A passive flow-control device for the Banbury flood storage reservoir

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SYNOPSIS. The Environment Agency is developing a scheme to protect the town of Banbury against flooding, principally by providing an 'on-line' flood storage reservoir on the River Cherwell upstream of the town. A flow control structure will be sited on each of the two branches of the river, incorporating a suitably designed throttle to limit discharges passed through the town in events up to a return period of about 200 years. Construction of the main works of the project is programmed to commence in 2005.

This paper describes the development of the design for the flow-control structures with the aid of a physical model at HR Wallingford. The design is based on a double-baffle orifice capable of maintaining discharges passed downriver within a target range of less than ±10% over a wide range of water levels in the flood storage reservoir.

INTRODUCTION

Banbury lies on the River Cherwell, a left tributary of the River Thames into which it flows in Oxford. The town has a long history of flooding, the most recent major flood being in 1998, with an estimated return period of about 100 years and total flood damage exceeding £12.5M. Flooding in Banbury is the result of the River Cherwell and associated local watercourses having insufficient capacity to convey the runoff from the upstream catchment, and has been exacerbated by development being allowed to take place on the floodplain.

The preferred solution, which was chosen taking account of technical, economic and environmental issues, is to provide an upstream 'on-line' flood storage reservoir, coupled with some local defences in the town. The flood storage reservoir will comprise the following main elements (see Figure 1):

Long-term benefits and performance of dams. Thomas Telford, London, 2004

- an embankment of maximum height about 5m and length 2.9km, running parallel to the northeastern side of the M40 and to the eastern side of the Oxford Canal;
- two similar flow control structures, one at the intersection of the embankment with each branch of the River Cherwell;
- service spillways incorporated into the control structures; and
- an emergency spillway incorporated in the embankment between the two control structures.

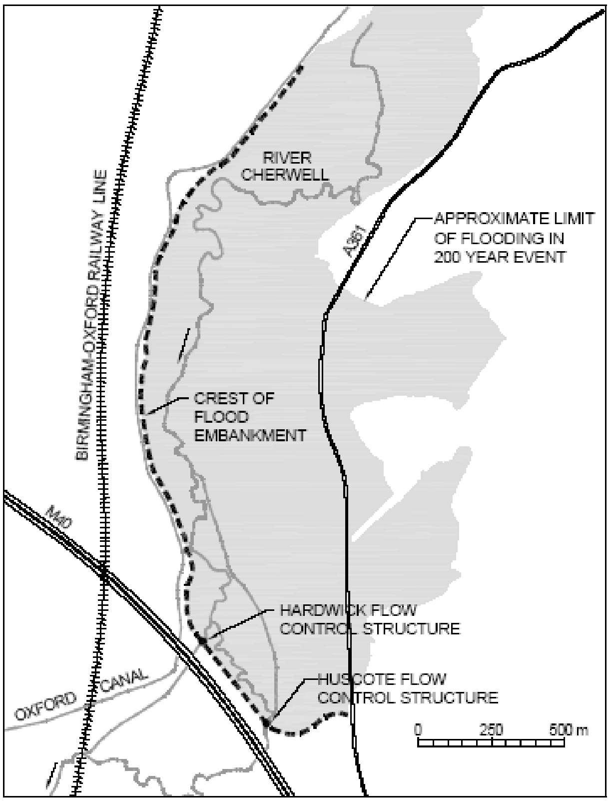

Figure 1 Location plan

The intention is that, in combination, the flow control structures should throttle the river flows to the maximum discharge which can be passed through the town, estimated as 38 m^3/s, impounding the additional flood discharge in the reservoir. The reservoir has been designed to accommodate the volume expected to be impounded in the design 200-year flood event.

When the reservoir is full, the spillways located alongside the control structure will overtop and provide a total discharge capacity approximately equal to that of the unattenuated peak of the 200-year flood. The emergency spillway will allow more extreme floods to be discharged without over-topping the rest of the embankments.

