Review of Investigation Report on the Flooding in Sha Po Tsai Village, Tai Po on 22 July 2010

By

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Executive Summary

On 22 July 2010, a severe flash flood occurred in Sha Po Tsai Village in the upper Tai Po River. More than 100 mm of rain was recorded between 4 pm to 6 pm on that day and a black rainstorm warning signal was hoisted from 5:30 to 7:50 pm. The Tai Po district received the heaviest rain in Hong Kong; maximum hourly and daily rainfall of 114.5 mm and 233.5 mm were recorded respectively.

The flash flood resulted in one casualty and considerable property damages. The Drainage Services Department (DSD) has conducted an investigation into the causes of this flooding incident and made recommendations for future drainage enhancement measures. An independent review of the investigation has been carried out.

Hydraulic modeling studies have shown that the 22 July 2010 flooding incident in Sha Po Tsai Village is caused by a combination of highly unlikely events: a rapid black rainstorm of unprecedented scale on a saturated catchment, resulting in large flash flood flows in excess of the designed capacity of the water supply intakes that continue to flow down the streams to the lower catchment. The village would have been flooded to similar levels had the river improvement works not been in place.

Field observations and hydraulic modeling show that the main source of the boulders is likely derived from upstream of the boulder trap. The high velocity of the turbulent flow (up to 9 m/s) led to serious erosion of the river bank and bed, and mobilized boulders and coarse sediment that are transported down the river. The observed soil erosion pattern correlates well with the predicted velocities.

The optimal construction sequence of river improvement works in the steep Tai Po River should be determined by a balance of construction practicability, site access and interim flood protection. The early construction of the boulder trap is reasonable and has protected the downstream villages from the boulder current.

It is recommended that the design of the Tai Po River training works having complex flow pattern be verified or fine tuned using the more sophisticated mathematical hydrodynamic models and/or physical models as appropriate to cross check the design of critical section and optimize hydraulic performance.

Acknowledgement

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INTRODUCTION

1.1 Background

On 22 July 2010, a severe flash flood occurred in Sha Po Tsai Village in the upper Tai Po River. More than 100 mm of rain was recorded between 4 pm to 6 pm on that day and a black rainstorm warning signal was hoisted from 5:30 to 7:50 pm. The Tai Po district received the heaviest rain in Hong Kong; maximum hourly and daily rainfall of 114.5 mm and 233.5 mm were recorded respectively.

The flash flood resulted in one casualty and considerable property damages. There has been some serious public concern on the causes of the flooding incident, especially amongst the villagers, in particular on whether the drainage improvement works entitled "River Improvement Works in Upper Lam Tsuen River, She Shan River and Upper Tai Po River" undertaken by the Drainage Services Department (DSD) had aggravated the situation.

DSD has conducted an investigation into the causes of this flooding incident and made recommendations for future drainage enhancement measures. The report on the investigation was submitted for review on 23 August 2010.

This independent review of the investigation report aims to address the following issues:

- the causes of the flooding and whether the above mentioned river training project has aggravated the flooding situation;
- the sources of the coarse sediment (e.g. boulders) and their impact on the flooding incident;
- the appropriateness of the construction sequence of the drainage improvement works;
- the proposed improvement measures and other related issues including the adequacy of the drainage impact assessment for this project.

1.2 Review methodology

This audit is based on a critical review of the "Investigation Report on the Flooding in Sha Po Tsai Village, Tai Po on 22 July 2010".

In addition, supplementary information on the completed river improvement works was provided. Two field trips have been undertaken to inspect the site conditions in the Sha Po Tsai village, the drainage improvement works, and the upstream river and catchment. A meeting has also been held with the village representatives to obtain first hand information on the flooding incident. The writer also met with DSD and AECOM several times to discuss the investigation, and in particular to clarify the various observations, constructed works, and hydraulic modeling issues. The following meetings and visits have been undertaken:

- Site visit to Sha Po Tsai on 30 July, 2010;
- Site visit to Sha Po Tsai and meeting with villagers and District Councilor on 4 September, 2010;
- Meetings with DSD and AECOM Consultants on:
  29 July, 30 July, 5 August, 16 August, 18 August, 19 August, 4 September, 2010;
- Meetings with Development Bureau on:
  3 August and 9 September 2010;

- Meeting with Water Supplies Department (WSD), Black & Veatch (BV) and DSD on 10 September 2010.

This flash flood on the steep upper Tai Po catchment embodies all the intricate complexities of a three-dimensional turbulent flow on an alluvial channel - supercritical flow and soil erosion, effect of complex solid boundaries, branching flow on braided gravel river, high velocity on flood plain, sediment transport and debris flood, and water supply vortex intake flow when the collection tunnel is significantly surcharged during severe storm events. Most importantly, there is a lack of data to directly verify various speculations and predictions on the causes of the flooding incident. As the investigation progressed, it became clear that an independent review of the relevant issues can benefit from two-dimensional (2D) and three-dimensional (3D) hydraulic modeling. The critical issues were examined by employing the following tools used or developed in our hydraulic research in recent years:

- Physically-based distributed hydrologic modeling using MIKE-SHE for estimating the catchment response and stream flows;
- 2D hydrodynamic modeling of supercritical flow on steep channel and flood plain using a 2D shock-capturing code;
- Modelling of 3D flow using the FLOW3d software (based on Volume-Of-Fluid method);
- Laboratory experiments to study the scroll vortex intake flow under surcharged drop shaft conditions.

CAUSES OF THE FLASH FLOOD IN SHA PO TSAI VILLAGE

2.1 Facts relating to the flooding incident

The flash flood on 22 July 2010 appears to have taken the Sha Po Tsai village by surprise. The only documented record of previous flooding at the site is 2 June 2006, with reports of flood depths of around 0.3 m. There are also indications that flooding occurred on 9 June 1998 and 27 June 2001; however no detailed record is available.

Based on the results of the post-flood questionnaire, photographs, videos and other data, it can be inferred that (see Fig.1 for location map):

Extent of flooding

- Flooding occurred between 5:30 to 6 pm; the time of flooding to maximum depth was around 20 min; the total duration of flooding was about one hour;
- Maximum flood depths of around 0.3 - 1.2 m; extreme depths of around 2 m were observed by a few villagers, especially around House 26 at the most upstream end of the village;
- First report on flooding at Sha Po Tsai was received by the police at 17:46 hr; there were four calls for help for a person being trapped by flood water between 17:59 and 18:16 hr;
- The flood swept through the village with high velocity and knocked down walls and fencing, and resulted in bridge collapse and severe erosion and damage of property along the river banks; the flood water also brought in large amounts of sediment into a number of houses;

- The flood flows in the downstream reaches (CH 400+) were also significant; the damage along the river banks is indicative of the high velocity flow down to Tat Wan Road.

<u>Erosion and sedimentation</u>

- Significant erosion of the river bed was observed at the foot of the two steep streams (Stream A downstream of the vortex intake, and Stream B downstream of the bottom rack intake spillway) upstream of the boulder trap - particularly near and downstream of the confluence of the two streams;
- The flood resulted in a 3 m deep scour hole immediately downstream of the boulder trap (ends at CH_C35);
- The gabion wall just downstream of the boulder trap (CH_C 50-110) remained intact, and the flood marks show depths that are below the wall height. There was significant flow behind the gabion wall that washed away noise barrier panels and fencing;
- There was significant transport of coarse sediment, gravel and boulders, and several bridges were completely blocked. The blockage was especially serious near the check dam (CH_C 230) and House 26 area, and CH_W 460 at the entrance to the village. As the bridge crossing near CH_C 230 was only around 1 m in height, the blockage has significantly raised the local river bed.

<u>The Engineering Works</u>

Before the 22 July 2010 flooding, river training works that have been constructed in the Sha Po Tsai area include:

- The 30 m long x 13 m wide x 4.8 m high boulder trap;
- A 60 m long gabion wall at the right bank downstream of the boulder trap (CH_C 50 – CH_C 110);
- A check dam and gabion wall near CH_C 230; a partially completed bridge abutment;
- A gabion wall at CH_C 350-400.

Of the above engineering works, the boulder trap was constructed to provide early protection to the village against boulders. The gabion wall downstream at CH_C 350-400 is judged to have negligible effect on the flooding. The main issue is whether the engineering works – especially the upstream gabion wall and the check dam near CH_C 230, and the construction works have aggravated the flooding situation.

2.2 <u>Causes of the 22/7/2010 flooding</u>

<u>Catchment hydrology</u>

- The Sha Po Tsai catchment lies to the northeast of Tai Mo Shan. The terrain elevation ranges from 777 m to 14 m; bed gradient varies from 25% uphill to around 3-5% in downstream ends of the river. The soil is mainly clayey silt overlying volcanic rock. The natural catchment mainly consists of grassland and woodland (Appendix A).

- The Tai Mo Shan station rain gauge recorded a maximum hourly rain of 114.5 mm - the highest since records began 10 years ago; this corresponds to a rainstorm with approximately a 20 year return period.
- In addition, the 7 km^2 catchment received a total rainfall of more than 100 mm within the 10 days preceding the flood event. This resulted in a significant ground moisture condition prior to the flooding incident.
- As the time of concentration for the steep catchment is rather short, around 50 minutes, the heavy rainfall of 22 July 2010 has resulted in a significant flood flow in the order of 120-140 m^3/s (Fig.A2).
- Even assuming an idealized single channel network at the village, the physically-based distributed hydrologic model predicts flood peak at around 6 pm and high velocities of around 4-6 m/s at the village.

<u>Overland and stream flow</u>

- The water flows from south to north into the Tai Po River. The overland flow collects into two main streams: Stream A downstream of the vortex intake, and Stream B downstream of the bottom rack intake spillway. These two intakes are designed to intercept part of the flows at the two streams into the Plover Cove Reservoir System. Stream flows in excess of the designed intake capacities will continue to flow down the streams to the lower catchment. During the rapid heavy black rainstorm, significant surface runoff from the already saturated upper catchment was collected to the two streams. Part of the incoming flow to the vortex intake might discharge from the air-regulated siphon into downstream when the collection tunnel is significantly surcharged (see later discussion).
- The 2D hydrodynamic model results show a fast supercritical flow down the steep slopes of the two streams, with depths of around 1-1.5m, velocity of 4-6 m/s, and Froude number of Fr=1.5-2. In particular, the longer and winding Stream B induces a complex pattern of both supercritical and subcritical flows, with hydraulic jumps in between. The jumps would have resulted in significant turbulence and intense flow recirculation along Stream B. At the confluence between the two turbulent streams, the two fast moving waters collide, leading to a hydraulic jump (sudden rise in depth), and extremely high velocity (8-9 m/s) after the confluence (Appendix B).
- High velocities in the turbulent flow resulted in significant scour of the river banks and the bed of the boulder streams and the flood overtopped the bridge in Stream A. Aerial photos reveal significant soil erosion downstream of both the intake and the spillway, and especially in the flow paths around the confluence. The soil erosion would dislodge boulders and coarse sediment that would be transported down the streams as bed load. The heavy rain storm of 22 July 2010 resulted in a very rapid turbulent flow of muddy water transporting coarse sediment including boulders.
- The pattern of computed velocities on the steep streams and after the confluence (Fig. B1-B3) is consistent with the field observations.

