvantages, such as high capital costs, slow processing rates, the necessity for vacuum conditions, challenges in saline concentrate disposal, and reliance on thermal energy sources [11].

DISCUSSION

The restoration and conservation of soda pan ecosystems require a careful balance between wastewater reuse and ecological protection. Treated thermal wastewater from spas represents a potentially valuable resource, but improper management can cause thermal shock, salinity shifts, or nutrient imbalances, threatening microbial communities, invertebrates, and bird populations. The discussion highlights three critical aspects: desalination technology selection, selective ion management, and temperature adjustment.

Desalination Technology Selection

Among thermal desalination options, MED and LTTD are the most suitable where low-grade or waste heat is accessible. These systems operate at lower temperatures, reduce scaling potential, and maintain water chemistry compatible with sensitive habitats. MVR offers high water recovery and low specific energy consumption but requires technical expertise and higher capital investment, making it most appropriate for industrial-scale operations. MSF, though mechanically robust, is energy-intensive and generally reserved for large-scale centralized plants with abundant thermal energy. For small to medium-scale applications or decentralized sites, thermal membrane technologies (TMD, VMD) provide additional flexibility. TMD is simpler and energy-efficient, suitable for rural or off-grid scenarios, while VMD achieves higher flux and recovery rates, ideal for industrial wastewater treatment with high-salinity streams.

Selective Ion Management

Maintaining chemical integrity is crucial for the survival of soda pan biota. Desalination and membrane processes allow for selective removal of harmful ions (e.g., sulfates, heavy metals) while retaining essential ions such as carbonates and bicarbonates. This preserves the natural mineral composition, supporting halophilic microorganisms and nutrient cycles necessary for ecological function. Continuous monitoring of water chemistry, including salinity, pH, nutrients, and trace metals, is critical to detect deviations and prevent long-term ecosystem disruption.

Temperature Adjustment

Thermal regulation is equally essential. Passive heat exchangers provide low-energy cooling suitable for small to medium flows, while constructed wetlands and cooling ponds offer multifunctional solutions that combine thermal control with water quality improvement and biodiversity enhancement. Mechanical cooling systems ensure precise temperature control in high-volume industrial discharges but come with high energy and maintenance costs. A combined or site-specific approach is recommended, matching system selection to flow rate, thermal load, ecological sensitivity, and spatial constraints. Gradual, controlled water introduction simulates natural hydrological cycles, reducing stress on biota and allowing ecosystems to adapt to new salinity and temperature regimes.

Integrated Management and Ecological Considerations

Using residual heat strategically can enhance ecological restoration. Moderately elevated temperatures during colder months maintain microbial activity and support early vegetation and zooplankton growth, benefiting higher trophic levels. Habitat design, including shallow basins, uneven bottoms, and surrounding halophytic vegetation, fosters diverse microhabitats, natural filtration, and soil stabilization. Pilot projects are essential to validate restoration strategies, monitor species response, and refine techniques prior to large-scale application. Long-term biodiversity monitoring ensures adaptive management, allowing intervention if harmful substances accumulate or ecosystem health declines.

CONCLUSION

Properly treated thermal wastewater from spas can serve as a valuable and sustainable resource for restoring soda pan ecosystems, but its successful integration requires careful consideration of both technological and ecological factors. Choosing the right desalination technology, whether MED, LTTD, MVR, TMD, or VMD, depends on site-specific conditions, energy availability, and scale, while maintaining the chemical integrity of the water through selective ion management is crucial for supporting the specialized organisms that inhabit these sensitive wetlands. Temperature regulation, achieved through passive, nature-based, or mechanical systems, prevents thermal stress and allows ecosystems to adjust gradually, supporting natural biological processes and seasonal cycles. Thoughtful habitat design and adaptive water management further enhance biodiversity and ecological resilience. Continuous monitoring and collaboration with scientific institutions ensure that restoration efforts remain responsive to environmental changes, while the integration of residual heat and renewable energy supports sustainability and resource efficiency. Overall, a holistic, carefully managed approach can restore and preserve soda pans effectively, demonstrating how technological solutions and ecological principles can work together to protect fragile saline-alkaline wetlands.

ACKNOWLEDGEMENT

This paper has been produced with the financial assistance of the European Union through the Interreg VI-A IPA Hungary-Serbia programme (HUSRB/23S/12/020), the Ministry of Science, Technological Development and Innovation (Contract No. 451-03-137/2025-03/200156) and the Faculty of Technical Sciences, University of Novi Sad through project “Scientific and Artistic Research Work of Researchers in Teaching and Associate Positions at the Faculty of Technical Sciences, University of Novi Sad 2025” (No. 01-50/295)”. The content of the paper is the sole responsibility of FTS and can under no circumstances be regarded as reflecting the position of the European Union and/or the Managing Authority of the Programme.

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