CONCEPT

The Environment Agency was keen that the control of discharges passed downriver from the flood storage reservoir should occur automatically, with no requirement for attendance by their operatives during floods. It was also considered desirable to place no reliance on power supplies or remote operation of the flow control structure. If practicable, a structure with no moving parts would also be preferred.

An ideal flow control device for an on-line flood storage reservoir would allow all discharges less than a target value to pass downstream without starting to impound. As the discharge continues to rise it would then allow the target discharge to pass downstream, impounding all of the excess. Such accurate control is difficult to achieve precisely, even in a fully automated gated system, but would have two advantages if it could be achieved:

- it would minimise the effect on the land within the impoundment area during minor floods (with a return period of up to about five years in the case of Banbury); and
- in the early part of larger floods, it would preserve as much as possible of the available storage volume for utilisation in attenuating the peak of the flood hydrograph, ultimately reducing the total flood storage needed and therefore lowering the peak water level in the flood storage reservoir.

A simple orifice meets the objective of having no moving parts, but results in the discharge rising as the square root of the net head. If a simple orifice is designed to limit the discharge to the target value when the reservoir is nearly full, this results in it starting to impound when the discharge is much less than that target value.

The above objectives led to consideration of the design concepts embodied in the baffle distributor devices which have been used for many years in irrigation systems, in particular the 'Neyrpic module'. Performance information on these devices is given by Neyrpic (1971), Alsthom Fluides (undated), UN/FAO (1975), Bos (1989) and a number of other standard references. The devices are designed to achieve a nearly fixed discharge out of a parent irrigation canal over a range of operating levels in the canal.

Two forms of the device are described in the references, one comprising a single baffle and the other a double baffle, of which the double baffle has the potential to provide a wider range of nearly fixed discharge, so was of particular interest. Although the performance information for double baffle distributors is apparently identical between the references consulted, at least three different variants on the shapes of the baffles are given.

Figure 2 shows the geometry of the device, based on the dimensions and shape quoted by Bos (1989), together with the quoted stage/discharge rating. As the upstream head rises, it impinges on the upstream baffle, which then acts as the control, with the jet clearing the underside of the downstream baffle. As the head rises further it overtops the upstream baffle and a transition to downstream baffle control occurs as the stage rises further. The discharge remains within a band of ±10% for heads between around 0.73 and 1.74 times a nominal design head.

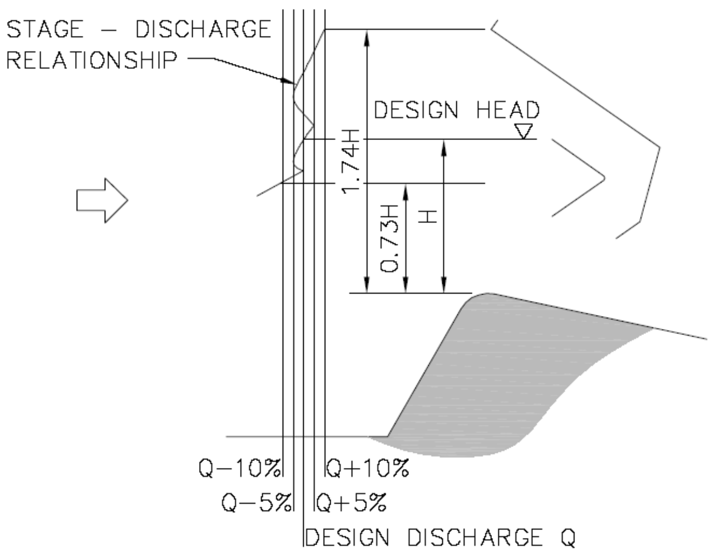

Figure 2 Double-baffle orifice layout and performance (after Bos, 1989)

PRELIMINARY DESIGN

Initial consideration of the outline design for the Banbury control structures indicated that the vertical and longitudinal dimensions should be exactly twice those of the largest standard irrigation distributor module illustrated by Alsthom Fluides (undated). The nominal design head is 2.58m, the nominal design unit discharge is 5.66 m^2/s and the target head range for ±10% is 1.88m to 4.50m. On this basis each bay would be 1500mm wide, giving a nominal discharge of 8.5 m^3/s per bay or 17 m^3/s per structure and therefore a total nominal downriver flow of 34 m^3/s, rising to about 38 m^3/s at the maximum positive deviation of 10%.

