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Hydraulics of Minimum Energy Loss weir: the Chinchilla MEL weir during the Nov-Dec 2021 Flood Event

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ABSTRACT

During the last five decades, a number of overflow embankment designs were developed including the earth dam spillway with precast concrete blocks, the concrete protection of the downstream embankment slope and the Minimum Energy Loss weir. The Minimum Energy Loss (MEL) weir design was developed specifically for the river catchments affected by heavy tropical and sub-tropical rainfalls where streams have very flat gradients, i.e. $S_o \sim 0.1\%$*, and erodible banks. The structure is designed to pass large floods with minimum afflux and with minimum energy loss without erosion of the banks. Several MEL weirs have successfully operated for several decades and their operations were documented during floods, including out-of-bank floods larger than the design event. Inspections during and after events highlighted a reliable operation associated with minimum maintenance. Both theoretical considerations and physical modelling showed that improper inflow conditions and poor streamlining could affect adversely the spillway operation. During the 2021 flood in November-December, quantitative measurements were conducted in the Chinchilla MEL weir. On the smooth chute, the observations showed that the inception of self-aeration was a three-dimensional process marked by a progressive change in free-surface roughness. An optical technique was implemented to estimate the surface velocities in the self-aerated region. The streamwise surface velocities were reasonably close to backwater calculations, showing large longitudinal surface turbulence levels.*

INTRODUCTION

Over the last few decades, a number of overflow embankment protection systems were developed and implemented (FEMA 2014, Chanson 2015). These includes the earth dam spillway with precast concrete blocks (Gordienko 1978, Pravdivets 1987), some Roller Compacted Concrete (RCC) protection of the downstream slope of embankment dams (McLean and Hansen 1993, Chanson 2001) and the Minimum Energy Loss (MEL) weir. The MEL weir structures are designed to pass large flood events with minimum energy loss (McKay 1971), and several MEL weirs have successfully operated for decades in Australia.

The present contribution aims to describe the process that led to the MEL weir design concept and to review the performance of MEL weirs taking into account recent observations of the effects of a major flood event on the MEL weir at Chinchilla in November/December 2021. The latter is supported by an unique series of field observations including quantitative optical measurements in the spillway overflow.