<u>River flow upstream of Sha Po Tsai</u>

- The combined flow after the confluence continues to flow as a supercritical stream with depth of about 2 m, and velocity of 5-9 m/s. The supercritical flood flow is contained within the boulder trap; there was some side spilling at the upstream right bank of the boulder trap.
- The flow immediately downstream of the boulder trap resembles a supercritical high velocity jet, with velocity of 5.5-6.5 m/s. A turbulent flow of this magnitude resulted

in significant scour of a loosely compacted bed downstream of the boulder trap (Fig.B4).

- The velocity field shows most of the flow going into the central branch; significant velocities behind the gabion wall are predicted. It also shows relatively little flow going into the east branch with a higher bed elevation - around 20 m^3/s.
- The velocity field without the gabion wall shows little difference. The flow split into the east branch is also relatively insensitive to the presence of the gabion wall.
- In general, the flow depth leading up to about CH_C 200 (upstream of Sha Po Tsai) is not large, about 1-2 m, with a velocity of around 4 m/s (Fig.B5).

Overall, there is a high degree of correlation between the computed flow (neglecting sediment transport) and the observations upstream of the Sha Po Tsai. The results also show that the presence of the gabion wall is not likely to induce any adverse impact to the flooding downstream.

<u>Flooding at Sha Po Tsai</u>

- The computed flow shows that the flow first splits into the central and east branches. As the flow approaches the village and the check dam area, part of the stream flows into the west branch. The east branch also rejoins the central branch near the check dam (Fig.B6).
- There is relatively little flow into the east branch with the higher bed elevation (Fig.B7).
- There is clear pile up of the water in front of the flood wall next to the check dam, with overflow into the west branch and also into the central branch above the fully blocked bridge crossing (see Appendix C).
- Flood levels of over 36 mPD are predicted at the check dam; when combined with a raised river bed (by 1-2 m due to coarse sediment), the flood levels can be even higher, approaching 38 mPD (Fig.B7).
- The large flow results in flooding of the village, with depths of around 0.5-1 m on the flood plain; impact velocity heads would result in higher depths. The flood flow sweeps longitudinally downstream along the axis of the village (south-north direction). Blockage of the flow by houses would result in minor local flows across the village (in the west-east direction).
- The flood level and bed level of the west branch is higher than those of the central branch; the flow along the west branch is complicated, with depths of 2.5-3 m, and velocity of 3-4 m/s (Fig.B7 and Fig.B8).
- The flow in the central branch is mostly supercritical, with velocity of 2.5-4 m/s, and depth up to 2.5 m.
- In the lower Sha Po Tsai (CH_W 460-550), the flow in the west and central branches has a depth of 2.5-3.7 m, with velocity of 4-5 m/s.
- In summary, the high velocity flows in both the west and central branches are capable of transporting coarse sediment and extremely hazardous.
- Overall, the predicted water surface levels correlate well with the field observations (Fig.B5 and B9).
- In the absence of all engineering works, both 2D and 3D model calculations show that flooding would still have occurred (Fig.B10, see also Appendix C).

COMMENTS ON INVESTIGATION REPORT

3.1 General comments on investigation

The investigation on the flooding was completed in a most comprehensive manner within several weeks after the incident. Several major tasks were accomplished: collection and analysis of the flood observations based on photos and videos, interviews of the villagers; documentation of site conditions before and after the flooding; analysis of hydro-meteorological data and flow estimation; hydraulic modeling to investigate representative flooding scenarios; evaluation of the impact of the completed and temporary river training works on flooding; and estimate of sediment erosion and deposition within the site boundary. Suggestions for future drainage improvement are also made.

In general the investigation has been carefully conducted and a credible and objective analysis of the flooding has been carried out.

3.2 MIKE11 hydraulic modeling

The use of this industry standard one-dimensional model to simulate the hydrology and flood flow is consistent with the mathematical framework used for the original drainage master plan. The choice of the five scenarios is reasonable and well-considered. The hydrological model that uses the SCS method has been previously calibrated against data, and acceptable comparison of predicted and observed flood levels can be achieved after calibration and careful interpretation. However, the limitations of this approach to simulate the complex flow in the steep braided river should be recognized in the interpretation of the MIKE11 predictions. For example, the weak sensitivity of the predictions to severe blockage of the bridges can be noted.

3.3 Flow estimation

The estimation of maximum flow on the day of flooding is of prime importance as it affects the calibration of the hydraulic models and different interpretations of the event, and prediction of drainage performance. The video records suggest a severe scary flood flow.

The flow is estimated based on the observed 20.6 mPD water level by assuming critical brink flow conditions (with critical depth yc) at the cascade. This can be questioned in two respects: (i) the flow in the central branch is not really a subcritical flow, and not a brink flow at the cascade; the assumption of critical flow at a location of 3 critical depths from the beginning of the cascades is not strictly valid; (ii) the flow estimation would be sensitive to the assumed location of the critical flow. It is not clear whether critical flow exists in the exact sense on the cascade steps. The 2D model shows that the flow is slightly supercritical in the central branch and slightly subcritical in the west branch. Fortuitously, it turns out the flow in the downstream river reach is near critical. The observed velocity of floating object near Tat Wan Road also supports the estimated flow of 140 m^3/s.

Hydrological calculations under this Review using the calibrated MIKE-SHE model (simulating the physical processes of infiltration and overland flow, rather than assuming lumped empirical parameters) suggest that the maximum flow at the downstream end of Sha Po Tsai Village is of the order of 140 m^3/s, including discharge from air-regulated siphon of vortex intake, discharge from bottom rack intake spillway and catchment runoff downstream of WSD water supply intakes. In this calculation, a single channel of bottom width 18 m and top width 24 m is assumed for Sha Po Tsai (Appendix A).

The hydrological model also shows the upstream flow arriving at the two water supply intakes is also of the order of 140 m^3/s; about 58 m^3/s from the catchment of vortex intake and 86 m^3/s from the catchment of bottom rack intake spillway. Part of the flow arriving at the bottom rack intake spillway was diverted to the vortex intake.

The overtopping of the bridge and significant scour at the downstream end of Stream A indicated that part of the flow arriving at vortex intake discharged from the air-regulated siphon on 22 July 2010. It is also relevant to note that the Plover Cove collection tunnel was surcharged at 90 m PD in the vortex drop shaft during the severe rainstorm event.

As confirmed by Ir Peter Clark of BV during the meeting with WSD on 10 September, 2010, it is possible that a discharge of the order of 20-30 m^3/s from the air-regulated siphon of the vortex intake could occur on 22 July 2010. The scroll vortex intake was designed to pass a maximum flow of 58 m^3/s, but during extreme events it is anticipated that the excess flow will be passed through the air-regulated siphon spillway adjacent to the vortex intake.

The data suggests that the drop shaft at vortex intake is surcharged during the rainstorm. The elevation of the spillway and bottom of the vortex intake are approximately 100 mPD and 95 mPD respectively - in other words, a maximum flow of around 58 m^3/s swirls down the drop shaft as a free vortex at 5 m head (relatively to intake bottom) under freely draining conditions. This would be the case provided the throat of the vortex is not “drowned” - i.e. not affected by downstream conditions.

When the drop shaft is significantly surcharged, as in this flooding event, the vortex flow impinges on the water surface resulting in significant turbulent air entrainment and a column of air-water mixture. This implies that the level of the air-water interface will be higher than that indicated by the hydrostatic pressure (piezometric head). When the pressure head indicates 90 mPD, the air-water interface will be higher, and it is probable that the vortex throat action may have been affected.

In the absence of detailed water level data, it is difficult to estimate the discharge from the air-regulated siphon. However, based on the velocities required to generate significant scour (Fig.B1), it was probable that while the vortex intake protected downstream flooding by intercepting part of the runoff as designed, a discharge of 20-30 m^3/s might have occurred.

3.4 Impact of engineering works:

Independent 2D and 3D hydrodynamic model calculation confirm that the main cause of the flooding is the extreme rainfall event and resulting flood flow. This supports the finding in the investigation report that “the Sha Po Tsai Village would have been flooded even if there were no drainage improvement works under construction; and even if there were no blockages of the seven bridges”. The July 22 flood flow far exceeds the drainage capacity of the narrow river reaches, in particular the 5-10 m wide west branch.

The 60 m long gabion wall downstream of the boulder trap did not affect the flow through the east branch which seems to be chiefly governed by the topography and flow capacity (Fig.B4 and Fig.C1, C2).

The presence of the check dam and gabion wall near CH230 did not aggravate the flooding situation in terms of maximum flood level and velocity in the Sha Po Tsai vicinity. The flood flow impinging on the pre-existing flood wall and the head of the island would result in a pile up of water and subsequent flooding; this would be further aggravated by any coarse sediment that would block the bridge crossings to some extent (Fig.C3, C4 and C5).

The calculations show that the check dam served to divert more flow into the central branch by about 3-4 m^3/s. In general the difference due to the check dam (Case 1 and 2 in Table C1; assuming bridge closure by boulders) is insignificant. Similarly the difference in water depth and velocity due to the boulder trap is insignificant (Case 1 and Case 3, Table C1).

The results show that even in its natural state, the Tai Po River would have flooded to similar levels when subjected to this flood flow (Fig.C6). Compared to the pre-project situation, the completed works have resulted in some minor decrease in flood level and velocity in some locations but increase in other locations. Overall, it is judged that the difference in flood risk due to the constructed works is acceptable.

The presence of the gabion wall at CH_C 350-400 is judged to have an insignificant effect on the flooding in the village.

Overall, the hydrological and hydrodynamic model calculations confirm the main finding of the Investigation Report. However, the results also reveal the complexity of the flow and the over-simplified interpretation that "the constructed works had alleviated the flooding in the village". The contrast of the computed longitudinal south-north flood flows and the assumed west-east flood flows across the village reflects the beneficial use of the 2D and 3D model for this challenging problem.

3.5 Sediment Balance

The steep upper Tai Po river is a high energy mountain stream with boulders and gravel on the river bed. The current state of knowledge on sediment transport in steep boulder streams is very limited. There have been many observations in connection with debris flow or debris floods, but there is no generally accepted theory. The existing predictive methods are primarily empirical and site specific.