In a distinct departure from the designs in the references, it was decided that the invert profile should resemble a Crump weir, with upstream and downstream slopes of 1:2 and 1:5 respectively meeting at a sharp vertex. Factors in this decision were the simpler construction than the round crest of the original device and the possibility of predicting the lower part of the rating curve (before impingement on the baffles) by the use of the standard formula for a Crump weir.

Prior to model testing, a 'target' stage/discharge relationship was prepared, based on the formula for a Crump weir at low heads and on the relationship for baffle control given by Neyrpic (1971). Although precise compliance with that relationship was not considered an essential outcome of the testing, it was a useful aid for comparing the performance when various details were adjusted during the design development.

MODEL STUDY

The Banbury flow control device will be much larger than the largest of the standard irrigation distributor modules described in the references. Although the reported design and hydraulic behaviour would clearly be amenable to Froude scaling, several factors led to the decision to undertake a programme of project-specific model testing:

- the differences between the references regarding the appropriate configuration for the device;
- a concern that the baffle design shown in Figure 2 (and the other versions) would be vulnerable to debris accumulation;
- a recognition that metal fabrication might not be appropriate for the larger structure and that the use of thicker concrete structural members would have an impact on both the design and the resulting hydraulic behaviour;
- a suggestion in one of the references (Bos, 1989) that the hydraulic performance of the device would exhibit hysteresis, with different ratings for rising and falling stages; and
- the need for a verified rating relationship for use in design.

The model testing commenced with two versions of the double-baffle configuration, as illustrated in Figure 3. One is based on the simplest of the three variants which appear in the references, comprising angled baffles expected to be fabricated in robust steel plate; the other comprises simple vertical baffles, which are thicker than the angled baffles and intended to be suitable for construction in reinforced concrete.

The model design, construction and testing were undertaken at HR Wallingford, with a model geometric scale of 1:12 selected. The model was built mainly from PVC, to provide a suitable boundary roughness (comparable to concrete in the prototype) and the sidewalls in the vicinity of the baffle devices were built in Perspex to allow flow visualisation. Discharges were provided via a centrifugal pump and measured using an electromagnetic flowmeter, giving a basic accuracy of around 1%. Water levels were measured using manual micrometer point gauges reading to an accuracy of about 0.25mm (3mm in prototype terms).

