The new Lee Valley White Water Centre is the host venue for the London 2012 Olympic Games canoe and kayak slalom events. The £32 million facility was completed in December 2010, 18 months before the games, and is now open to the public. This paper explains how computational and physical hydraulic modelling validated the design and successfully mitigated design risk. Moveable obstacles were used within a fixed channel geometry to create flow constriction points and fine-tune white-water features, while the addition of a separate channel and highly efficient pumping system helps to minimise energy demand while achieving a world-class white-water course.
competition venues (ICF, 2002). These criteria, shown in Table 1, define certain course specifications for world-class competition and training.

The client design team consisted of a landscape architect, building architect, multi-disciplinary engineers and a white water park specialist. The design was advanced to completion of Royal Institute of British Architects (RIBA) Plan of work stage D (RIBA, 2007), with the early engagement of ICF by the client design team during the concept design stage. From the stage D design, a detailed performance specification was developed.

Planning approval was obtained in October 2008 and ODA chose to award the work as a single package using the NEC3 Engineering and Construction Contract (ECC) option A (priced contract with activity schedule), with the scope being defined on a RIBA stage D design, using the ‘accelerated restricted’ procedure set out within the UK Public Contract Regulations 2006 (HMG, 2006). Supply chain analysis had suggested that economic conditions had created a high level of interest and competition from tier 1 main contractors for work on the London 2012 programme, with contractors showing a willingness to agree to manage more commercial risk and technical performance criteria.

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The contract options offered by NEC3 allow selection of the most appropriate risk profile balancing time, cost and quality. In this case, ECC option A was the preferred form as the design of the assets was well-defined at tender stage, thus avoiding excessive risk premiums. Option A provides cost certainty while facilitating the same transparent administration of contract change found within the target contract options C and D. The stage D design was included within the contract as a ‘compliant’ design which the contractor adopted and developed into a detailed design for construction.

After the contract award, the design management, engineering and white-water disciplines of the client design team were retained to act as ODA’s external technical reviewers, responsible for reviewing the contractor’s design and construction proposals for compliance with the works information.

Each new Olympic white-water course comes with the challenge of achieving the sport standard for suitable difficulty and character of white water, and therefore requires ICF approval and sign-off. A design compliant with the performance specification was the successful contractor’s responsibility. Under the contract, the courses had to be complete and operational 3 months in advance of overall completion to allow adequate time for course calibration and to facilitate ICF approval and sign-off. In addition, the contractor had to provide three tranches of design information – for course channel, obstacles and masts/gates – for ICF approval 3 months before construction of these elements started.

After completion, Lee Valley Regional Park Authority is responsible for the operation of the venue during the pre-games period, providing more opportunity for further fine-tuning of the white water in the channel while it is in use.

3. Planning and design

The main elements of the project were established during the feasibility and conceptual design stages as

- a 300 m long Olympic course on an engineered-fill embankment 2–6 m high
- Olympic course pumping station and start pool
- a 160 m long intermediate course on an artificial engineered-fill embankment, about 2 m high
- intermediate course pumping station and start pool
- combined finish pools and water supply lake holding around 24,000 m³
- boat conveyors to take rafts, canoes and kayaks and their occupants from the finish pool to the start pools
- facilities building
- access road and car parking facilities
- landscaped embankments comprising engineered fill.

The landscape masterplan developed the vision of creating a ‘hybrid landscape’ which fully integrated the engineered sporting requirements the Olympic venue and legacy function, while strengthening the existing park’s ecology and range of landscape experiences. The new landscape encourages activities and interactions beyond the narrow functionality of a canoe course, welcoming elite canoeists, recreational rafters and general park users alike. The challenge of creating a ‘mountain stream on a flat plain’ was central to the design (Figure 1).
The facilities building for the development was integrated into the landscape and the course and is partly embedded to reduce the visual impact (Figure 2). At the lower level, the mass of the building is slid partly beneath the start pool with the principal elevation facing the lake; this level contains the functional aspect of the support facilities. At the upper level, the terrace faces the start pool and gives views over the whole development (Figure 3).

4. Earthworks strategy

The land selected for the Lee Valley White Water Centre development was that of a former landfill site with contaminated ground and groundwater. The strategy adopted was to build above the landfill by importing material to site, minimising the need for treatment and disposal of the underlying material. Detailed groundwater modelling and a quantitative risk assessment were carried out to demonstrate there would be no detrimental effects to the shallow groundwater flow regime and water quality in adjacent surface waters respectively, confirming this was a sustainable approach.

