Article, Published Version

Falconer, Roger; Sutherland, James

Cardiff Bay: a coastal reservoir for urban regeneration

Hydrolink

CARDIFF BAY: A COASTAL RESERVOIR FOR URBAN REGENERATION

BY ROGER FALCONER & JAMES SUTHERLAND

The world faces considerable water management challenges now and increasingly in the future; primarily brought about by: the predicted impacts of climate change, the increasing need to provide more water, food and energy for a growing global population, and increasing globalisation - leading to a wider global wealth distribution and a corresponding increase in demand for water, associated with the need for more commodities (such as cars, clothes) etc. In addition, in most countries world-wide there is an increasing population shift away from rural communities to larger urban cities, where there are better employment prospects, and with these cities often being located near the coast.

However, coastal cities are frequently vulnerable to limited access to adequate water resources, poor water sanitation, coastal and estuarine flooding, sea level rise, increased energy demands etc. It is therefore timely that we look to the future to address some of these challenges in a sustainable manner and working with nature to develop coastal reservoirs to contribute to the solution of some of these challenges.

Coastal reservoirs have recently been primarily considered as a means of providing a cost effective solution for storing freshwater towards the end of a river basin, enabling the freshwater to be treated and distributed around the city at a lower cost than such alternatives as building high head reservoirs, upstream along the river basin, and then having to pump the treated water to the city for distribution. The water level can also be controlled in coastal reservoirs, thereby also offering opportunities to reduce flood risk from the sea locally and abstract more water during river floods, thereby lowering upstream water elevations, and hence reducing city flood risk. Furthermore, by taking water from the estuary at the end of the river basin, rather than from an impounded reservoir some distance upstream, then the river flow is not reduced disproportionately during drought conditions and the river ecosystem is less affected by water abstractions.

Coastal reservoirs can also be developed to provide other opportunities for urban regeneration and potentially renewable tidal energy. An excellent example of a coastal reservoir built for urban regeneration is that provided through the Cardiff Bay Barrage project, opened in 1999, to reconnect Wales' capital city of Cardiff with its waterfront. In the period mid-1800s to 1920 the Port of Cardiff grew considerably, with significant investment and expansion leading to the port reaching its full potential by about 1920 (see Figure 1), and with the port then being ranked as one of the largest in the world, shipping coal and iron-ore globally [1]. From the 1920s onwards the port went into decline; there was a major loss of trade to other ports world-wide, as the ships became larger and with the increasing challenges associated with the Bristol Channel and Severn Estuary having the second largest tidal range in the world.

In 1987 the UK government set up the Cardiff Bay Development Corporation with a brief to regenerate Cardiff Bay and reconnect the city of Cardiff to its waterfront. The Corporation prepared a strategy for regenerating the area with the aim of creating 30,000 new jobs, 840,000 m2 of industrial development and commercial premises and 6,000 new homes. The strategy was underpinned with a tourism potential of bringing 2 million visitors annually to Cardiff's waterfront [2]. However, the major problem with Cardiff's existing waterfront at that time was that Cardiff Bay was sited along the Bristol Channel, which experiences the second highest tidal range in the world, with spring tidal ranges being typically 14 m. At low tide Cardiff Bay was virtually dry and the Bay exposed mud-flats for typically 12 h per day. In overcoming the challenge of developing a water-front in such conditions, it was decided to construct a 1.4 km long tidal exclusion barrage across the mouth of the Bay, impounding the rivers Taff and Ely and creating a 200 ha fresh water lake, with a constant water level.

In 1987 initial legislation was commenced alongside feasibility studies, led by Wallace Evans and Partners. From 1987 to 1988 HR Wallingford undertook hydraulic feasibility studies covering flows, waves, flow routing, morphology and water quality [3].
HR Wallingford's 500 m grid numerical flow

Figure 1. Illustration of Cardiff Port taken in its heyday around 1900

Figure 2. Physical model at HR Wallingford with Gibb design

model of the Severn Estuary was used to provide boundary conditions for a new 90 m grid TIDEFLOW-2D depth-averaged flow model. TIDEFLOW-2D is part of the of the TIDEWAY modelling system developed at HR Wallingford. This extended 16 km alongshore and 7 km offshore [3] including the barrage and showed that the effects of the barrage were confined to an area close to the barrage. As expected, flows in front of the barrage (including the approach channel to Queen Alexandra Dock) were reduced, while flows were increased on the Penarth shoreline (to the south of the barrage). A physical model was constructed to scales of 1:250 (horizontal) and 1:100 (vertical) and had a pneumatic tidal generator driven by water levels from the 90 m grid TIDEFLOW-2D model. This was used to study the conditions prior to and after construction and sedimentation [4]. It was viewed by many interested parties.

