Hydraulic Structures
At the Heart of 21st Century Global Sustainable Development

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For millennia, societal progress, health and prosperous economic growth has been closely linked to development of water infrastructure. Now in the 21st century, humankind faces some immense challenges including increasing and migrating populations, water and food security, damaged ecosystems, and a growing energy crisis, all coupled with the effects of climate change. Considering these challenges, future hydraulic structures must play a grander role in sustainable development through balanced preservation of societal, environmental, and economic goals collectively. This article showcases the positive contribution of hydraulic structures on these three pillars of global sustainable development through six newly defined thematic impact areas.

Let's envisage a world where all hydraulic structures and associated services were suddenly erased from existence. Most households would not have clean drinking water. The absence of sewage infrastructure would manifest in critical sanitation problems and serious public health issues. Local environments and ecosystems would be in major flux with undesirable impacts from pollution, flooding, droughts, and sediment transport. The absence of hydroelectric power would significantly decrease renewable energy production and hence impact energy prices and greenhouse gas emissions, whereas coastal erosion and flooding would threaten shoreline and estuarine communities.

Thankfully, the reality is that many hydraulic structures have provided security in water related services that lies at the very heart of global sustainable development[1,2]. Hydraulic services underpin societal development and economic wealth[2,3], whether they function deep beneath the ground as drainage or storage systems or operate remotely to convey water for purposes. Unseen to the public eye and not fully appreciated until there is a problem, essential water infrastructure ensures continuous water supply, waste removal and energy and food security amongst many other benefits to society[1,3,4].

Nonetheless, there is still a growing need for sustainable hydraulic structures, with requirements for water infrastructure accounting for more than half of the budget required for all global infrastructure by 2030[5]. In the face of 21st century societal, environmental, and economic pressures of population growth, energy and food consumption, damaged ecosystems due to natural and human disturbances all coupled with intensifying climate change effects, the hydraulic structures community is now at a crossroads towards the sustainable development goals (SDGs)[1]. There is a call for a renewed scientific understanding of how hydraulic structures interact with the environment to manage and repair problems inherited from prior generations and to better plan for future sustainable hydraulic structures development.

Figure 1 | The Great Salt Lake railroad causeway disrupts natural lake currents between northern and southern sections. Lowering of lake levels in recent times due to climate change and consumption is intensifying salt concentrations in the southern section to critical levels, creating a serious threat to the ecosystems and the economies that depend on it. This is an exemplary case of how hydraulic structures interact with societal, environmental, and the economic goals collectively in the face of climate change. Now, hydraulic engineering research groups at Utah State University are providing insights into the complex flows through the breach to inform management during drought periods[6]. Photo courtesy of Brian Crookston.

To address 21st century challenges, concrete action is required in (**1**) adaptation, (**2**) mitigation, and (**3**) enhanced resilience through hydraulic structures development. However, robust sustainable development can only be achieved by preserving a good balance between societal, environmental, and economic goals of a project collectively (**Figure 2**).

To support this strategy, six newly defined thematic application areas have been identified. Each theme is described below with highlights of exemplary activity, impacts and challenges in each area with reference to the SDGs.

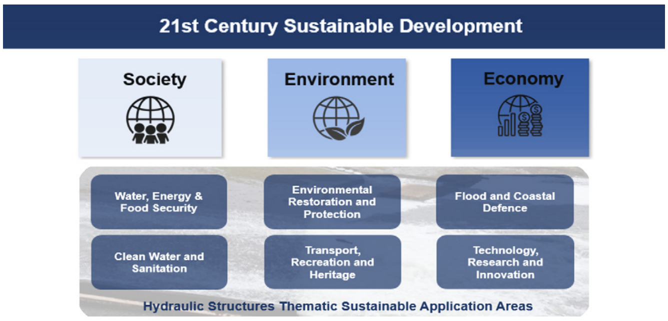

Figure 2 | Hydraulic structures thematic application areas underpin 21st century sustainable development pillars: society, environment, and the economy.