Due to the unpredictable nature of the landfill, the main structures with relatively small footprint areas were piled while the course was constructed on embankments. The concept was to surcharge the landfill by building additional height to the channel embankments, and then removing this when the rate of consolidation settlement had reduced to an acceptable limit (Figure 4). The predictions for the settlement magnitude and consolidation time using traditional geotechnical methods were shown to give a good prediction of the actual settlement recorded during construction.

5. Water supply and quality

The water supply for the course was an essential element of the development. Initial ideas for the water supply included excavating into the ground and forming a lake in the shallow groundwater. However, this option was discounted due to the contamination within the landfill. A self-contained lined lake was selected as the preferred solution with losses replenished from a major aquifer deep below the site, due to restrictions on river abstraction.

To secure the borehole water supply, analysis was carried out to

A self-contained lined lake was selected as the preferred solution with losses replenished from a major aquifer deep below the site.
establish the likely yield and the zone of influence of the aquifer abstraction. Following confirmation that the supply was viable, full-scale field trials, using a production-size well, were carried out. These were in accordance with the Environment Agency’s requirements to assess the yield accurately and to confirm no detrimental effects to existing abstractions, including a major seasonal abstraction for the north London recharge scheme.

The concept for the white-water courses, with two independent channels and a dedicated man-made water supply lake, made the development unique. It led to a challenge in that when the pumps are switched on, thousands of cubic metres of water are taken from the lake as the course fills and this causes the lake level to drop. With a single course, a large drop in water can be acceptable so long as the correct lake level was achieved when in operation. The complexity of the two-course solution was that, depending on whether the courses are operated alone or together, the drop in the lake water level varies, thus affecting the head available on the course and, in particular, the hydraulic features at the downstream end of the course. The lake surface area was therefore dictated by an acceptable drop in water level should the courses be operated alone or together, while working within the site boundary constraints. When both courses are operated together, the water level drops around 0·4 m and an additional good hydraulic feature arises at the bottom of the intermediate course. The level drop for the various course operation scenarios was confirmed at the detailed design stage using two-dimensional (2D) computer hydraulic modelling.

Having a self-contained lake gave the opportunity to control water quality. A water treatment system was incorporated allowing an exceptionally high standard for water quality with criteria based on World Health Organization guidelines (WHO, 2003) and UK Water Supply Regulations (HMG, 2000). A risk-based approach was adopted in setting the standards, particularly in relation to the UK regulations, based on likely exposure to the water. To minimise treatment requirements, several steps were taken to limit the pollution in the lake, such as sides sloping away from the lake edge to prevent contaminants and nutrients washing in, and avoiding shallow margins and providing near-vertical edges to discourage wildfowl.

Submersible axial-flow pumps, which are ideal for high-flow and low-head situations, were selected for the courses. These had been used on the previous three Olympics and were therefore a low-risk strategy. However, they are the most sensitive to flow conditions at the inlet which, ideally, should be uniform, steady and without swirl, vortices or entrained air. It was therefore essential to get good flow conditions from the end of the courses into the pumping station forebays.

At the conceptual design stage, three-dimensional computational fluid dynamic modelling was used to establish the relationship between the end of the courses and the pumping station intakes. At the detailed design stage, the layout was confirmed using the 2D hydraulic modelling (Figure 5) combined with a 1:20 scale physical model of the pumping stations.

6. Course design principles

The overall performance characteristics of existing white-water venues were used to inform the selection of appropriate head (difference between the level at the top and bottom of the course) and flow parameters for the Lee Valley White Water Centre (Table 2). A configuration for the Olympic channel of 300 m length, two major drops, a flow variable up to 15 m$^3$/s, a head of 5·5 m and a generally trapezoidal cross-section with an average 10 m width at the base was taken forward into detailed design.

A separate training or ‘intermediate’ channel to fulfil the athlete warm-up and training functions in Olympic mode, as well as much of the legacy objectives, was decided upon. This was to be 160 m long, have a flow of 10·5 m$^3$/s and a head of 1·6 m, with a width averaging 7 m at the base.