Application of existing empirical methods suggest that a turbulent flow velocity of 4 m/s is sufficient to mobilize coarse sediment of up to 1 m size on the river bed. This correlates with reported observations in previous debris floods. Given the high velocities in Stream A and Stream B, it seems clear that significant upstream erosion has occurred. The estimation of sediment deposition in the work site is credible and conservative as it is computed by both (i) interpretation of photos before and after the flood; and (ii) by site surveying and truck loads.

The average sediment yield per meter is about 40% higher in Stream B than Stream A. This is evidently related to the larger flow and stronger turbulence in Stream B; the serious erosion around the confluence appears also to be related to the collision of the two high velocity streams, resulting in hydraulic jumps and intense flow circulations.

The estimation of the sediment transport out of the site based on suspended solid concentration determined by comparing the river color with muddy water of known concentrations is rather crude, but may be acceptable considering most of the bed load would have been deposited at the downstream end in Tat Wan Road.

Overall, the sediment balance is carefully performed. The boulder trap has served the purpose of protecting the village by trapping significant amount of sediment. The evidence suggests that the main source of boulders and sediment is derived from upstream of the boulder trap.

3.6 Construction sequence

In a river basin the stream flow normally increases downstream; in river training works, the construction sequence is typically from downstream to upstream as this would afford greater flood protection and avoid significant backwater effects from downstream. This is normally the case for rivers of typical length of the order of kilometers. For the steep Tai Po River, the optimal construction sequence may not be governed rigidly by the above general considerations: first, the site is a short reach of 700 m; and differences in flow upstream and downstream are not significant; second, this is a steep river where supercritical flow generally prevails; the flow control is mainly from upstream and there is insignificant backwater effect from downstream. Site access for the construction works is also a practical consideration. It is also evident that the early construction of the boulder trap to channelize the upstream flows and to provide early protection of the village from large boulders is beneficial. The optimal construction sequence should be based on a balance of construction practicability, flood hazards, and adequate protective measures.

As shown in the hydraulic modeling calculations, this flooding incident is caused by a combination of highly unlikely events: a black rainstorm of unprecedented scale on a saturated catchment, resulting in rapid and large flash flood flows that exceeded the capacity of the water supply intakes. The village would have been flooded had the river training works not been in place. On the other hand, best construction practices and an awareness of the possible impacts of drainage improvement construction works should be heightened in guidelines of construction practice. The model calculations show that the check dam at CH230 served to decrease the flow into the west branch by about 4 m^3/s, but the effect is not very marked.

3.7 Short term and long term improvement measures

A number of short term improvement measures are suggested, including temporary wire boulder fence, grille at boulder trap, and enhancement of flow capacity by concrete pipes at the river crossings in the central branch. In particular, the demolition of the bridge crossing at CH-C 230 and replacement by a significantly elevated footbridge (from 35.8 mPD to 37.2 mPD) would be a critical step in improving the drainage capacity. All these measures will be beneficial in alleviating flood risks.

It should be noted that the modeling results reveal complex flow patterns in the bifurcated braided rivers and there is also currently no universally adopted design method for the stepped channel. In the light of the severe flooding on 22 July 2010, it would be prudent to verify or fine tune the design of the Tai Po River training works using the more sophisticated mathematical hydrodynamic models and/or physical models as appropriate to cross check the design of critical section and optimize hydraulic performance.

It is recognized that sediment transport in steep mountainous boulder streams is not well-researched and many technical issues are not resolved. In view of the relative lack of experience in upland drainage management, a survey of other boulder streams for which river improvement works are being implemented in the territory is appropriate. In the long term, local expertise on these complex sediment laden floods needs to be developed. Experimentation on these flows, either on field or laboratory scale, should be encouraged to provide the needed data and to develop applied R&D to support drainage engineering in

Hong Kong. For example, remotely controlled water level (pressure) and video records at critical locations would have greatly facilitated our unraveling of these transient events.

An additional boulder trap is proposed. In view of the lack of experience in the design of boulder traps, and the complex causes of the 22 July 2010 flood, the location and design of the proposed second boulder trap should be further investigated.

CONCLUSIONS AND RECOMMENDATIONS

1. Independent hydraulic modeling studies have confirmed the key finding of the Investigation Report - that the 22 July 2010 flooding incident in Sha Po Tsai Village is caused by a combination of highly unlikely events: a rapid black rainstorm of unprecedented scale on a saturated catchment, resulting in large flash flood flows in excess of the designed capacity of the water supply intakes that continue to flow down the streams to the lower catchment. The village would have been flooded to similar levels had the river improvement works not been in place.

2. Aerial photos, field observations and hydraulic modeling have collectively shown that the main source of the boulders is derived from upstream of the boulder trap. The high velocity of the turbulent flow (up to 9 m/s) led to serious erosion of the river bank and bed, and mobilized boulders and coarse sediment that are transported down the river as bed load. The observed soil erosion pattern correlates well with the predicted velocities.

3. The optimal construction sequence of river improvement works in the steep Tai Po River should be determined by a balance of construction practicability, site access and interim flood protection. The early construction of the boulder trap is reasonable and has protected the downstream villages from the boulder current.

4. It is recommended that the design of the Tai Po River training works having complex flow pattern be verified or fine tuned using the more sophisticated mathematical hydrodynamic models and/or physical models as appropriate to cross check the design of critical section and optimize hydraulic performance.

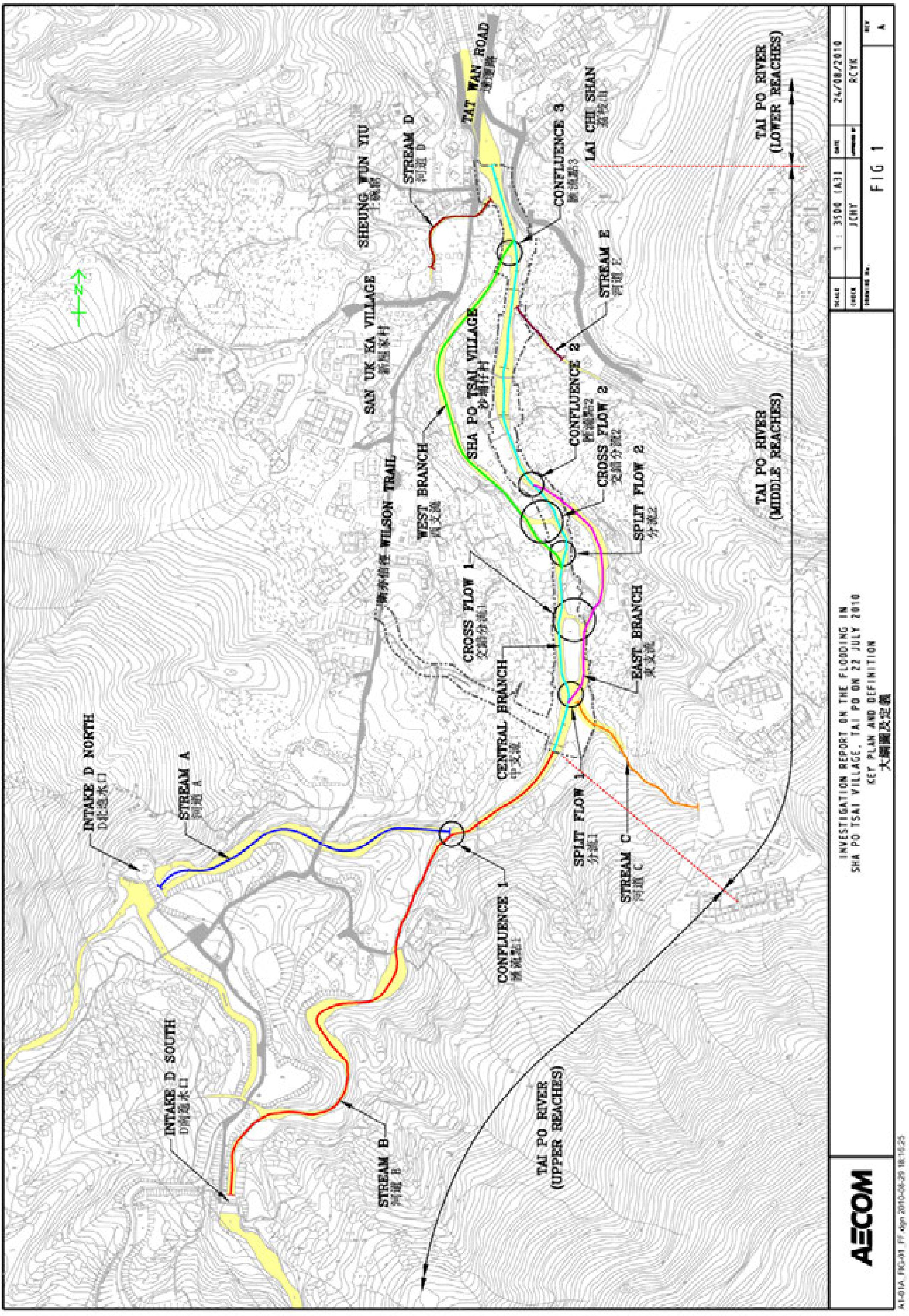

TAT WAN ROAD
SHEUNG WUN YIU
STREAM D
CONFLUENCE 3
LAI CHI SHAN
TAI PO RIVER (LOWER REACHES)
STREAM E
SAN UK KA VILLAGE
SHA PO TSAI VILLAGE
CONFLUENCE 2
CROSS FLOW 2
SPLIT FLOW 2
WEST BRANCH
WILSON TRAIL
TAI PO RIVER (MIDDLE REACHES)
CROSS FLOW 1
EAST BRANCH
CENTRAL BRANCH
SPLIT FLOW 1
STREAM C
INTAKE D NORTH
STREAM A
CONFLUENCE 1
INTAKE D SOUTH
STREAM B
TAI PO RIVER (UPPER REACHES)
INVESTIGATION REPORT ON THE FLOODING IN SHA PO TSAI VILLAGE, TAI PO ON 22 JULY 2010
KEY PLAN AND DEFINITION
大綱圖及定義
AECOM
1 : 3500 (A3)
24/08/2010
FIG 1