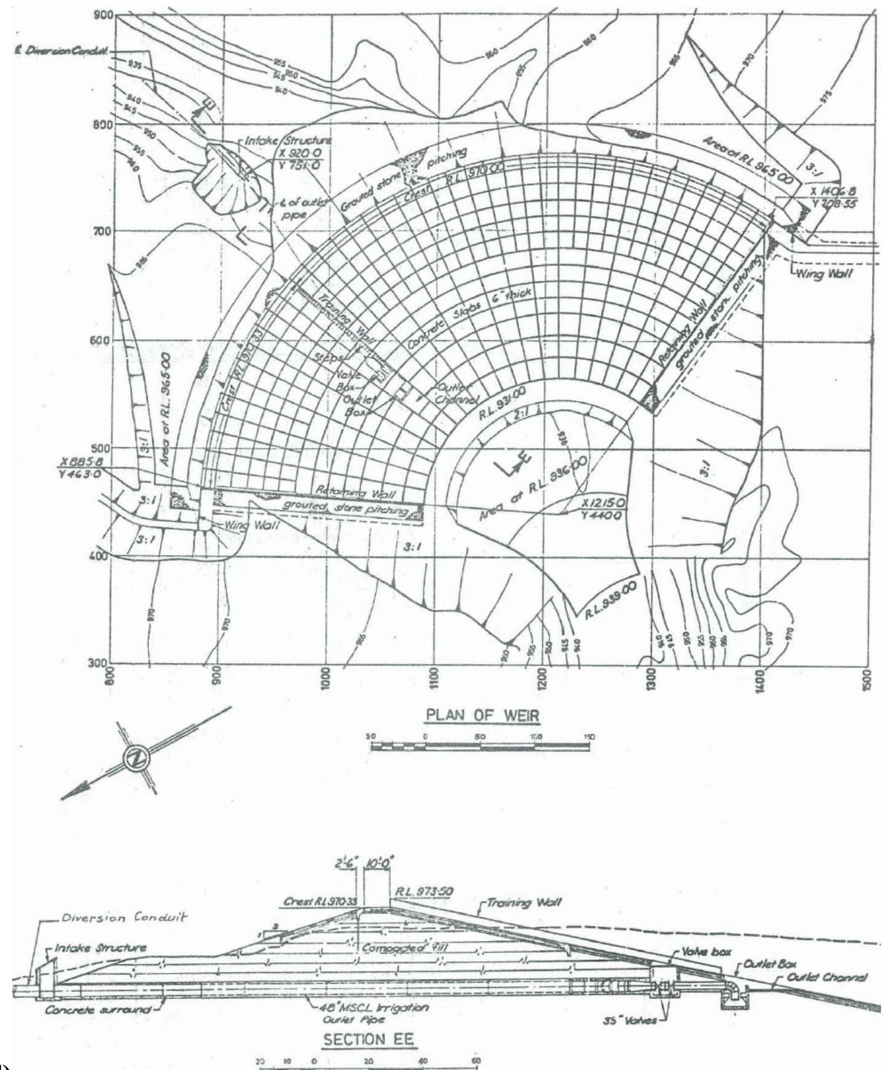
CONCEPT AND DEVELOPMENT OF MINIMUM ENERGY LOSS WEIR DESIGN

The Minimum Energy Loss (MEL) weir design approach was developed in response to the failure to achieve a satisfactory design of a "conventional" weir for a site on Sandy Creek near Clermont, Queensland. Through physical model tests of many conventional weirs, late Professor Gordon Reinecke ("Mac") McKay (1913-1989) progressively refined the weir design. In essence, his strategy had as its main features: (i) arrange the level of the crest in several steps, rising progressively on each side from the central section in order to reduce the difference between the flow distribution over the weir and that in the natural stream and thereby reduce the potential for bank erosion; (ii) reduce as much as possible the afflux across the weir when the upstream flood level overtopped the banks in order to reduce the potential scour at the abutments: (iii) design adequate scour protection for the embankments to prevent scour there. An example of such a design is the weir near Dalby, Queensland (Fig. 1A). However, eventually it proved impossible to develop a satisfactory design based on these principles for the site on Sandy Creek, despite a large number of attempts. The competing requirements for this weir and for many others constructed in streams with erodible banks are: (1) maximum in-stream storage, (2) protection against erosion of the stream banks at the abutments of the weir and downstream and (3) no increase in the frequency of out-of-bank flooding. The conventional type of weir caused excessive afflux and over-bank flow and massive erosion of the alluvial banks at the abutments and downstream, even for flows considerably less than the design flow. When C.J. Apelt (2002) was invited to observe the performance of the last of these unsatisfactory model tests, it was clear that the weir was causing too much constriction of the flow with large energy losses. He noted that the flow over the weir was analogous to that past an orifice plate in a pipe and suggested an approach analogous to a Venturi tube. The idea was to minimise the energy loss across the structure by using a more streamlined geometry everywhere and a gradual expansion downstream to recover as much as possible of the kinetic energy of the flow at the weir crest. A large number of trials finally produced a satisfactory design for the site on Sandy Creek, Clermont and the first MEL weir was built there in 1962 (Fig. 1B) (Apelt 2002).