The concept of two separate courses, each with its own dedicated, stand-alone pumping station, was taken forward to

![Figure 5. Two-dimensional hydraulic modelling was used to ensure good flow conditions between the end of each course and the submersible axial-flow pumping stations](image-url)

<table>
<thead>
<tr>
<th>Olympic channel</th>
<th>Year</th>
<th>Flow: m$^3$/s</th>
<th>Duty pumps: no.</th>
<th>Average gradient: %</th>
<th>Drop: m</th>
<th>Length: m</th>
<th>Width: m</th>
</tr>
</thead>
<tbody>
<tr>
<td>International Canoe Federation requirement</td>
<td>2002</td>
<td>8–18</td>
<td>n/a</td>
<td>n/a</td>
<td>5–8</td>
<td>250–400</td>
<td>&gt;8</td>
</tr>
<tr>
<td>Lee Valley White Water Centre</td>
<td>2012</td>
<td>15</td>
<td>4</td>
<td>1·8</td>
<td>5·5</td>
<td>300</td>
<td>10</td>
</tr>
<tr>
<td>Beijing</td>
<td>2008</td>
<td>17·5</td>
<td>4</td>
<td>2·1</td>
<td>6·0</td>
<td>280</td>
<td>&lt;9</td>
</tr>
<tr>
<td>Athens</td>
<td>2004</td>
<td>17</td>
<td>5</td>
<td>2·2</td>
<td>6·2</td>
<td>270</td>
<td>10–12</td>
</tr>
<tr>
<td>Sydney</td>
<td>2000</td>
<td>14</td>
<td>5</td>
<td>1·7</td>
<td>5·5</td>
<td>320</td>
<td>8–14</td>
</tr>
<tr>
<td>Ocoee</td>
<td>1996</td>
<td>30–40</td>
<td>n/a</td>
<td>1·6</td>
<td>8·2</td>
<td>520</td>
<td>10–30</td>
</tr>
<tr>
<td>Seu d’Urgell</td>
<td>1992</td>
<td>10</td>
<td>n/a</td>
<td>1·9</td>
<td>6·5</td>
<td>340</td>
<td>5–17</td>
</tr>
<tr>
<td>Augsburg</td>
<td>1972</td>
<td>10–14</td>
<td>n/a</td>
<td>1·1</td>
<td>3·2</td>
<td>305</td>
<td>7–9</td>
</tr>
</tbody>
</table>

Table 2. Technical specifications for Olympic canoe/kayak slalom courses
improve functionality during the games and to enable the operator independently to manage flows relative to the programme and ability of users in legacy (Figure 6). The location of training environments within the venue also allows athletes to warm-up on either the lake or the training course, away from media and spectators.

A review of shapes of other contemporary courses, including those used at the last three Olympics, found that all have limitations. In Sydney in 2000, for example, the horseshoe shape provided an excellent platform for the sport, but visibility was compromised at the start and the finish of the course due to the linear distance from most of the viewing stands (Figure 7(a)). This excessive viewing distance from start and finish occurs in the Beijing 2008 design as well, along with the added viewing obstruction created by the high mound in the course infield (Figure 7(b)). In Athens in 2004, the course was in a circular shape, with a much tighter turning radius. Here the issues were restricted visibility at the top of the course and water continually being pushed to the outside of the turn, which can be problematic for course tuning (Figure 7(c)).

Different approaches to the ICF warm-up course provision had previously been taken, with some being in series, resulting in a single pumping station that needs to lift water the full height of the combined Olympic and training course head at all times, and some being in parallel and requiring additional pumping capacity.

The flattened C-shaped channel layout adopted for the Lee Valley Olympic course allows the closest and best possible viewing experience for spectators. It also provides a more consistent white-water experience for athletes, as it establishes the greatest possible length of straight-flowing water, while also keeping the finish of the course close to the start-pool conveyor.

7. Energy efficiency

ODA’s priority themes of sustainability and legacy were key design drivers to give the venue the best opportunity for long-term operational success. Pumped slalom courses are one of the most intensive consumers of energy per user of any facility for an Olympic event. From a sustainability standpoint, the high electricity component gives rise to a large carbon dioxide footprint, and from a legacy commercial viability standpoint, it forms a significant element of legacy running cost.

Minimising the energy demand of the venue was the obvious place to start, and this was achieved at concept design stage by addressing the course in use. The energy demands of the facilities building, although a small fraction of the course, were reduced by incorporating solar hot water, reverse-cycle ground-source heat pumps (using the lake) and natural ventilation.

Three specific areas were targeted for reducing the energy requirements of the course in use.