Figure 1

Appendices

Appendix A Hydrological simulation

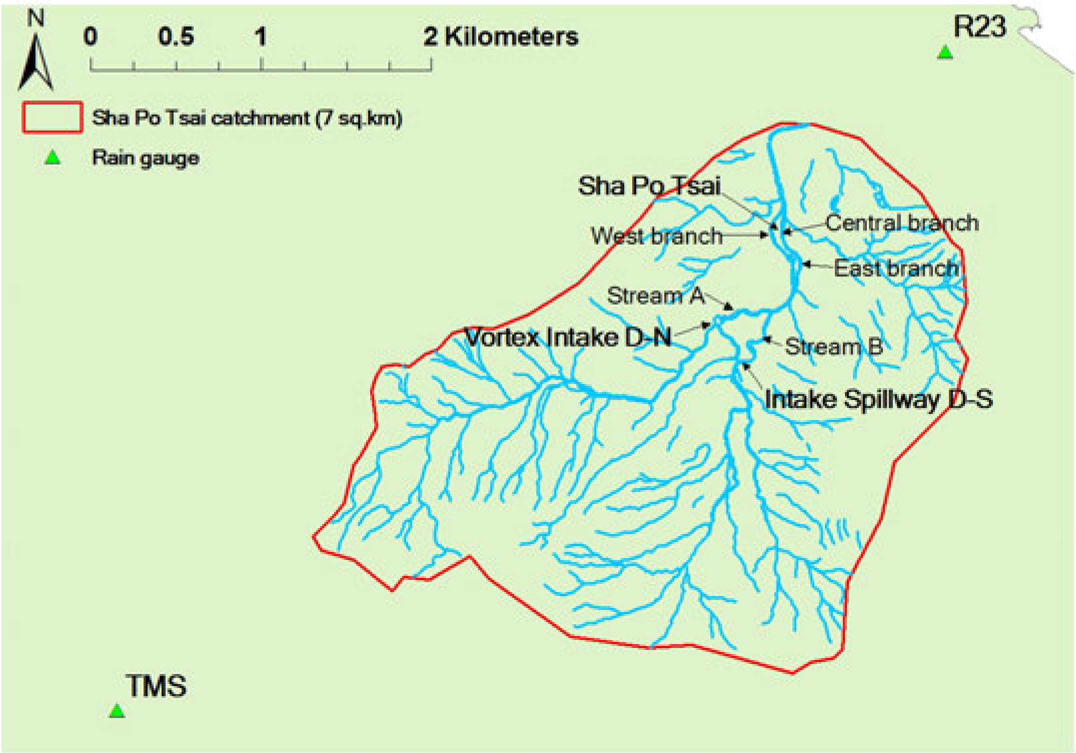


Figure A1 Sha Po Tsai catchment

The physically-based distributed hydrological model MIKE-SHE is used to predict the rainfall - runoff response of the Sha Po Tsai catchment. Unlike the empirical SCS curve number method, MIKE-SHE models the physical processes of the hydrological cycle (rainfall, evaporation, surface and subsurface flow) and incorporates the topography of the basin derived from a Digital Elevation Model (DEM). The model has been successfully applied to predict the flow at an un-gauged Ho Chung catchment in Sai Kung, with model parameters being calibrated against stream flow record of a nearby catchment at Siu Lek Yuen.

As model inputs, a DEM of 50 m x 50 m is generated by interpolation of a 1:5000 contour map. Soil type is based on land use pattern and past bore hole records in the Tai Po area. 5-minute rainfall (aggregated from 1 min data) at two Hong Kong Observatory rain gauges, Tai Mo Shan (TMS) and Tai Po Wong Shiu Chi Secondary School (R23), and 5-minute potential evapo-transpiration at King's Park are used as meteorological inputs. Model parameters such as saturated hydraulic conductivity and Manning's coefficient are estimated based on physical characteristics and literature values. The 3-minute averaged flow and velocity at the Sha Po Tsai catchment are obtained from the model.

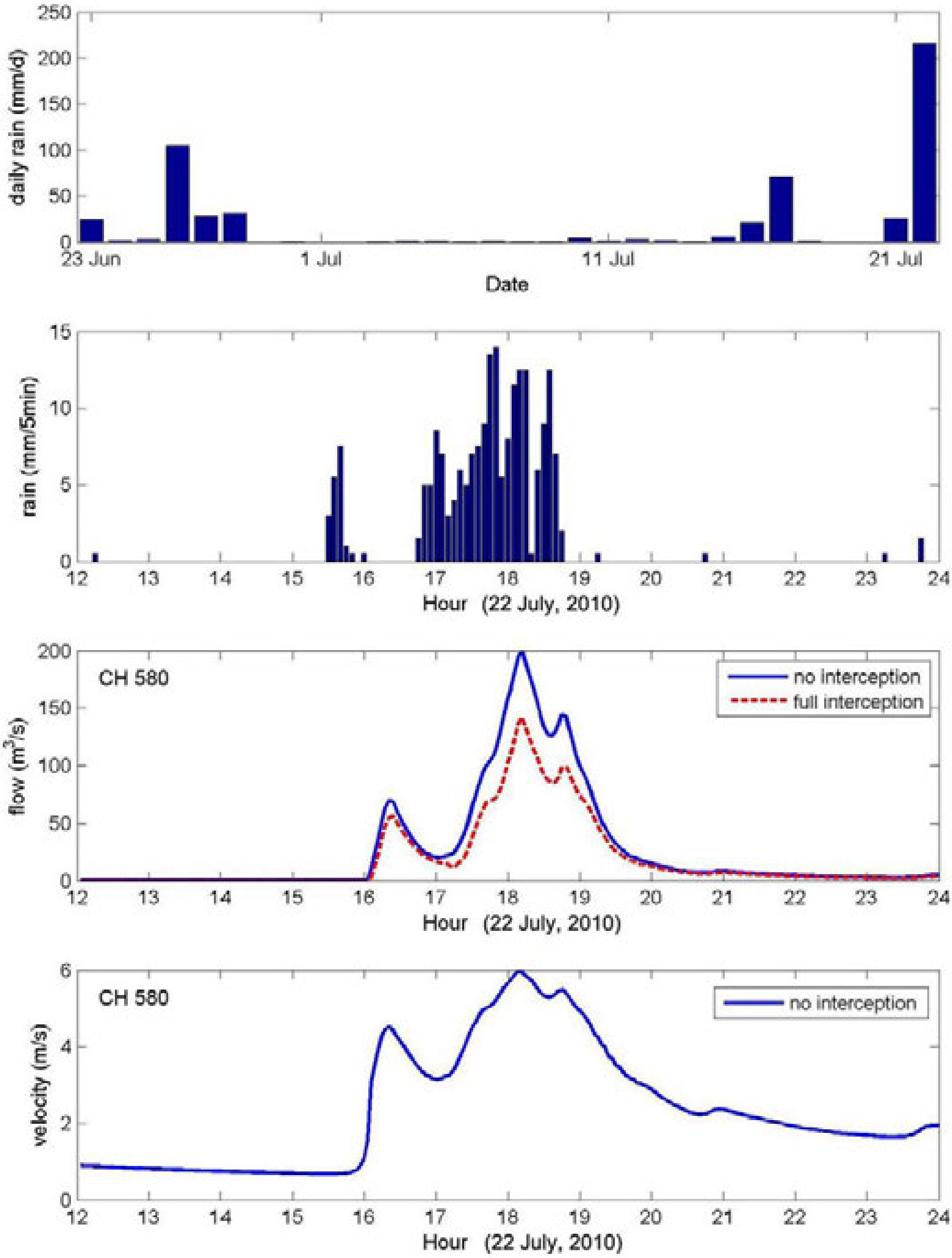


Figure A2 Observed rainfall and the predicted flow and velocity at Sha Po Tsai village (CH580) on 22 July 2010

Appendix B   Predicted flow in Tai Po River (2D hydrodynamic model)

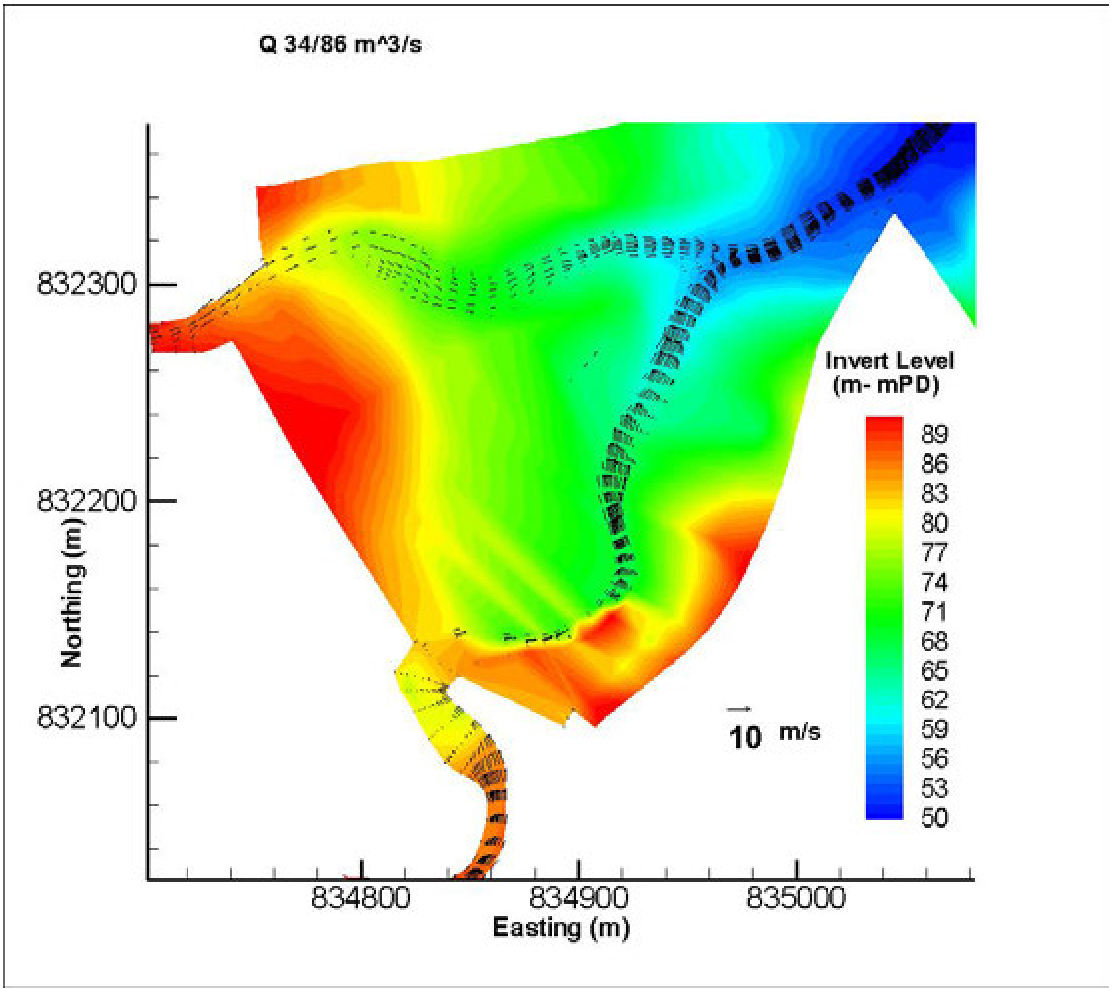


Figure B1 Velocity field at Stream A and Stream B

The two-dimensional (2d) hydrodynamic model solves both supercritical and sub-critical flow problems using a shock capturing method (Arega and Sanders 2004). The depth-integrated continuity and momentum shallow water equations are written in conservative form, and Godunov-type finite volume method is used to advance the solution in time. Quadrilateral cells in curvilinear coordinates are used. Fluxes are computed with an accurate second order accurate scheme. The solution method allows for possibility of sharp gradients, making it highly suitable for simulating discontinuities such as hydraulic jumps. The method has recently been successfully applied to the Yuen Long Bypass Floodway (Arega et al 2008).