The essential principles of the approach, described as the Minimum Energy Loss (MEL) weir design, are simple: (i) the crest is made long enough to pass the bank-full flow at critical conditions without causing any change in the upstream water level; (ii) the weir crest in plan is a circular arc of the length required by the first principle and concave downstream in order to converge the flow horizontally towards the centre of the stream after it has passed the crest; (iii) the faces of the weir must have relatively flat slopes to reduce energy losses by avoiding rapid lateral convergence horizontally and expansion of the flow in the vertical plane as it passes over the weir; the downstream face has a much flatter slope than does the upstream face. In order to satisfy the first two principles, the upper levels of the banks immediately upstream from the weir crest are excavated sufficiently to provide for efficient flow normal to the crest, uniformly distributed along its full length. The model of Clermont weir (Fig. 1B) and the design drawings of the Chinchilla MEL weir (Fig. 1C) illustrate these principles. Figure 2 shows the weir passing flows much smaller than the design flow.

(A)

(B)



(C)

Figure 1. In-stream weirs and Minimum Energy Loss (MEL) weirs in Queensland (Australia). (A) Weir near Dalby, QLD; (B) Sandy Creek MEL weir at Clermont, discharging a small flow (Top left) (Collection of late Professor G.R. McKay) in July 2003 (Top right) (Courtesy of Bruce Mason), and physical model tests for a prototype flow of 710 m^3/s (Top centre) (Collection of late Professor G.R. McKay); (C) Plan view and cross-section of Chinchilla MEL weir (after Turnbull and McKay 1974) - Note the imperial system units.

Discussion

The MEL weir design presents a number of advantages. The weir passes the bank-full flow with little afflux. The simple design approach implies that no energy loss occurs as the flow approaches and passes over the weir crest. Clearly, this is an oversimplification and, inevitably, some energy loss occurs though it is much smaller than that for a conventional weir. Consequently, the bank-full flow with the weir in place will be slightly smaller than for the undisturbed stream. As a consequence of the small energy loss, the crest level of the MEL weir can be much higher than would be feasible for a conventional weir for the same design flow and the water storage capacity is much increased. The horizontal convergence of the flow downstream from the crest results in a flow distribution much closer to that of the natural stream than is achievable with a conventional weir and the potential for bank erosion is much reduced.

There are however a number of disadvantages. Because of the flatter cross-sectional shape, the construction of a MEL weir involves a much larger volume of material than is needed for a conventional concrete gravity weir. Typically, the approach has been to construct the weir as a compacted earth embankment covered everywhere by concrete slabs with provision for drainage to relieve any water pressure that develops in the embankment. Inevitably, there is risk of damage should a significant flow occur during construction. The MEL weir on Sandy Creek at Clermont was built in 1962. When it was nearly completed a minor flood overtopped it and caused considerable damage. The weir was completed at the next attempt. Construction of the MEL weir on the Condamine River at Chinchilla began in late 1972 but was interrupted by a large flood in October 1972 that caused extensive damage when the weir was nearly completed. Unfortunately, when the renewed construction was almost finished, another flood in July 1973 caused extensive damage. Eventually the weir was completed successfully in December 1973. (Turnbull and McKay 1974).

Whether an MEL weir is appropriate for a particular site will depend on the design criteria and on the relative costs – that must include some insurance against possible damage during construction if there is a risk of flooding.

Historical performance of MEL weirs

The weir at Clermont has been in operation for about 60 years, that at Chinchilla for nearly 50 years and a review of their performance is instructive. The significant criteria in such review are whether there have been issues concerning erosion and the hydraulic performance.

The MEL weir on Sandy Creek, Clermont was designed for a design head of 2.9 m. McKay (1971) reported that the MEL weir "has been overflowed many times, but the size of the maximum flow is not known. No scour or erosion has taken place downstream". In Apelt (1978), J.D. Turnbull reported that "no further problems have been reported from the weir" since completion of construction. Figure 1B presents a photograph of the weir in operation and the model test with discharge about 80% of discharge flow. The weir is still in use as an emergency water supply (Chanson 2003).