Numerical models were used to look at wave disturbance in the approach channel to Queen Alexandra dock and raised concerns that were addressed in design studies. Water routeing studies looked at different combinations of river flows, tidal levels and sluice operations on water levels within the barrage, while the morphology study looked at how the bed of the rivers Taff and Ely, would change. Water quality in the barrage was examined using a 1-D model in the Ely, and a combination of a TIDEWAY-3D flow model, a water quality model and a primary production model within the impoundment. These studies also revealed some concerns.

Sir Alexander Gibb and Partners began detailed design in 1989 and in 1990 HR Wallingford was commissioned to undertake the hydraulic studies of a revised design that included a single set of sluices and a harbour of refuge outside the lock gates. This work included siltation, navigation studies, morphological change (including the effects of extreme flows through the single set of sluices) tests on the wave screens used at the harbour of refuge, flow routing, water quality and studies on providing an alternative feeding ground for birds [3].

The 1:250 scale physical model was recommissioned and modified to include the Gibb design (Figure 2) for use in siltation and navigation studies. A 1:50 scale model of the harbour of refuge was constructed to test wave disturbance, while a 1:16 model of the cross-section of the barrage was tested in a flume. Flume tests were also used to minimise the reflection coefficients from the wave screens, used to form the breakwater of the harbour of refuge. An innovative approach to joint probability was adopted for the assessment of flood risk [5]. Studies were substantially complete in 1992, by which time five physical models and thirty numerical models had been used. At the peak of activity 30 research staff were involved simultaneously on the design studies.

Figure 3. Cardiff Bay (taken 2008): a coastal reservoir and urban regeneration project

In 1993 the Cardiff Bay Barrage Act was passed through parliament and given Royal Assent. The act required that dissolved oxygen levels within the Bay were at least 5 mg/l at all times for the benefit of migratory fish. In addressing this requirement a system of aerators was installed across the Bay, with the aerators injecting air into the water body, rather than oxygen, and being designed to operate continuously during the period March until September each year. The barrage was designed and constructed to include: an 800 m long embankment wall with a 25 m crest, a fish pass allowing for the passage of migratory fish and with a design flow of 10 m^3/s, five sluice gates, each 9 m wide and 7.5 m high, with the total capacity of the sluices being 2300 m^3/s and three locks provided for small craft access between the Bay and the outer estuary. The Barrage was completed in 2001, with regeneration of the region now virtually complete (see Figure 3).

In addition to the barrage and lock gate structures etc, the impoundment of the two rivers and the change of the Bay from an estuary, with extensive flooding and drying, to a freshwater reservoir would have major impacts on the hydro-environmental characteristics and water management issues upstream of the barrage. In particular, and following impoundment, the main water quality issues needing to be addressed were as follows:

- the Bay now experienced long retention times, whereas previously the estuary was well flushed with substantial tidal variations, particularly during spring tides;
- several combined sewer overflows (CSOs) discharged directly into the watercourses under wet weather flow conditions, thereby leading to effluent discharges reaching the Bay;
- nutrient and pathogenic diffuse source inputs were expected from agricultural runoff etc, particularly via the River Ely, which primarily drained agricultural land; and
- low dissolved oxygen levels were expected in the lower layers of the water column of the Bay, particularly during summer months, leading to potential stratification and interaction with the contaminated sediments.

As a result of some of these concerns the Hydro-environmental Research Centre (HRC) at Cardiff University undertook a number of research studies to refine and apply an integrated modelling tool for water quality management of the Bay. The project strategy consisted of integrating a CSO model (namely

SWMM), with a 1-D river model (namely FASTER) and a 3-D hydro-environmental numerical model (namely TRIVAST). The latter two models were developed by the Hydro-environmental Research Center (HRC) at Cardiff (HRC), whereas the model SWMM is a stormwater rainfall-runoff model developed by the U.S. Environmental Protection Agency. An example of such a research study involved investigating the impact of a barrage and the creation of a freshwater coastal reservoir on the Faecal Indicator Organism (FIO) levels in the Bay, before and after construction of the barrage. The numerical modelling studies were complemented with an extensive field monitoring programme to establish more precise values for the kinetic decay rates in the Bay, for various meteorological conditions (such as different sunlight intensities), thereby providing improved predictions of FIO levels across the Bay. A scaled hydraulic laboratory model study was also constructed of Cardiff Bay Barrage for: numerical model validation, retention time predictions and estimating scaled dispersion values within the basin (see Figure 4).

The numerical model was set up (in 1998) for the Bay and riverine inputs, using a regular grid of 50 m grid cells, and with the downstream boundary being governed by the barrage and its operating conditions. The 3-D model had 10 vertical layers, each of height 1.25 m. Simulations were first undertaken to predict the movement of an arbitrary spillage of a conservative tracer with zero decay into the rivers Taff and Ely. The corresponding predictions were compared to the results obtained from the scaled physical model results, with good agreement being obtained between both sets of results [6]. The model was then set up to study the impact of episodic inputs into the rivers and for a range of wind and riverine flow conditions. Some of these predictions were compared with the field data, with the corresponding comparisons for different boundary conditions enabling a comprehensive set of conclusions to be drawn to indicate water management strategies for the coastal reservoir and the river basins.