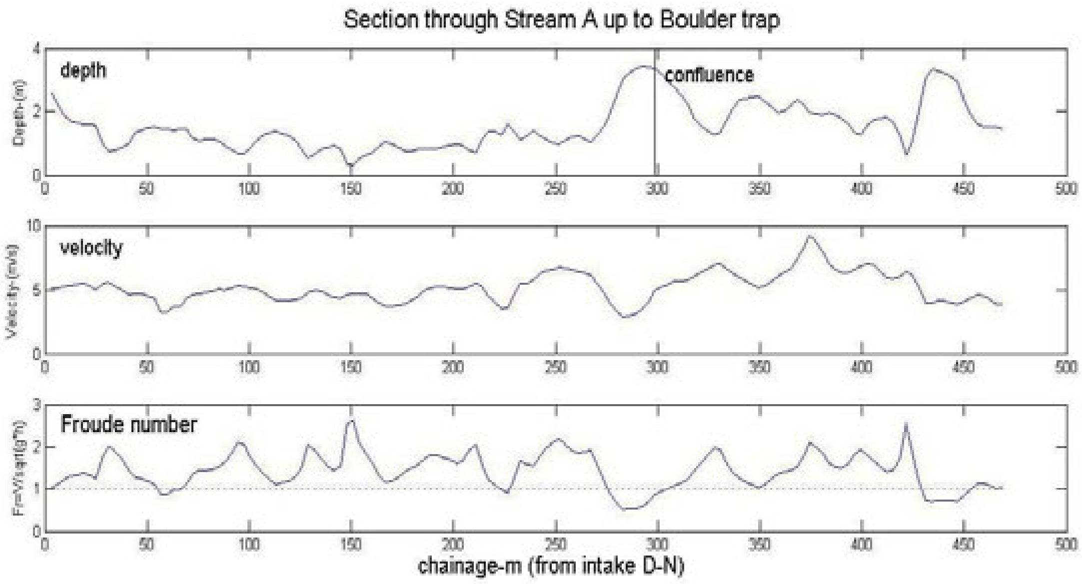


Figure B2 Predicted supercritical flow along Stream A (2D model)

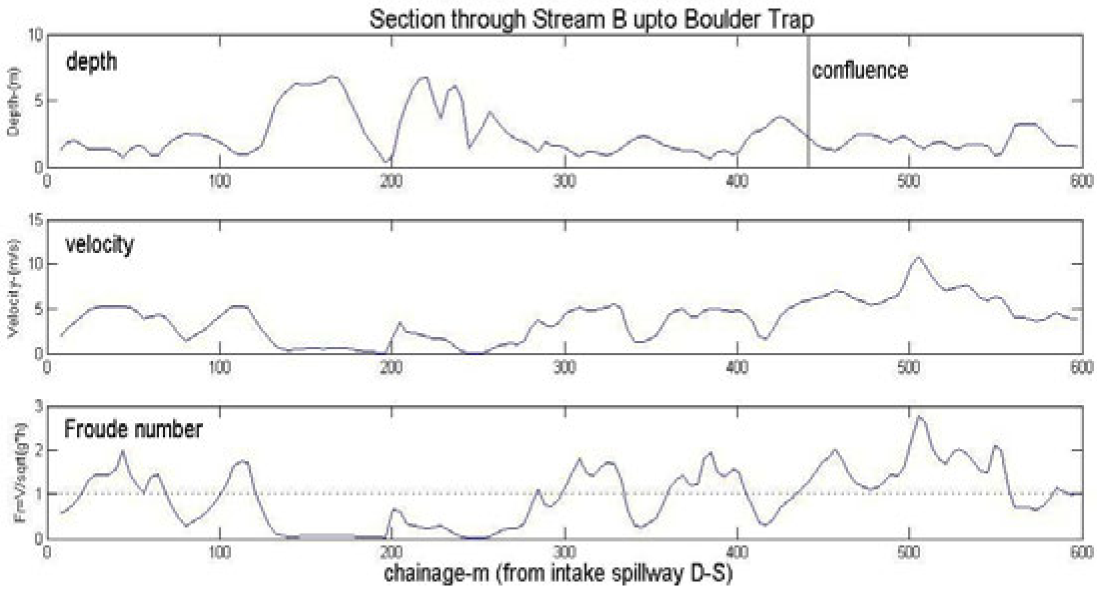


Figure B3 Predicted flow along Stream B (2D model)

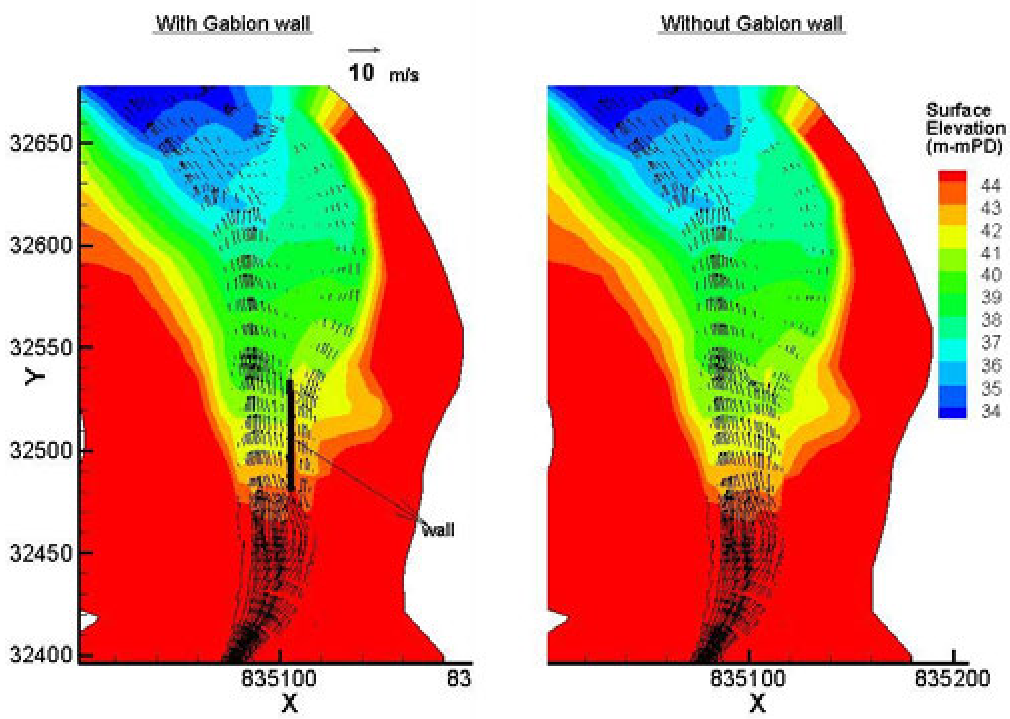


Figure B4 Predicted flow downstream of boulder trap - with and without gabion wall