The Chinchilla minimum energy loss weir (QLD, Australia) (Figs 1C & 2) is located in the Western Downs, along the Condamine River. The longitudinal river bed slope is S_o = 0.215% in average between Brigalow and Chinchilla weir. Completed in 1973, the weir provides irrigation water, and it is listed as a "large dam". With a catchment area of 19,192 km^2, the weir is a 14 m high earth fill embankment with a 410 m long dam crest including abutments. The overflow spillway (Figs. 1C & 2A) has a design capacity is of 850 m^3/s corresponding to bank full at a design head 1.83 m. The spillway system consists of a broad crest that is 214m long, followed by a smooth converging chute with a 1V:5H slope. There is no stilling basin. After completion, grass was planted in the top soil and protective mesh was placed on the subsidiary earth embankments on each bank. Before this had time to grow, the weir was subjected to a major out-of-bank flood of order 1,130 m^3/s, one of the highest on record, and that overtopped the embankments (Turnbull and McKay 1974). At the peak of the flood, it was difficult to see where the weir was, because it was completely drowned out. As the flood receded, it was wonderful to see the structure emerge from the flood waters relatively unscathed. The top soil and grass planted over the plastic mesh and gravel on the top of these embankments were washed away for the most part, but the mesh held and the damage was minor. The soil and grass were replaced and the grass became well established before the next flood. (Apelt 1978). Since its completion, the weir has been overflowed many times. The Condamine River at Chinchilla has carried a large number of floods in that period, many of them being major out-of-bank floods. Between 1973 and 2022, the weir was overtopped by a number of large flood events, including events larger than the design flow (Table 1). The weir operated safely and properly, and inspections after the flood showed no damage. The second author has inspected the weir several times and found no evidence of erosion. Most recently he visited soon after a major out-of-bank flood in November/December 2021. The flood level had risen to at least 2.5 m above the right bank at the carpark, and no erosion had occurred.

The Chinchilla MEL weir was designed to give no afflux at bank full flow, 850 m^3/s, when the head over the weir is only 1.83 m, (Turnbull and McKay 1974). Although the design of the weir itself was based on the assumption that no energy losses occurred, "the level of the supplementary embankments was determined from theory and the model as the lowest head water level at which there would be an afflux of less than one foot (300 mm)" (Turnbull and McKay 1974). The term "afflux" is used here to describe the increase in the actual water level upstream from the weir above the undisturbed water level that would have existed in the absence of the weir. Implicit in this definition is the assumption of steady flow in a uniform channel. During the major flood in 1973 of order 1,130 m^3/s the measured afflux at the bank full flow was only 100 mm - the head over the crest was 1.93 m, only slightly larger than the simple design assumption (Turnbull and McKay 1974). It is not stated how this was measured – it would be a very difficult procedure during a major flood. Elsewhere, the cited authors state that, for the same conditions, the measured afflux was approximately six inches (0.150 mm) compared with the model estimate of over one foot (0.305 m).

With the uncertainty about the stated magnitudes of afflux based on observation during the flood, it is thought that the most likely magnitude is that measured on the model - "over" 300 mm. The photograph of the model in Figure 1B shows that this measurement was made just upstream from the weir. In contrast to the usage here, the usual meaning given to afflux is the difference between the observed headwater and tailwater elevations at a structure such as a weir (Apelt 1983, Chanson 2004). This is discussed further in the context of flood levels recorded during a major flood in November/December 2021.

The historical performance of both MEL weirs discussed has shown that, even during large out-of-bank floods, they cause no significant erosion at their abutments or downstream – the regions that are most at risk and require extensive protection for conventional weirs. There is evidence that they do cause some small increase in flood levels upstream during what would have been a bank-full flood, but it is difficult to assess the magnitude of this.

