Reservoirs are among the largest human interventions on earth. Worldwide the number of dams is staggering and still increasing. Approximately half of these dams create reservoirs for irrigation purposes, the other half have reservoirs for hydropower generation, flood control and water supply, either as single-purpose or in combination. With electricity and freshwater demand still growing, storage reservoirs are an indispensable component in the sustainable development of many countries.

At the same time dams pose vast challenges with respect to social and environmental impacts, optimization of reservoir operations and dam safety. Dams modify the river regime, change water quality, trap river sediment and create a barrier for migrating fish. Reservoir creation often involves resettlement and land clearance. Dams in transboundary rivers may stir legal and political sensitivities. Climate change causes rainfall patterns to shift, leading to seasonal increases or decreases in reservoir inflow. Hence, be it for existing reservoirs or proposed projects, such challenges ask for specialized knowledge and tools from a wide range of disciplines in support for making planning decisions as well as for real time operation rules.

Deltares’ unique hydrological, hydraulic, geotechnical and ecological expertise contributes to this much needed knowledge for reservoir planning and operation. Our specialized consultancy advice, applied research and integrated studies focus on:

- River basin planning and water resources distribution
- Environmental impacts and environmental flow assessments
- Sediment modelling and management
- Reservoir water quality modelling
- Hydraulic design of pipes, turbines and outlet structures
- Real time reservoir operations and optimization
were further processed in estimations of livelihoods impacts for different groups of people in the Delta, such as farmers, fishermen, and reed harvesters. In the Mekong Basin Development Plan project Deltares was involved in an analysis of the economic, environmental and social impacts of basin-wide water resources scenarios, including large dams.

Environmental impacts and environmental flow assessments
Reservoirs alter the natural variation in higher and lower discharges. Such flow regime changes will have an impact on the river, floodplain and estuary ecosystems. They may disturb typical riverine ecological processes such as spawning and migration of fish species. It is therefore important to study such possible adverse impacts and to take precautionary or mitigating measures. Deltares has gained much experience in assessing the impacts of flow regime changes as well as advising on flow regimes that are required to support ecosystems and ecosystem services in various projects.

Projects in Vietnam (Cumulative Impact Assessment of Small Hydropower Cascades, Figures 2 and 3) and in Southern Africa (Dam synchronization and Flood Releases project) focused on ecologically-relevant flow regime alterations due to river regulations. In the project ‘Integrated Water Resources Management in the Sistan Inland Delta, Iran’, an analysis was made of how upstream flow regulation and water use affected the condition of a downstream wetland. Results were further processed in estimations of livelihoods impacts for different groups of people in the Delta, such as farmers, fisheremen, and reed harvesters. In the Mekong Basin Development Plan project Deltares was involved in an analysis of the economic, environmental and social impacts of basin-wide water resources scenarios, including large dams.

Reservoir sedimentation
Most dams lead to a significant disturbance of the river sediment-balance, as an important part of the incoming sediments is trapped. Reservoir-sedimentation processes lead to loss of active storage, invoke damage to power stations and other facilities, and lead to upstream and downstream changes in morphology and bed composition of the river, as well as the coastal areas connected to the river mouth. Management of these issues requires sediment-management strategies that involve methods to displace deposits, or prevent deposition, such as flushing and dredging. Deltares has been extensively involved in both studies on local-scale processes (e.g. deltaic deposition, flushing), and on studies on system-wide impacts on sediment and morphology (e.g. cumulative impacts, downstream impacts).

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Downstream sediment transport
Deltares has been advisor to many projects that deal with predicting and mitigating the downstream impacts on sediment and morphology, such as the Nile River in Egypt and the Red River in Vietnam. These studies generally involve modelling of a full system (e.g. 1D models) with detail models for individual elements. An example is the study done by Deltares for the Colorado River in the Grand Canyon, USA. To arrest the loss of sand bars, the US Authorities have chosen to release periodically artificial high flows from Glen-Canyon dam. Deltares participated in survey and numerical modelling studies in a research cooperation with the USGS. The Delft3D model has been applied to simulate the detailed 3D hydrodynamic and morphological processes that were observed at an eddy-bar system during the 2008 artificial high flow (Figure 5).

Reservoir water quality modelling
Detailed 2 or 3-dimensional analysis of stratification processes, water quality processes (temperature, dissolved oxygen) and sedimentation.

Many freshwater reservoirs are eutrophic have poor water quality and ecological status, often associated with high external pollutant loads to the system. As a result, water managers today face a wide range of water quality issues such as prolific phytoplankton blooms, toxic cyanobacteria scums, poor water column transparency and anoxia, as well as bacterial pollution, elevated levels of harmful contaminants, excessive macrophyte growth and a loss of natural ecosystem functioning. Collectively, these problems reduce resource values and may lead to not meeting legislative requirements such as the European Water Framework Directive or other water quality standards or targets.

Resolving specific water quality issues as well as defining sustainable and long-term water quality management strategies to preserve, improve or restore lake water quality requires a comprehensive understanding of key underlying processes and system functioning at both the lake and catchment scale. The Deltares water quality modules in our software products (Delft3D, Sobek, Ribasim) are often very useful to assess the feasibility and effectiveness of various mitigation measures prior to implementation as this enables quantitative and predictive assessments in terms of water quality impacts and drivers.