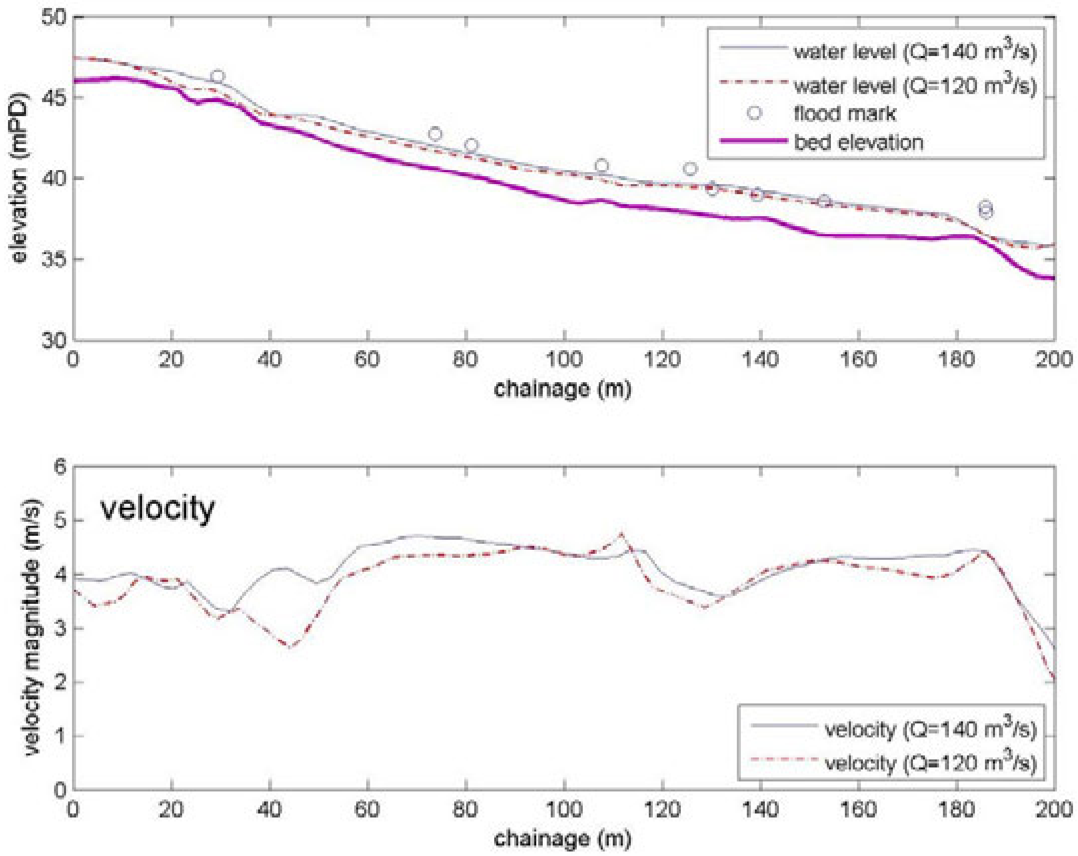


Figure B5 Predicted water surface elevation along central branch CH_C 0-200

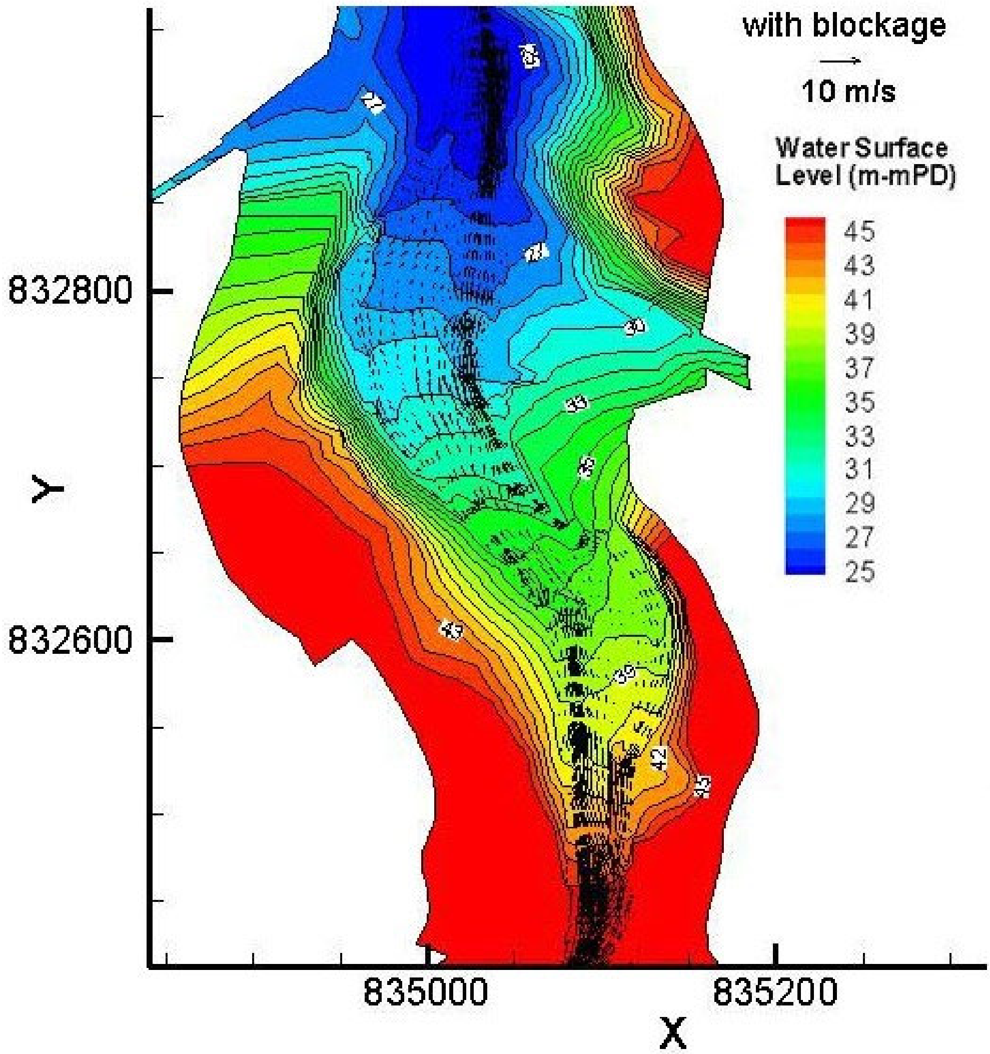


Figure B6 Predicted flow field from boulder trap to Sha Po Tsai Village

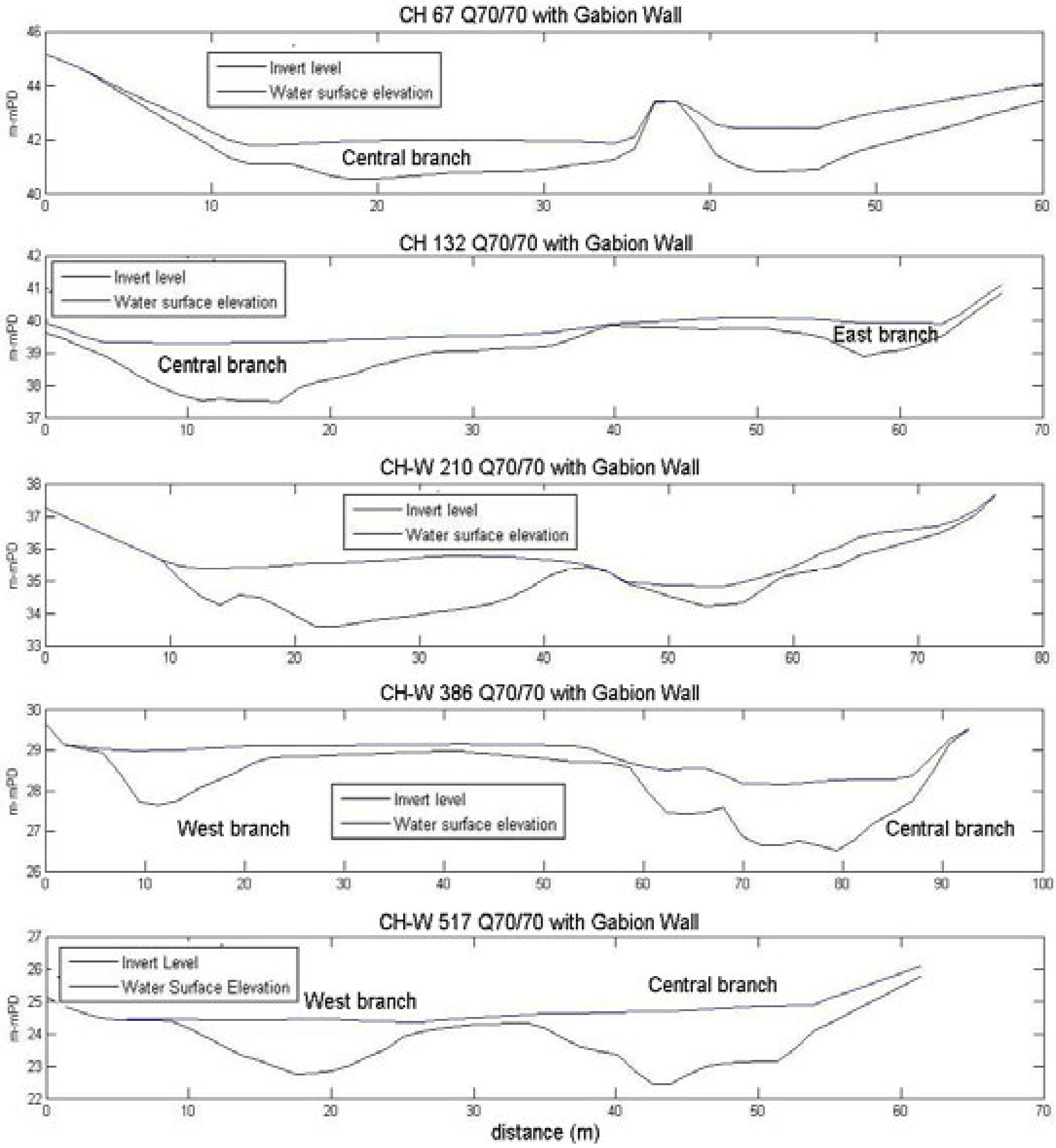


Figure B7 Predicted transverse water surface profile at different cross-sections

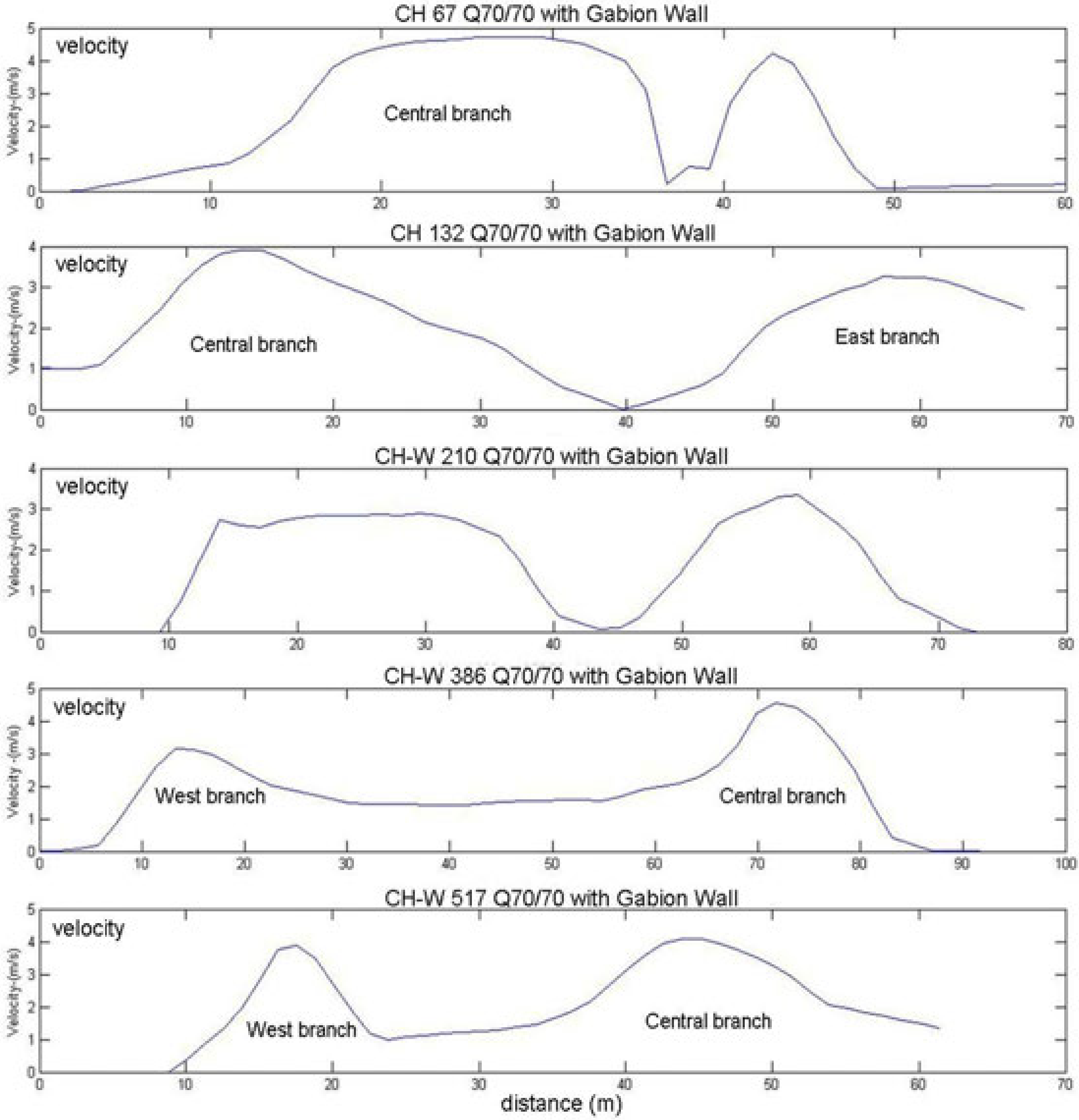


Figure B8 Predicted velocity profile at different cross-sections

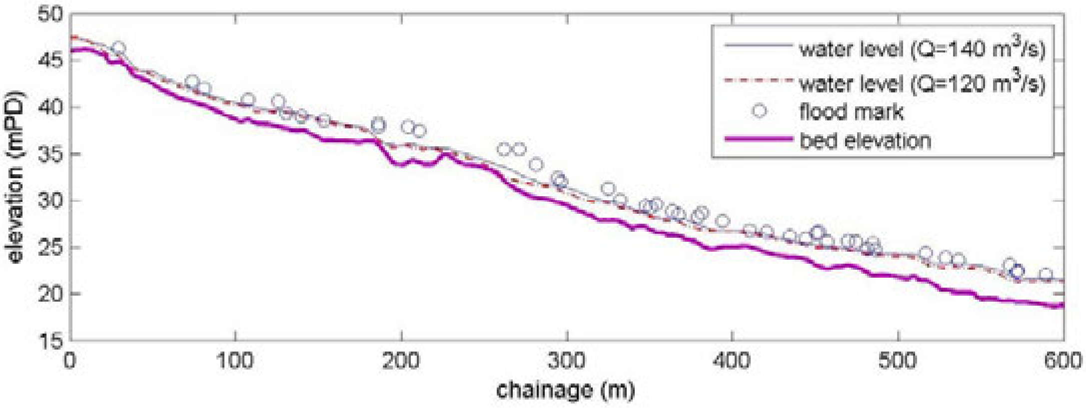


Figure B9 Predicted water surface elevation along central branch (22/7/2010)

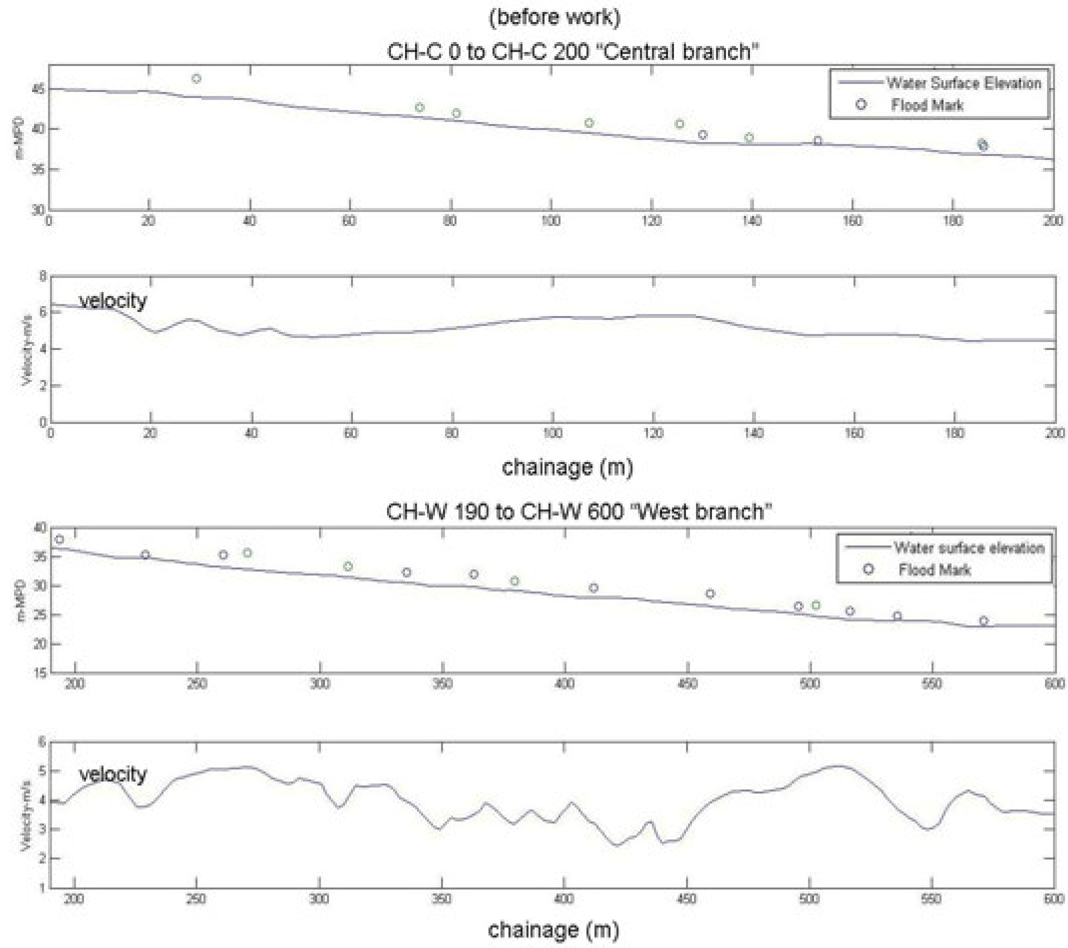


Figure B10 Predicted water surface elevation along central and west branches (pre-project)

Appendix C Predicted flow in Tai Po River on 22 July 2010 (Flow3d)

The three-dimensional free surface flow downstream of the boulder trap is simulated using the Flow3d software. The governing Reynolds-averaged Navier Stokes equations are solved; free surfaces are handled using the Volume-of-Fluid technique, and a standard k-e model is adopted for turbulence closure. A