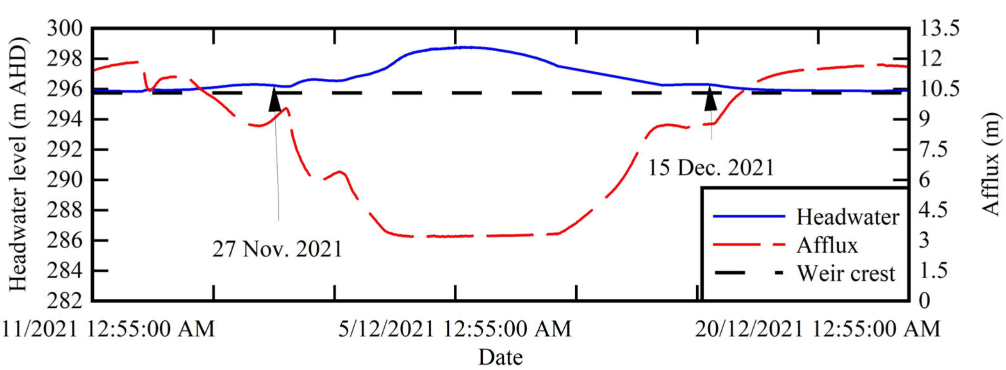
CHINCHILLA MEL WEIR AND ITS OPERATION IN NOV./DEC. 2021

The Condamine River experienced a major flood in Nov./Dec. 2021, following widespread rainfall in the upper and middle catchment. The Chinchilla MEL weir overflowed for more than a month. The water elevations were recorded by Sunwater and DRDMW gauging stations, and the spillway discharge was estimated from broad-crest calculations. The peak discharge was observed on 5 December 2021. For nearly a week, the spillway discharged more than the design discharge, with a maximum discharge about 1,930 m^3/s. Some inspection on 15 December 2021 indicated that the abutments were overtopped by nearly 3 m of water at the time of maximum discharge (Chanson and Apelt 2022). During the event, the afflux at maximum discharge was 3.23 m, with the afflux being the difference between the observed headwater and tailwater elevations (Fig. 2B). The maximum tailwater elevation and afflux during the 2021 flood event is compared with several documented major floods, including several major floods in 2022 in Table 1.

The differences between the magnitudes of the afflux given in Table 1 and those reported in the preceding section on historical performance are due, at least partly, to the difference between the meaning of the term implicit in the discussion of the afflux reported to have been observed during the major flood in 1973 (Turnbull and McKay 1974) and its meaning as specified for Table 1. Clearly, the assumption of steady flow in a uniform channel, implicit in the use of the term in Turnbull and McKay (1974) is not valid for a time varying flood event in a real river – the Condamine River is very nonuniform in cross - section. In Table 1, the headwater and tailwater elevations are those observed at the respective flood gauges maintained by the Australian Bureau of Meteorology. These are some distance from the weir and part of the afflux reported in Table 1 would be due to the flood gradient at the time. Further, it is not known whether all of the flow diverted from the river upstream from the weir during over-bank stages returns to the main channel upstream from the tailwater gauge. Nevertheless, it is clear that the increase in flood levels upstream due to the weir, while small, are larger than those implicit in its design, but it is not possible to estimate the magnitude of this difference from the available information.

During the Nov./Dec. 2021 flood event, visual observations were conducted from the right bank of the spillway on 27 November 2021 and 15 December 2021. The spillway system consists of a broad crest, followed by a smooth converging chute with a 1V:5H slope. There is no stilling basin. As noted above, the overflow spillway (Figs. 1C & 2A) has a design capacity is of 850 m^3/s corresponding to bank full. The chute convergence is -2.18 m/m. Figure 2A present a hand-held photograph. The observations were conducted using dSLR cameras and an iPhone, with movies recorded in high definition (1920×1080 pixels) between 25 fps and 60 fps. Free-surface features were analysed manually and using an optical flow (OF) technique. The latter approach was based upon movies recorded from a camera fixed on a sturdy tripod and derived the surface velocity field based upon the detection of flow motion between consecutive frames (Liu and Shen 2008, Zhang and Chanson 2018). Noteworthy, no attempt was made to 'calibrate' the OF data analyses because a number of intrinsic difficulties with field measurements (Chanson 2021,2022a).

(A)



(B)

Figure 2. Chinchilla Minimum Energy Loss (MEL) weir operation during the Nov./Dec. 2021 flood. (A) Operation on 15 December 2021 for Q = 144 m^3/s. (B) Observed afflux.