Example:
Water quality modelling Marina Reservoir (Singapore)
Singapore, one of the most densely populated countries in the world, is heavily reliant on catchment rainwater runoff to generate drinking water supplies. The Marina Reservoir (Figure 6) has recently been created through the impoundment of Marina Bay in the heart of Singapore’s business district to increase water supply, as well as provide flood control and recreation. To determine the future water quality state of the Reservoir, provide insights into key water quality processes and steer management options, a fully integrated and comprehensive water quality modelling framework was applied. Storm water runoff, external pollution sources and river discharges in the Marina catchment were simulated using 1D-hydrological and water quality models while reservoir water quality, including nutrient and dissolved oxygen concentrations, phytoplankton biomass and species composition were simulated using coupled 3D hydrodynamic-water quality-ecological models (Figure 7). The complete modelling framework was further applied to assess the effectiveness of numerous catchment and in-lake mitigating scenarios to improve reservoir water quality with respect to recreational, drinking water and ecological targets.
Example: Operational water quality forecasting in Marina Reservoir (Singapore)

The management of multi-functional reservoirs can be highly challenging due to issues such as water quantity management, eutrophication, bacterial pollution and phytoplankton blooms, all of which may impact water supply, water quality and recreational and aesthetic values. Reservoir managers are often faced with having to make sudden and very rapid decisions on water level management and water quality mitigation strategies.

The Deltares Operational Management System (OMS) platform, based on the leading Delft-FEWS software, integrates real time monitoring data with hydrodynamic and water quality models to form a comprehensive operational framework for the real-time assessment of water quantity and water quality (Figure 8). The modelling component of the OMS resolves both rainwater runoff and pollutant loads from the upstream catchment as well as active flood control measures by the Marina Barrage and water quality control measures such as aeration. Forecasted meteorological data is continuously uploaded to the system and used as input for the automated modelling framework to make continuous predictions on future system state, thereby serving as an early warning system for water levels (flooding), water supply and a wide range of water quality issues for reservoir operators, scientists and policy makers. The OMS has been developed and tested for the Marina Reservoir and is further being extended to the Punggol and Serangoon Reservoirs in Singapore.

Real time reservoir operations and optimization

Delft-FEWS

Operational rules for reservoir management must be implemented in daily operations, by preference using up-to-date measurements and real time forecasts of weather and flow conditions. Deltares is worldwide leader in implementing operational forecasting systems for water systems using the Delft-FEWS software platform. Delft-FEWS can be combined with existing hydrological and hydraulic models to a decision support system for real-time control within operational water management.

Having included forecasts in operational management, the next stage of reservoir management is within reach: multi-purpose optimization of real time reservoir operations. Model predictive control (MPC) is a powerful method to support real-time operations. Different to the conventional control methods, where control decisions are based on the current system state, MPC predicts future state trajectories under the applied control operations. This makes it possible to anticipate on future events, for example approaching flood events or droughts. The control performance is represented by an optimization problem consisting of control objectives and constraints. It is solved with the help of mathematical optimization algorithms in such a way that all operational and physical constraints are met and an optimal result is achieved. This requires internal modelling of the controlled water system for assessing and optimizing the impact of control actions on the system and its control performance. Control targets can be assigned with different weighting factors, which make MPC very suitable for reservoir operations with conflicting usages.

The model predictive control method used in the real-time control platform RTC-Tools supports both conventional control methods and model predictive control. For the latter method RTC-Tools includes a variety of water resources models such as a mixed kinematic-diffusive wave routing approach and as a reservoir model. The reservoir model accounted for the reservoir-related processes, including power generation (Figure 9).
Hydraulic design of pipes, turbines and outlet structures

Pump stations and waterpower stations have to produce adequate quantities of fluid or the predicted amount of energy. The critical issues for designers are control of the water flows in the structures, and shaping the water flows as they enter the systems. Deltares predicts hydraulic patterns and stability issues in all possible circumstances.

Our clients are plant or station owners with plans to build new stations or adapt existing ones. Problem-free operation is the simple goal, demanding complex models and sophisticated testing. The efficiency of hydraulic machines (pumps and turbines) depends on the design of the pump sump or the smoothness of the flow onto a turbine. Small modifications (during maintenance and so on) can push systems to the critical limit. Swirling flows must be avoided at all means. Sediment transport through the machines must be prevented if impellers or blades are not designed to cope.

Despite the possibilities afforded by computers, experience demonstrates that physical testing is still needed. Deltares partners engineers throughout all project phases, from the first designs to testing, training, and actual operations.

WANDA 4 Turbine component

WANDA is a powerful and user-friendly program for the hydraulic design and optimization of pipeline systems. Both engineers and operators use WANDA to study the steady and dynamic behaviour of liquid, heat, gas and slurry flows in arbitrarily configured pipeline networks. The software can be easily linked to other applications, e.g. for operator training systems or advanced real-time control. WANDA has been extensively tested, validated and designed for engineers by engineers.

Wanda 4 features a new turbine component for modelling hydropower systems. This new component models the dynamic behaviour of a reaction-type turbine for variations in blade angle, wicket gate position, electric power and flow. This new functionality enables engineers to solve new hydropower problems, such as load acceptance and load rejection scenarios.

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