Figure 6. Aerial view showing the two separate pumping stations under construction (with light blue risers) adjacent to the facilities building

Figure 7. The venue layout aims to minimise the limitations experienced on the Olympic white-water courses in Sydney (a), Beijing (b) and Athens (c)
Separating the Olympic and warm-up/intermediate channels. The intermediate channel has an energy consumption 80% less than the Olympic channel. Hence in legacy mode, large energy savings can be made in the careful balance of usage so that the Olympic channel only runs during periods of specific elite-squad training needs or where large numbers of recreational users can commercially justify its use.

In comparison with the past two Olympics, significant reductions were made on flow rates and head for the pumping station, while continuing to ensure an Olympic-standard course and legacy requirements.

Minimising energy losses in the pumping system by using separate pumping stations so that pump duties are specific to the course, submerged outlets so water is not lifted higher than necessary and detailed specification and analysis of pipeline fittings to limit head loss.

8. Channel design and modelling

In contemporary Olympic canoe slalom venues, a combination of channel geometry and an adjustable obstacle system are used to create flow constriction points and adjacent white-water features.

At the time of completion of stage D design, the most likely commercially available option for providing the moveable obstacles necessary for fine-tuning the hydraulic features required for Olympic mode was a plastic movable system with accompanying pegboard-style base plates, as is used in Penrith and Athens. A similar system was utilised for the slalom events for the 2008 Beijing games but was not offered commercially.

The adjustable obstacle systems are typically used in conjunction with fixed gnyenes to provide a solid infill component between the tapered wall of the trapezoidal-shaped channel and the obstacles. They require specific detailing for proper function and safety, and to allow water to flow through or around them.

The obstacles are attached to the channel floors in such a manner that allows them to be moved to another position if needed. The advantage of this type of system is the ease with which adjustments can be made and that flexible fine-tuning of course hydraulics can be accomplished post-construction. The components are lightweight and fully modular, allowing for very subtle modifications to be made.

An output specification was included within the tender documentation with the aim of detailing system performance requirements in such a way so as not to favour any one supplier, as well as allowing the contractor flexibility to carry out any new product design development thought necessary in this respect.

In response to the output specification requirements for obstacles, the contractor chose to develop a new movable-plastic-block-based obstacle system (Figure 8). Anchors reach through the blocks and are attached to a track in the block beneath or into the embedded track in the channel base, each stack of blocks being effectively prestressed back to the concrete base. Lids cover the block anchorage mechanism and provide the ability for pedestrian access on the top of the obstacles. Security-headed bolts can be used to retain the lids. The modular nature of the blocks allows an additional wedge (groyne) to be moulded and then fixed into position against a regularly graded trapezoidal channel side.

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The contractor sought further to validate the compliant design through use of an additional 1:10 scaled physical hydraulic model. This was constructed and calibrated to the course layout to gain confidence that the specified white-water performance requirements could be achieved and to evaluate the performance of the obstacle system (Figure 9).

The Olympic and intermediate channel physical models replicated, at a 1:10 scale, approximately 300 m and 150 m respectively of channel in addition to the top pools and a portion of the bottom pool. Flows entered the top pools by way of scaled pipe sections, mimicking the flows coming from the pumping stations. An adjustable flap gate was used to adjust the tail water elevation.

Analysis of the model highlighted that the performance requirements of the stage D channel design were achievable. Additionally, considerations specific to water depths, velocities and stability were addressed through experimenting with different adjustable obstacle placements and configurations in the model. An initial obstacle layout was then established as a starting point for course commissioning.

9. Course commissioning

The course commissioning and tuning process was accomplished in four steps.
Configure the completed channels with the initial adjustable obstacle configuration established through the 1:10 scale modelling.

Perform initial tuning utilising the expertise of Locog Sport and British Canoe Union (BCU) representatives to make necessary obstacle configuration changes to develop white-water performance.

Tune and configure the channels with the ICF representative in attendance to ensure a configuration that was in the spirit of, and met the requirements of, ICF.

Complete commissioning to meet the all performance specifications, while maintaining priorities listed by the ICF representative.

On completion of commissioning, the courses delivered consistent white water that met the brief requirements and the expectations of the ICF (Figure 10).

10. Cost and programme

The out-turn cost of the project was £32 million, £1 million more than the business case budget. Of this, £10 million was from third-party funding by Sport England, East of England Development Agency and Lee Valley Regional Park Authority.

Work started on site in May 2009 and the project was handed over on schedule in December 2010. Key project milestones are shown in Table 3.