Table 1. Maximum water elevation observations during major flood events at Chinchilla weir tailwater and headwater (QLD, Australia) (Data: TMR 1969, BOM 2017, Present study).

Date	Time	Tailwater (m AHD)	Headwater (m AHD)	Afflux (m)
Feb/1942	--	296.76	--	--
Jan/1956	--	296.69	--	--
Feb/1976	--	296.72	--	--
May/1983	--	296.33	--	--
May/1996	--	296.14	--	--
Jan/2004	--	290.23	--	--
Dec/2010	--	298.20	--	--
Jan/2011	--	297.21	--	--
Feb/2013	--	295.23	--	--
5/Dec/2021	11:20	295.54	298.77	3.23
4/Mar/2022	00:00	294.25	297.58	3.33
1/Apr/2022	07:00	295.27	298.48	3.21
11/Apr/2022	06:00	293.77	--	--
20 May 2022	08:10	294.33	297.69	3.36

CHINCHILLA MEL WEIR OPERATION: OBSERVATIONS

The Chinchilla MEL weir observations took place at the start and end of the major flood (Fig. 2B). The spillway discharge then was 121 m^3/s and 144 m^3/s respectively. On both days, the reservoir inflow approached smoothly the weir crest, with a waveless water surface. The flow was critical on the crest and accelerated rapidly downstream. The upstream chute flow was smooth and waveless (Fig. 2A). Further downstream, the free-surface became rough and choppy, and then self-aeration occurred. The air-water region had a "brown" colour, implying a sediment-air-water flow, i.e. a three phase flow. At the chute toe, the supercritical flow plunged down the pool of tailwater and a hydraulic jump took place on the submerged sloping chute (Fig. 2A). The jump roller was highly turbulent and fluctuating about a mean position, with large three-dimensional eddies developing in the roller.

The video movies showed the occurrence of some form of roll waves in the self-aerated flow region. The phenomenon was clearly seen on 27 November 2021, and less visible on 15 December 2021. Although the same camera system (camera body and lens) was used on both occasions, the difference might be linked to differences in light conditions as well as slightly different water discharges. (For completeness, the roll wave patterns was not visually seen in-situ, but it was clearly evidenced during the movie replay, as well as in the OF data.) For both flow conditions, the instability criteria of Keulegan and Patterson (1940) was fulfilled (Dressler 1949). The Vedernikov number (Chow 1973, Montes 1998) was greater than unity at the chute toe, being equal to 2.5 and 3.7 on 27 November and 15 December 2021 respectively. The observed longitudinal (roll) wave length was $\lambda/d \approx 18.4$ and 19 on 27 November and 15 December 2021 respectively, and the amplitude of the longitudinal oscillations of the time-averaged streamwise surface velocity was about $\Delta V_s/(g\times d)^{1/2} \approx 0.11$ and 0.26 respectively, with d and V the local water depth and mean velocity. Dressler's (1949) calculations of the roll wave speed yielded a celerity about equal to the chute toe velocity, implying some quasi-stationary roller waves, that would be consistent with the interpretation of the video movies for both flow conditions.

Based upon video records from a sturdy tripod, the movies were analysed using an OF technique to characterise the longitudinal and transverse free-surface motion of the spillway chute. A typical result in terms of the time-averaged longitudinal surface velocity is presented in Figure 3. In Figure 3, the horizontal axis is a transverse coordinate, the vertical axis is the vertical elevation in m AHD, and the contour data are the longitudinal surface velocity measured parallel to the invert. Beside, on the left, an instantaneous snapshot is shown. In the contour map, the headwater and tailwater levels and the mean location of self-aeration inception are shown also.