Water, Energy and Food Security

Dams and reservoirs have provided an essential security belt around the world in ensuring water, energy, and food supply[2]. Hydropower plays a role in climate change mitigation, yielding circa 16% of the world's generated electricity as a low-carbon energy source[2,7]. Large hydropower reservoirs have been essential for providing flexibility and storage in large quantities and over periods from hours to years to facilitate fast response to demand along with black start possibility. Dams and reservoirs are also critical for water storage and conveyance to satisfy irrigation and food production for growing populations. It is reported that one third of the world is still undernourished, and a large population is threatened by famine. This risk can be lessened by irrigation of arid regions by hydraulic structures[3].

An example is the development of the Kaleshwaram Lift Irrigation project in India with a capacity to pump 56 million m^3/day to provide water for irrigation, consumption and industrial use across drought prone regions using flood waters. In terms of adaptation, dams and reservoirs also act as a buffer to water resource changes. Following learnings in the past, careful attention to avoid or mitigate negative impacts is a necessity in future developments through a balanced approach in assessing environmental and social costs of the project during planning stages[1]. Significant investments are also being made in the management and refurbishment of existing dams to add capacity, reduce maintenance, and extend lifespan. In this context, reservoir sedimentation is also a critical problem for management agendas, where 0.5–1% of the world water storage capacity is lost annually to sedimentation[8].

Environmental Restoration and Protection

A specific theme for the environment has been introduced where hydraulic structures will play a vital role in both restoration and protection against natural and human disturbance in the future. In terms of natural impacts, examples are protection of habitats and ecosystems against erosion, sea level rise, floods etc; however, any indirect or cumulative effects of protection structures (e.g., sediment transport) should be understood in detail and mitigated where practical ahead of design. More importantly, impacts on the environment due to human activity and infrastructure development are inherent, where many current challenges have been inherited from development of prior generations. Ongoing and future hydraulic structures practice will require collaboration with other professionals and specialists in the field to manage existing challenges[3,6], restore natural environments and to innovate infrastructure development and management strategies to minimise impact on the environment.

For example, the field of eco/etho-hydraulics is maturing to understand and better integrate hydraulic structures and ecosystems (**Figure 3(b)**). Another example is combined sewer overflows which continue to be a pollution source across the world; however, large-scale interception structures are being constructed in many key locations to help mitigate discharges and restore natural waterways and habitats.

Flood and Coastal Defence

The growing frequency of significant flooding disasters instils great urgency to adapt flood and coastal protection measures to the compounding effects of climate change and increased urbanisation. Such strategies should consider holistically the system and corresponding behaviours, including the cause or source, for solutions to be effective and proactive whilst ensuring environmental goals are being preserved. For example, shoreline management plans are increasingly integrating a range of green-gray solutions such as artificial structures with ecological features, like vertipools or habitat tiles (**Figure 3(c)**). To mitigate flooding risk, sustainable planning and upgrades are being developed across cities such as more effective levee networks and, where possible, deep sewer conveyance systems, storm storage, and pumping systems.

Clean Water and Sanitation

Hydraulic structures play a pivotal role in the provision of water supply for clean water consumption, industrial use, and irrigation along with sanitation across the world. Before and after treatment, water is primarily collected and stored in reservoirs and distributed through extensive canal and pipeline systems. Sanitation systems include sewers, culverts, drop structures, and pumping stations, which safely transport wastewater away from society towards treatment infrastructure for efficient cleaning prior to environmental discharge. There are also recent strides towards the circular economy in this regard, where for example pollution abatement projects in India are adopting a “use, treat and reuse” approach in wastewater management where hydraulic infrastructure is fundamental to its success[9] (**Figure 3(d)**). However, with some 46% of the world still having no access to safely managed sanitation, there remains a lot of work to be done. The hydraulic structures engineer will continue to play a key role in this context in collaboration with environmental and process engineers and scientists.