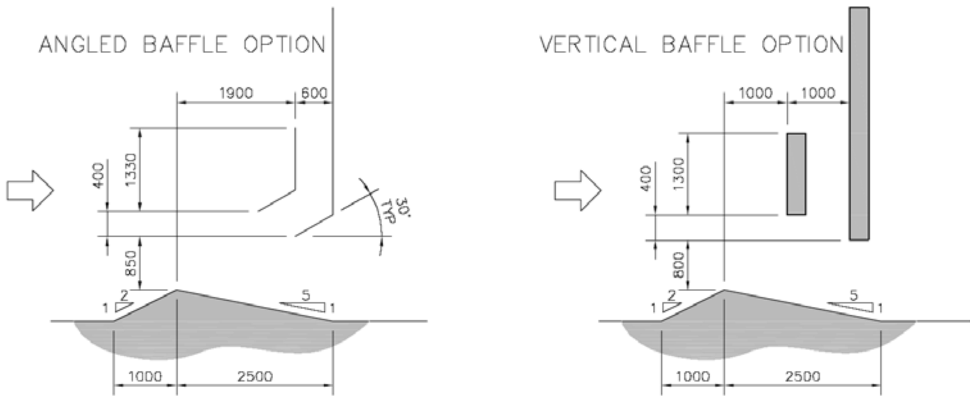

Figure 3 Double-baffle designs for preliminary testing

Each of the two flood control structures was expected to comprise a pair of the orifice devices side by side, separated by a central pier with a semi-circular nose. It was decided to reproduce a complete structure, including the two bays and central pier, in the model, although not the detail of the approach channel and exit channel. In the preliminary tests each bay contained one of the two different versions of the double baffle orifice device, with the approach channel to each bay closed off in turn in order to test one bay at a time. When the design development was complete, the chosen design was built into both bays and confirmation tests undertaken.

The model test programme thus comprised three stages:

- preliminary tests, using the preliminary designs illustrated in Figure 3;
- optimisation tests, in which a series of design adjustments, affecting the baffle positions, elevations and shapes were made and evaluated in a single bay; and
- final tests of the optimised structure in both bays of the model.

The preliminary and optimisation tests were carried out with the down-stream water level low enough to avoid any effect on the flow conditions in the structure. The final tests also used tailwater levels derived from flood simulations.

<u>Preliminary tests</u>

The preliminary tests on the configurations shown in Figure 3 showed a close agreement between the test results for the angled baffle and the target relationship (Figure 4), suggesting that the configuration chosen for the angled baffle testing was indeed a valid variant. The flow conditions during the transition from upstream baffle to downstream baffle control were unstable, with strong air-entraining vortices forming upstream of the upstream baffle, leading to oscillations in the approach channel. The instability was associated with water surface drawdown around the nose of the central pier and the formation of a standing wave immediately upstream of the baffles.

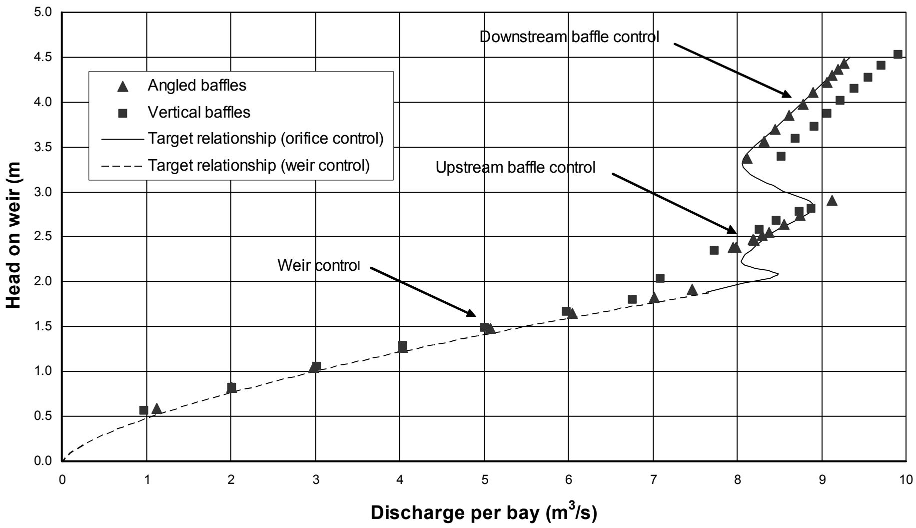

Figure 4 Stage-discharge relationships from preliminary tests

The preliminary vertical baffle arrangement gave a stage/discharge relationship (Figure 4) which diverged from the target relationship somewhat, with an earlier transition from weir to upstream baffle control. The flow conditions during the transition were again unstable, leading to oscillations in the approach channel, but without the strong vortex action found in the angled baffle device. The instability was again associated with the surface drawdown around the nose of the central pier.

Another notable feature was that the initial water surface contact on rising stages was with the downstream baffle, although the resulting effect on the approaching flow profile caused rapid contact with the upstream baffle, which then took over flow control, with the downstream flow surface clearing the underside of the downstream baffle.