Figure 10. After various fine-tuning operations, the completed Olympic channel met all white-water performance specifications

<table>
<thead>
<tr>
<th>Key milestones</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning consent received</td>
<td>30 September 2008</td>
</tr>
<tr>
<td>Contract award</td>
<td>09 March 2009</td>
</tr>
<tr>
<td>Start on site</td>
<td>06 May 2009</td>
</tr>
<tr>
<td>White-water development phase 1 – construction of channels design</td>
<td>19 August 2009</td>
</tr>
<tr>
<td>White-water development phase 2 – installation of tuning system</td>
<td>06 October 2009</td>
</tr>
<tr>
<td>White-water development phase 3 – installation of gate suspension</td>
<td>22 October 2009</td>
</tr>
<tr>
<td>Construction of intermediate course complete</td>
<td>14 July 2010</td>
</tr>
<tr>
<td>Lake construction and fill complete</td>
<td>21 July 2010</td>
</tr>
<tr>
<td>Power up Olympic course for Midland Canoe Club</td>
<td>21 July 2010</td>
</tr>
<tr>
<td>Access for course commissioning</td>
<td>22 July 2010</td>
</tr>
<tr>
<td>Completion date/contractual handover</td>
<td>17 December 2010</td>
</tr>
</tbody>
</table>

Table 3. Key programme dates
11. Lessons learned

Lessons learned that future projects of a similar nature could benefit from, include the following.

- Team membership – ensure appropriate experience and expertise is present in all elements of the project team throughout the project life cycle.
- Past successes – thoroughly review existing facilities developed for the same function and draw from their most successful elements. Take advantage of opportunities to confirm new designs by examining similar parameters already being demonstrated in existing, full-scale contexts.
- Modelling – utilise a range of modelling exercises to validate design assumptions and technical profiles needed for targeted hydraulic function, with the understanding that, while computational and scaled modelling can approximate full-scale conditions, a functionally adjustable tuning system as an integral part of the design allows for in situ white-water modifications and ensures required performance specifications are achieved.
- Innovation – encourage innovation through the wording of contract technical requirements that specify performance outputs rather than limiting to traditional solutions. Allow time in the programme for the development, assessment, testing and acceptance of new products.
- Risk mitigation – develop an appropriate risk mitigation strategy when designing a unique facility requiring third-party sign-off. Implement a programme of engagement, staged design submissions and sign-offs prior to construction of each element.

12. Conclusion

Construction of the Lee Valley White Water Centre was completed in December 2010, some 18 months before the 2012 Olympic Games (Figure 11). Prior to its completion, the course was tuned to deliver Olympic-standard white water to the satisfaction of the International Canoe Federation. It is now handed over to its legacy owner and operator Lee Valley Regional Park Authority.

The venue is innovative and designed to meet the project-specific requirements of the Lee Valley White Water Centre for its games and legacy use. Items not needed for legacy are to be provided as overlay by Locog.

Many engineering challenges were encountered and overcome, such as the simple surcharge approach for the landfill consolidation and the provision of a water supply lake fed from the groundwater. Computational and physical hydraulic modelling validated the design and successfully mitigated design risk.

Minimising the energy demand of the venue in use and adding legacy value was achieved through the provision of a separate intermediate channel in parallel with the Olympic channel, to enable the operator independently to manage flows relative to the programme and ability of users; minimising flow rates and head for the course while achieving world-class white water; and design of an efficient pumping system.

Delivery of the project was greatly aided by the formation of a steering group that had expertise in all the requisite areas of the project, a pre-tender design that was cognisant of the games and legacy use requirements and was subject to little client-instigated change post-contract, and a well-rounded contractor’s team with appropriate experience to delivering a venue of this type.

Acknowledgements

The steering group members were British Canoe Union, East of England Development Agency, Locog, Lee Valley Regional Park Authority and Sport England. The client design team was led by Drivers Jonas Deloitte and included Michael Van Valkenburgh Associates (master planner), Faulkner Browns (architect), Cundall (engineer), Northcroft (quantity surveyor) and Whitewater Parks International (pre-construction white-water channel designer). The contractor’s design team was led by Galliford Try Construction and included S&P (architect), Hyder (engineer, detailed design) and EPD/S2O (canoe/white-water consultant and obstacle system). The British Canoe Union and the International Canoe Federation provided technical input on the course design, tuning and course commissioning.

Figure 11. Aerial view of Lee Valley White Water Centre at completion

References