total of 2.2 million cells are used for modelling the river flow with complex geometry and solid boundaries. The impact of the boulder trap, 60 m gabion wall, check dam and bridge closure are modelled.

Table C1 Predicted flooding in Sha Po Tsai Village for different scenarios; the maximum water surface level, depth-averaged velocity, and depth in the cross-section are shown

Section	Maximum	Case 1 Boulder Trap + Gabion wall + Check dam	Case 2 Boulder Trap only	Case 3 Pre-construction
Check dam	Level (mPD)	36.46	36.44	36.95
	Velocity (m/s)	3.00	3.02	3.71
	Depth (m)	2.56	2.36	0.81
CH-C260	Level (mPD)	34.02	34.15	33.91
	Velocity (m/s)	3.94	4.31	4.06
	Depth (m)	2.44	2.51	2.37
CH-C340	Level (mPD)	29.86	29.87	29.89
	Velocity (m/s)	4.42	5.26	4.82
	Depth (m)	1.87	1.90	1.84
CH-C420	Level (mPD)	27.54	27.56	27.66
	Velocity (m/s)	3.29	3.04	3.61
	Depth (m)	2.35	2.29	2.47
CH-C500	Level (mPD)	24.16	24.15	24.43
	Velocity (m/s)	3.47	3.57	4.15
	Depth (m)	2.09	2.14	2.19

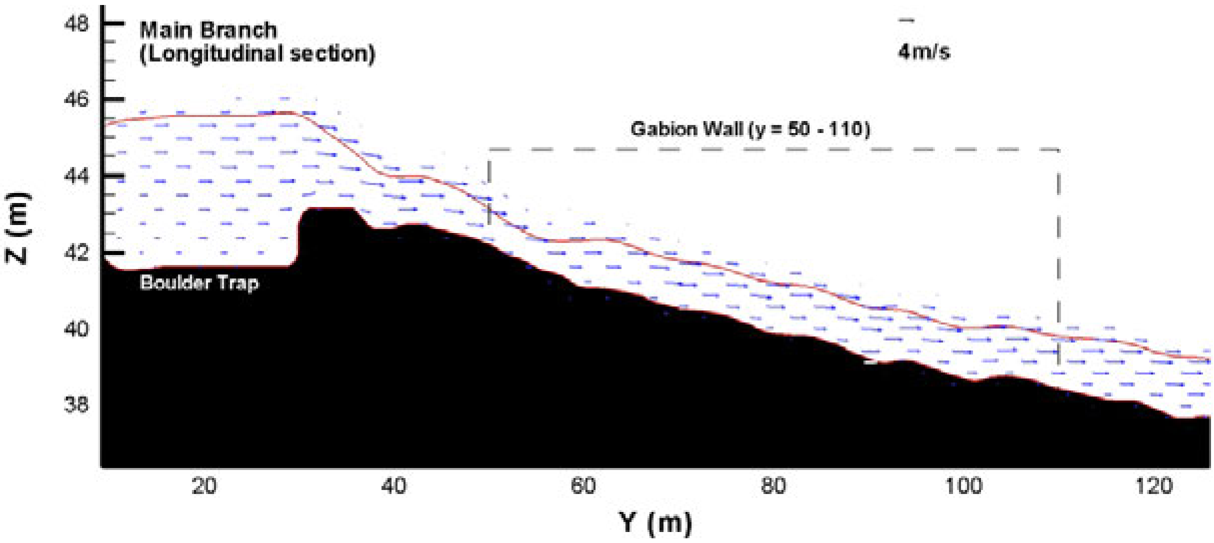
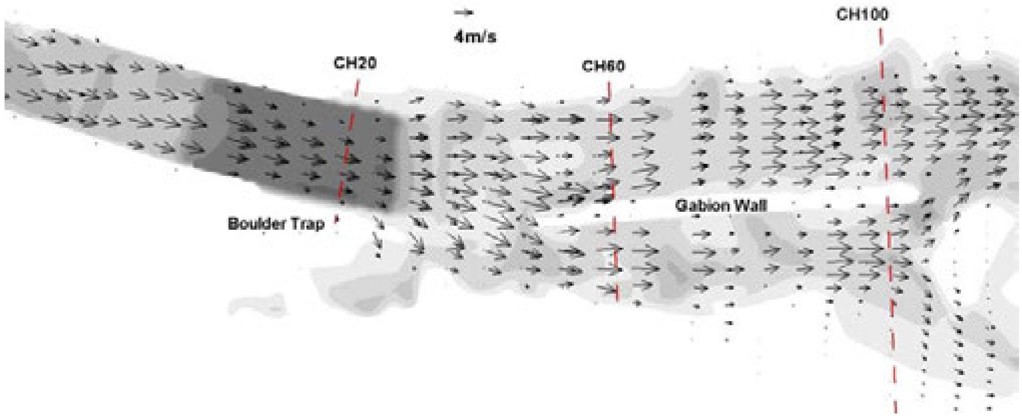
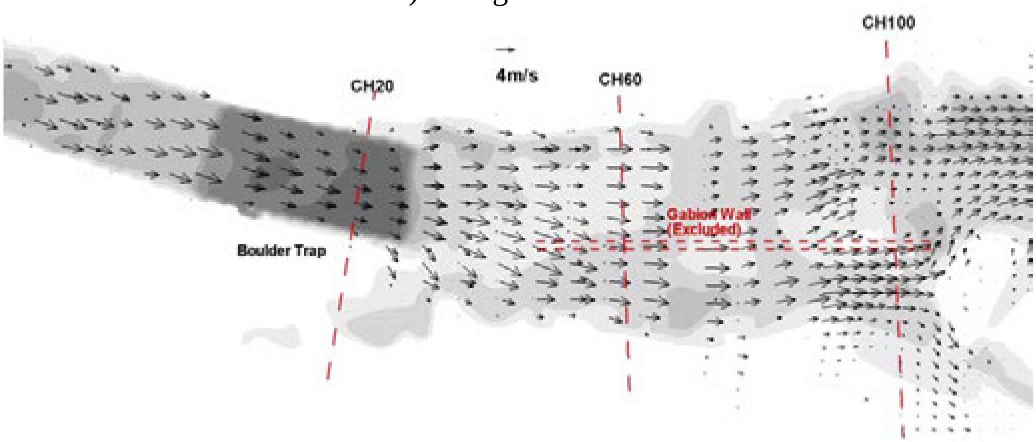