The surface velocity data in the self-aerated flow region were close to the application of the backwater equation to the converging chute spillway (Chanson and Apelt 2022). As seen in Figure 3, the results in the non-aerated flow were unreliable because of the surface glare, seen in Figure 2A. Further, the surface velocity data were not reliable below elevation 288 m AHD, because of the surface splashing and spray above the hydraulic jump at the chute toe. Indeed, visual observations by the second author showed drops and splash reaching heights of more than 0.5 m to 1 m above the roller surface.

In the self-aerated flow region, the surface velocity data implied some regions of high-velocity and others of low-velocity, despite the very smooth inflow conditions.. That is, longitudinal "canyons" of faster flowing water, with streaks of lower surface velocities in between, in the self-aerated flow region downstream of the inception region. The observations were not unlike recent field observations at the Hinze Dam Stage 3 (Chanson 2021,2022b). The findings are relevant to the design of stilling basins, because these regions of high-velocity are associated with concentrations in kinetic energy to be dissipated in the stilling structure.

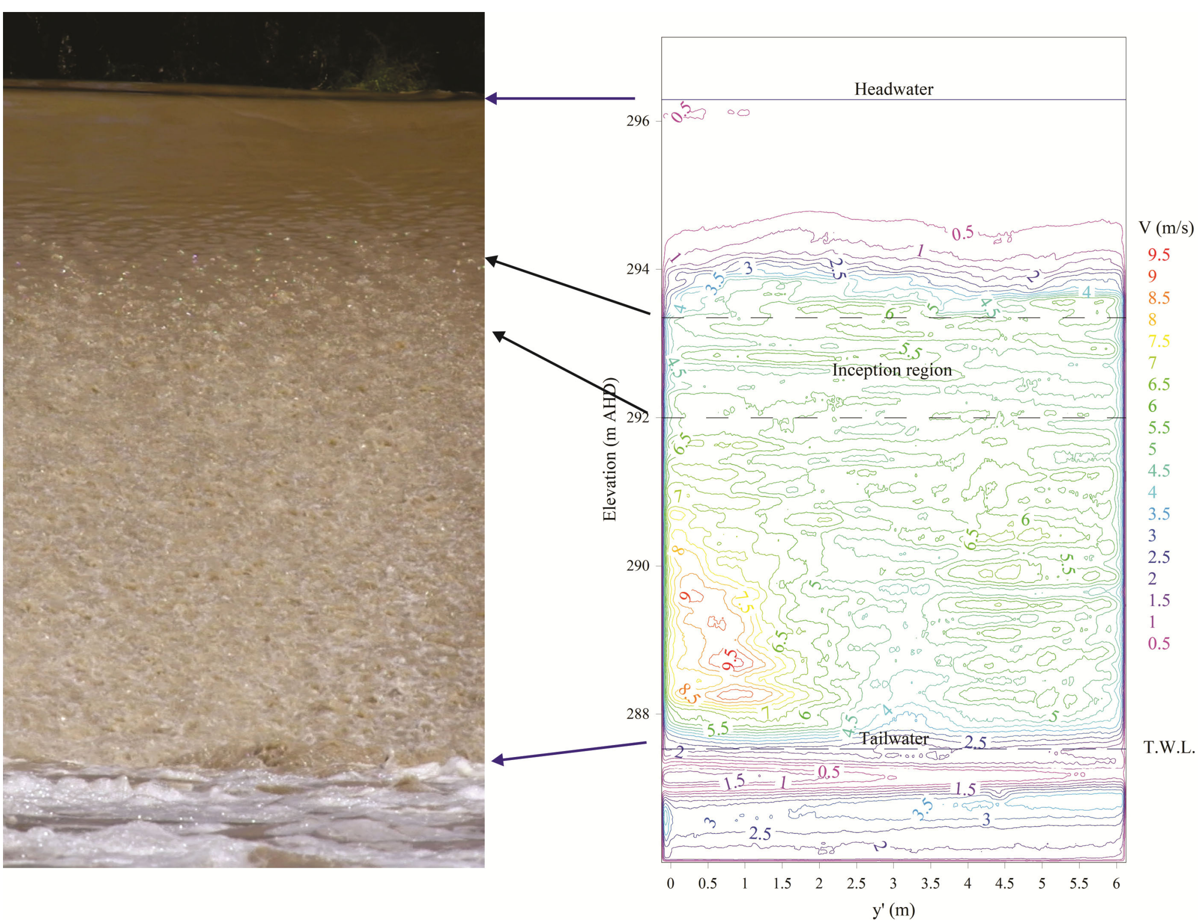


Figure 3. Contour map of time-averaged surface velocity at Chinchilla Minimum Energy Loss (MEL) weir on 15 Dec. 2021. Location: middle of left spillway bay. Time: 14:31. Number of analysed frames: 18,090. Left: instantaneous (single) frame. Right: Time averaged contour map.

CONCLUSION

The Minimum Energy Loss (MEL) weir design was developed in Queensland, specifically for the river catchments affected by heavy tropical and sub-tropical rainfalls where stream have very flat gradients and erodible banks. A number of MEL weirs have successfully operated for many decades and the operations of two of them were discussed. Inspections during and after major flood events indicated a reliable operation associated with minimum maintenance. The historical performance of these weirs has confirmed that the design can pass large floods with small afflux and with very small energy loss and that they cause no significant erosion at their abutments or downstream – the regions that are most at risk and require extensive protection for conventional weirs.

The concept of the MEL weir design requires a cross section that has relatively flat slopes, especially that on the downstream face. The weirs discussed above were built as compacted earth embankments with all surfaces protected by concrete slabs. Each was damaged by flood during construction. Consequently, estimates of the cost of construction of such a design must include some provision for insurance against possible damage during construction if there is a risk of flooding.