<u>Optimisation tests</u>

As a result of the observations in the preliminary tests, it was decided to extend the central pier further upstream and to change its nose shape to a lens, with a 90° internal angle, in order to reduce the severity of the local drawdown and to allow substantial recovery upstream of the weir crest and baffles. Because the angled version of the device had already closely met the target relationship, efforts were concentrated on optimising the performance of the vertical baffle option, as this was seen to offer a number of potential advantages, if a satisfactory rating relationship could be achieved.

A total of eight different versions of the vertical baffle device were investigated, adjusting the elevations of both baffles and the spacing between them, but in all cases with the upstream face of the upstream baffle 1000mm downstream of the vertex of the Crump weir. The various adjustments made were aimed at achieving two effects:

- a narrow range of discharges under baffle control, with the curve for downstream baffle control lying directly above the curve for upstream baffle control; and
- if possible, a direct transition from weir control to upstream baffle control, without the water surface first impinging on the downstream baffle.

The tests confirmed what was expected, that these two objectives are mutually exclusive – raising the downstream baffle to avoid it impinging first on the water surface inevitably shifts its control curve to the right and therefore increases the spread in the rating relationship.

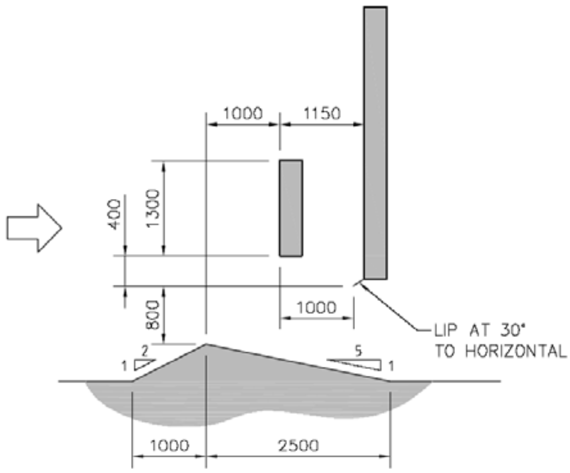

Figure 5 Optimised baffle arrangement

In order to reduce the spread between the curves for upstream and downstream baffle control, it was decided to introduce a small angled plate onto the front of the downstream baffle, resulting in the configuration shown in Figure 5. By making the contraction effect for the downstream baffle more severe than that for the upstream baffle, this had the desired effect, as illustrated in Figure 6. This figure also shows for comparison the relationships for the two designs shown in Figure 3, but now with the central pier extended.

Measurements throughout the preliminary and optimisation tests were made under virtually steady-state conditions, but in the course of rising or falling stages. In no case was any hysteresis effect detected.