Transport, Recreation and Heritage

Most of the world’s most valuable transport systems are via the sea and inland waterways which will also be the case for the future[3]. Many of these transportation routes have been enabled by pioneering hydraulic designs (**Figure 3(e)**). An exemplary project is the Panama Canal that was constructed over 100 years ago. Over 1 million vessels have transited the canal since it opened. Economic dependence on such structures was ominously exhibited by the Suez Canal blockage accident in 2021, which had caused major disruption to global commerce. Hydraulic structures such as harbours, canals, bridges, locks, and waterway promenades also represent important historic areas of recreation and heritage amongst society where efforts for preservation must be incorporated in project development strategies. For example, Thames Tideway launched a heritage interpretation strategy ahead of construction of their £5 Bn super sewer, which set out the historic and cultural themes to inspire the design and delivery of the project to align with local recreation and heritage[10].

Technology, Research and Innovation

Technological advancement and innovation will continue to be important for the sustainable development of hydraulic structures. Some examples of impactful research include the use of Acoustic Doppler Current Profilers for determining the efficiency of sediment bypass tunnels, application of phase-detection intrusive instrumentation in full scale high Reynolds number flows[11], enhancements of 3D printing for rapid physical model development (**Figure 3(f)**[12]) and advancements in multiphase modelling for predicting behaviours of complex flows in hydraulic structures[13]. These strides in research are providing exciting opportunities in the development of hydraulic structures, yet field data is greatly needed in many applications including hydromachinery, treatment, sedimentology, nature-based solutions, and digitalisation of water management systems[14].