During the November-December 2021 flood, visual and quantitative observations were undertaken at the Chinchilla MEL weir. On the smooth converging, chute, the observations showed that the inception of self-aeration was a three-dimensional process with a 'progressive' change in free-surface roughness. An optical technique was implemented to derive the contour maps of surface velocities based upon video movies taken from a sturdy tripod. The present data sets showed results close to the backwater equation in the self-aerated region, while highlighting large transverse difference in longitudinal surface velocities across the chute, with region of high-velocities, despite the very smooth inflow conditions.

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In line with recommendations of the International Committee on Publication Ethics (COPE) and the Office of the Commonwealth Ombudsman (Australia), Hubert Chanson declares a major conflict of interest with Matthias Kramer (UNSW, Canberra).

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BIOGRAPHY

Colin James Apelt is an Emeritus Professor at the University of Queensland. He was appointed Professor of Civil Engineering in 1979. Throughout his career, he was committed to engineering education, research and professional practice in fluid mechanics and water engineering. He strove to inter-relate these fields so that they enriched and were enriched by each other. His main research fields were in Computational Hydraulics, Computational Fluid Mechanics; Experimental Fluid Mechanics and Hydraulic Modelling applied to flows past bluff bodies with relevance to flood and debris loads on bridges and to the efficient passage of flood flows through waterways. He worked closely with the late Professor G.R. McKay in developing the principles of Minimum Energy Loss waterways and weirs.

Hubert Chanson is Professor of Civil Engineering at the University of Queensland, where he has been since 1990, having previously enjoyed an industrial career for six years. His main field of expertise is environmental fluid mechanics and hydraulic engineering, both in terms of theoretical fundamentals, physical and numerical modelling. He leads a group of 5-10 researchers, largely targeting flows around hydraulic structures, two-phase (gas-liquid and solid-liquid) free-surface flows, turbulence in steady and unsteady open channel flows, using computation, lab-scale experiments, field work and analysis. He has published over 1,250 peer reviewed publications including two dozen of books. He serves on the editorial boards of International Journal of Multiphase Flow, Flow Measurement and Instrumentation, and Environmental Fluid Mechanics, the latter of which he is currently a senior Editor. His Youtube channel is: {https://www.youtube.com/channel/UCm-SedWAjKdQdGWNbCwppqw}.