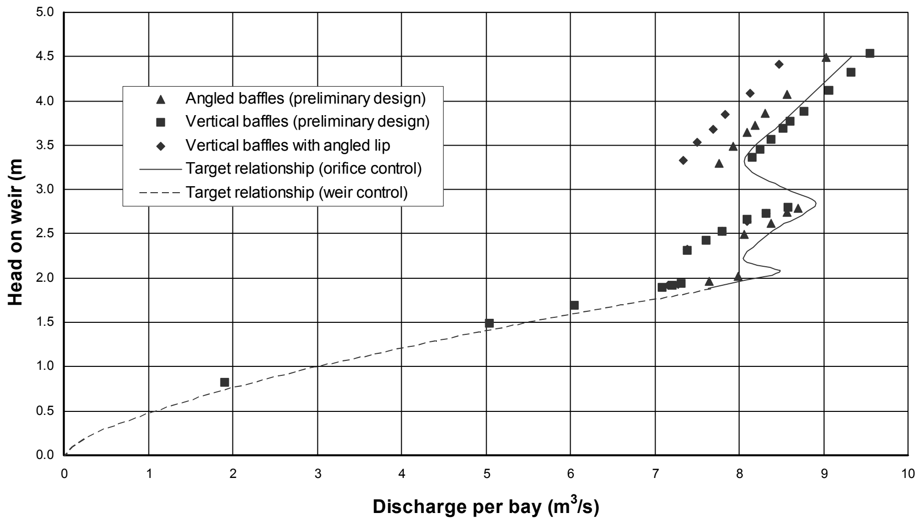

Figure 6 Stage-discharge relationship for optimised design

Although the results for the design shown in Figure 5 lie typically about 10% to the left of the target relationship, this was considered acceptable, because the requisite discharge capacity could be achieved by simply increasing the width of each bay to approximately 1.65m, which would have minimal cost and layout implications.

Final tests

The optimised baffle design shown in Figure 5 was built in both bays and tested under the following tailwater conditions:

- low, as used in the preliminary and optimisation tests;
- rising stage, as on the rising limb of a severe flood hydrograph; and
- falling stage, as on the recession of a severe flood.

The rising and falling stage tailwater levels were taken from mathematical model simulations of the 200-year return period flood, with the scheme in place and using the target rating relationship for the control structures. They are not necessarily representative of all flood conditions under which the flood storage reservoir will operate, but nevertheless give a realistic indication of the general effects of the natural range of tailwater levels on the performance of the control device.

Figure 7 shows the results for all the above cases, including a 'by-eye' best-fit line for the rising tailwater case. The results plotted with solid symbols relate to steady-state measurements, whilst those with open symbols are the results of measurements when steady conditions could not be maintained. (In the latter case, the discharge was measured taking account of the rate of change in the volume stored in the model between the device and the flowmeter.)

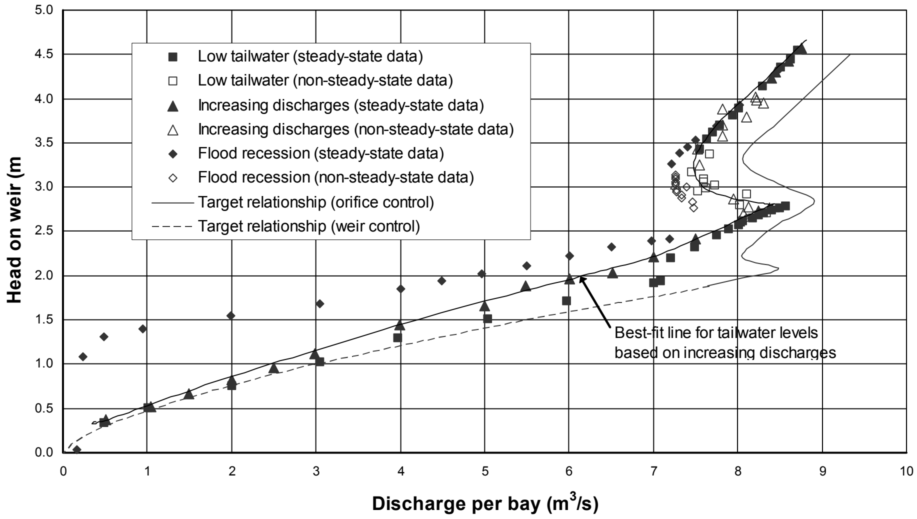

Figure 7 Final stage-discharge relationship for optimised design in two bays with various tailwater conditions

It may be noted (by comparing the results with those in Figure 6) that, for low tailwater levels, there is only a marginal difference in performance for the twin-bay version compared with the single-bay version. With the tailwater levels based on rising flood stages, the rating is affected by tailwater for heads between approximately 0.7m and 2.2m, but there is no significant difference in the performance of the device for heads between 2.2m and 4.5m. On falling stages, the higher tailwater levels have a modest effect on the behaviour of the device for stages between about 3.9m and 2.5m and a larger effect at lower stages. It should be noted that the hysteresis in this case is wholly driven by the applied tailwater levels and is not a fundamental characteristic of the device.

Plates 1 to 6 show various stages of flow behaviour for the optimised design with low tailwater levels and rising upstream heads.