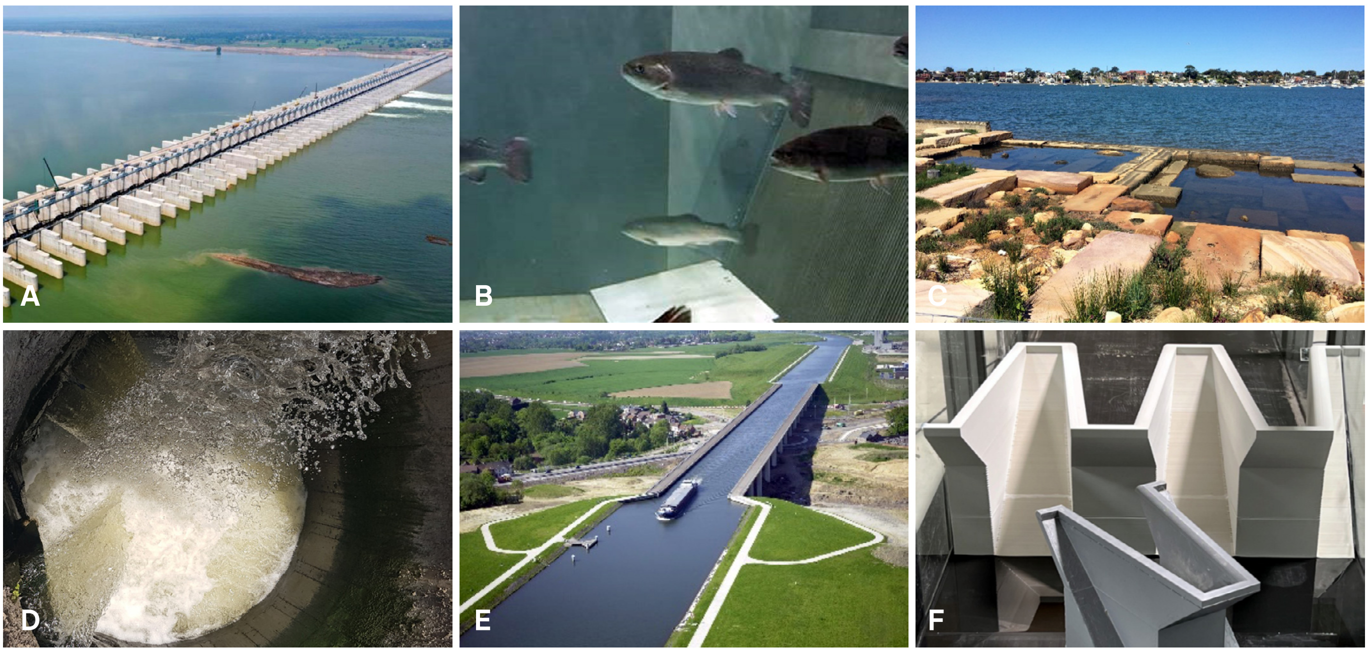

Figure 3 | The six thematic application areas of sustainable hydraulic structures engineering, by image example **(a)** Energy and Food–Kaleshwaram Lift Irrigation project (https://bhoopalapally.telangana.gov.in/), **(b)** Environmental Restoration and Protection–Fish bypass tunnel and rack physical model (photo courtesy of Elena Pummer), **(c)** Flood and Coastal Protection–Environmentally friendly seawall at Carss Bush Park, NSW, Australia (photo courtesy of James Carley, UNSW Water Research Laboratory), **(c)** Water Supply and Sanitation-Effluent discharge downstream of a sewerage treatment plant for water re-use purposes (photo courtesy of Sean Mulligan), **(e)** Transport and Recreation-Sart canal bridge in Belgium on the Center canal (photo MET-D.434) and **(f)** Technology Research and Innovation-3D printed physical models of non-linear weirs (photo courtesy of Mario Oertel).

There is a need for water engineers (practitioners and researchers) to be aware of how the SDGs relate to their work, to better progress and promote their activity[2]. The purpose of the discussion of the six thematic application areas is to raise awareness amongst the community about the role of hydraulic engineering in sustainable development. It is important to also note that each application area is not independent and overlaps broadly with other application areas. For example, environmental restoration and protection overlaps with impacts and objectives in dams, flood/coastal defence, sanitation etc., whereas technological development overlaps with all themes. However, it must be appreciated that elements of society, environment, and economy are present across all thematic areas with goals which can vary widely. Therefore, to enact strong sustainable development, these goals should be well understood to ensure that an inclusive and practical balance of the three pillars is maintained in future projects.

The success of the hydraulic structures field depends on a shared vision for sustainability where dissemination and knowledge sharing has been, and must continue to be, at the heart of the community's activity. For example, the International Junior Researcher and Engineer Workshop on Hydraulic Structures (IJREWHS) 2021 and the International Symposium on Hydraulic Structures (ISHS) held in Roorkee, India in 2022 brought together junior and senior hydraulic professionals from around the world to present and discuss research and projects, reflecting the ever-growing and diverse interest in the hydraulic structures engineering field. In addition, a working group in the EU COST Action has recently been founded to promote "Sustainable hydropower and its adaptation to climate change" (PEN@Hydropower) and a masterclass on hydraulic structures engineering will also be launched at the IAHR World Congress in Vienna in 2023.

However, key challenges still exist which should be continually addressed to accelerate progress. Some key examples are:

- There is a growing need for diverse, interdisciplinary partnerships in addressing the challenges, particularly those between policy makers, utilities/contractors, and academia.
- It is predicted that natural and climate related disasters will continue to rise. Given experience that spans hydrology, data analysis, fluid dynamics and construction, the hydraulics structures community have a lot to offer in advancing solutions to address these critical challenges in future years through adaptation, mitigation, and resiliency measures.
- The hydraulic structures community can advance its role further towards global decarbonisation efforts. For example, the remaining feasible hydropower projects can significantly replace electricity sourced from fossil fuels[2]. Such projects should however undergo a screening process to holistically assess and quantify impacts on the environment and society to determine if the benefits sufficiently outweigh any such negative impacts[1]. Energy efficiency of hydraulic infrastructure can provide a significant contribution also, along with integration of low carbon materials and construction methods in future developments.

It is not an over exaggeration to state that hydraulic structures will be fundamental in future development[3](e.g., water, energy, and food security). However, in many cases, there will still be inherent competing interests between societal, environmental, and economic goals. The future sustainability challenge will be for the community, comprising a host of multidisciplinary stakeholders, to fully appreciate these goals collectively on a project-by-project basis, in order to nurture a better balance between them, from policy development and design all the way to construction and long-term management.

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