As part of this research study, simulations were also undertaken to investigate the impact of using dynamically varying decay rates for predicting the FIO levels in the receiving coastal reservoir. In particular, comparisons were undertaken for a range of variables and the results showed that the FIO levels in the Bay were highly dependent upon the key variables of sunlight intensity and darkness and daylight conditions. The model was first run for hypothetical spillages into the rivers and for a constant decay rate (T90), both for day- and night-time conditions. The model was then re-run for dynamic day- and night-time decay rates, ranging from 10 h to 100 h respectively and based on field data and genetic algorithm based equations (see Figure 5). The difference in the predictions was significant and indicated that, for this freshwater reservoir, night-time spillages during the autumn and winter months led to reduced FIO levels in the Bay, in comparison with corresponding spillages occurring during the notional 12 h day-time period. Further field measurements and model predictions were undertaken, with the die-off being related to sunlight intensity, temperature and irradiance.

In conclusion, the creation of a coastal reservoir in the form of Cardiff Bay has been a considerable success in terms of re-uniting the City of Cardiff with its waterfront. The bay region has met and surpassed most of its urban regeneration targets and has rejuvenated an area of Cardiff City that had gone into decline since the loss of the coal and port industries to deeper ports around the UK. An evaluation of the regeneration of the Bay published in 2004 concluded that the project had "reinforced the competitive position of Cardiff" and "contributed to a massive improvement in the quality of the built environment". Brief details are herein given of the project background and design, and an example is cited of part of a major research study to investigate the change in the faecal indicator levels, both before and after construction of the barrage. This study showed that coastal reservoirs can provide significant urban regeneration and recreational opportunities, as well as freshwater supplies for coastal cities. ■

References:

[1] http://www.cardiffbay.co.uk/history/
[2] Crompton, D. (2002) Cardiff Bay Barrage. Proc Water and Maritime Engineering, 154 (2) 81-88.
[3] Burt, N. (2002) Cardiff Bay Barrage: overview of hydraulic studies. Proc Water and Maritime Engineering, 154 (2) 93-102.
[4] Burt N. and Littlewood, M. (2002) Cardiff Bay Barrage: sedimentation aspects. Proc Water and Maritime Engineering, 154 (2) 103-107.
[5] Samuels, P. and Burt, N. (2002) A new joint probability appraisal of flood risk. Proc. Water and Maritime Engineering, 154 (2) 109-115.
[6] Harris, E., Falconer, R.A., Key, D. and Stapleton, C. (2002). Development of a modelling tool to quantify faecal indicator levels in Cardiff Bay. Proc Water and Maritime Engineering, 154 (2) 129-135.

Roger A. Falconer is Professor of Water Management (P/T), in the School of Engineering, at Cardiff University and an Independent Water Consultant. He has managed a wide range of research projects on hydro-environmental modelling and has been involved in over 100 EIA worldwide. He is a Fellow of the Royal Academy of Engineering, Hon. Member and Past-President of IAHR and currently Vice President of the International Association for Coastal Reservoir Research. He regularly lectures and advises on a wide range of topics, including: flood and health risk management, tidal renewable energy, coastal reservoirs and global water security.

James Sutherland is a Technical Director in the Coasts and Oceans group at HR Wallingford. He is an internationally known specialist in coastal & marine processes with 25 years' post-doctoral experience of working and publishing on coastal management projects. His areas of expertise include sediment transport, scour around structures, coastal erosion, beach management and wave forces on maritime structures.

Figure 4. Cardiff Bay physical model as sited in the tidal basin at Cardiff University

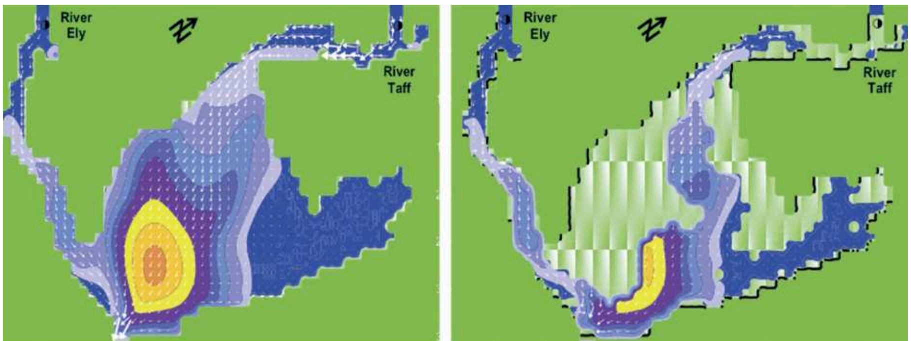

Figure 5. TRIVAST predictions of surface and third layer FIO concentration distributions for an arbitrary input into the rivers