Plate 1 First contact with downstream baffle

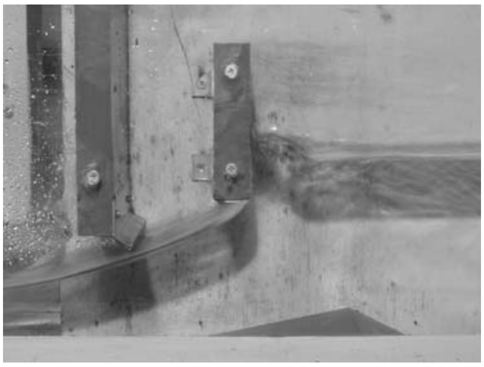

Plate 2 Control quickly transfers to upstream baffle

Plate 3 Upstream baffle starting to overtop

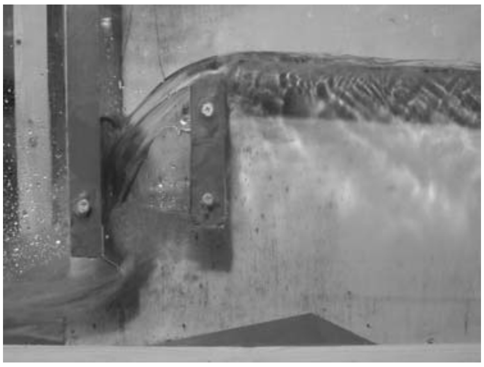

Plate 4 Downstream baffle starting to control flow

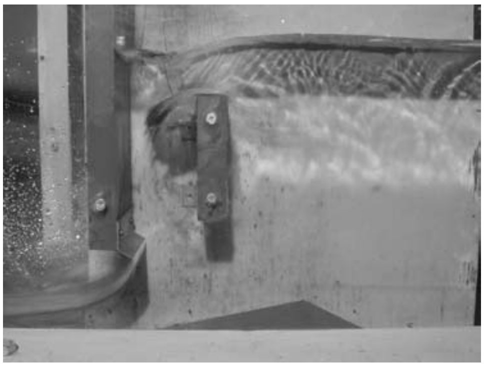

Plate 5 Upstream head still affected by weiring flow over baffle

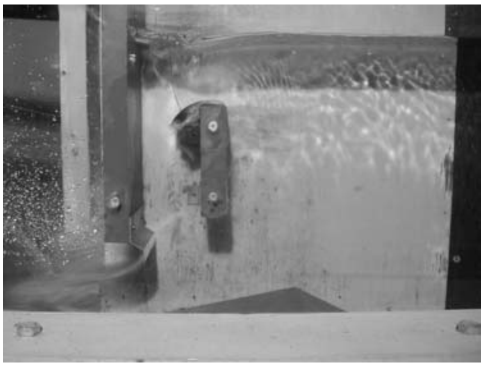

Plate 6 Upstream baffle virtually submerged

CONCLUSIONS

A passive flow-control device, based on a Crump weir profile and twin baffles, has been developed with the aid of a physical model, from the concepts embodied in the baffle distributor devices used in irrigation systems.

The device, which includes simple vertical baffles, with an angled lip on the downstream baffle only, is capable of controlling discharges within a band of ±10% for stages between 2.0m and 4.5m, provided that the downstream water level does not influence the flow conditions. No evidence of hysteresis was found.

On rising and falling stages in a simulated 200-year flood, the performance of the device is affected by the anticipated tailwater regime. On rising stages, which affect the utilisation of flood storage, the bottom of the ±10% discharge band is raised from about 2.0m to 2.2m.

ACKNOWLEDGEMENTS
The authors thank the Environment Agency for permission to publish this paper and gratefully acknowledge the assistance of their colleagues who provided assistance and comments on the draft paper. Whilst the model test results and other statements in this paper are believed by the authors to be an accurate reflection of the research work described, they should not be relied upon for any other purpose.

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