Figure C1 Longitudinal variation of depth along central (main) branch (CH 10 – 125)



a) with gabion wall



b) without gabion wall

Figure C2 Computed flow downstream of the boulder trap (CH 20 – 100)

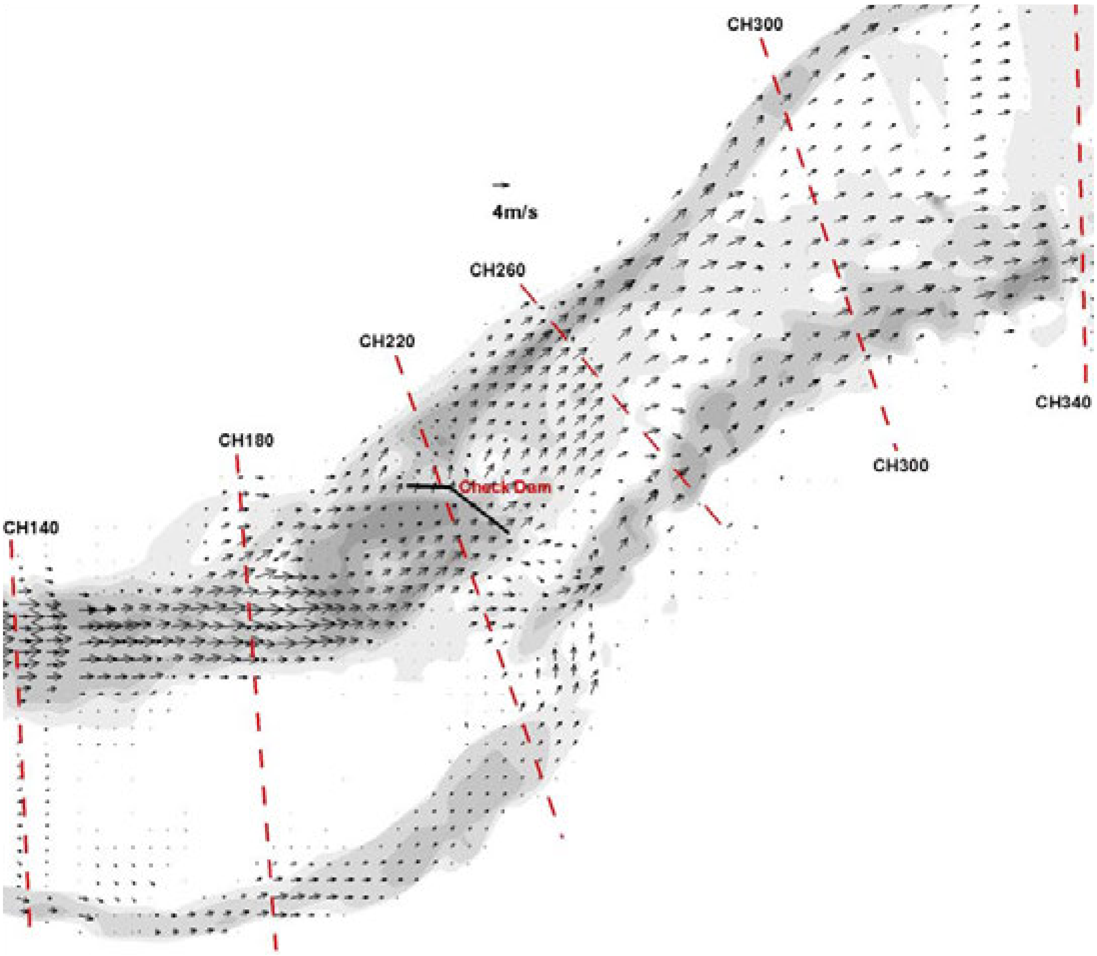


Figure C3 Computed surface velocity field near check dam (CH 140 – 300)

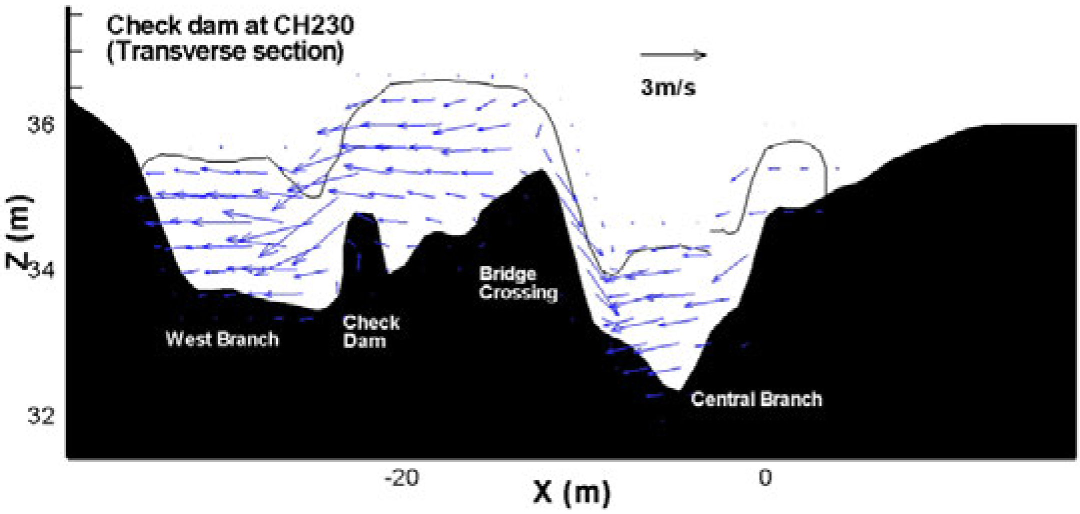


Figure C4 Computed flow field in cross-section near check dam (CH 230)

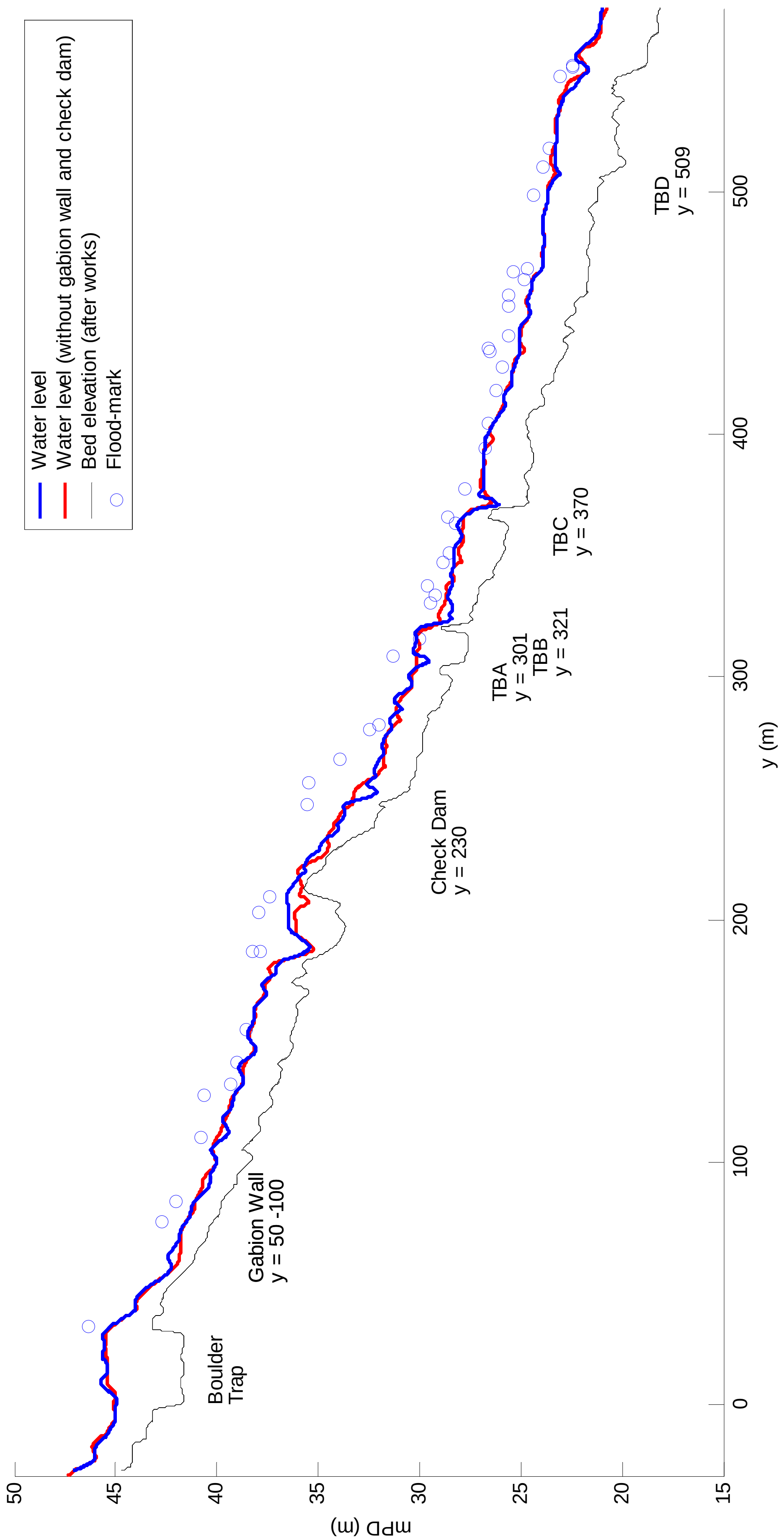


Fig.C5 Predicted water level along main (central) branch of Tai Po River

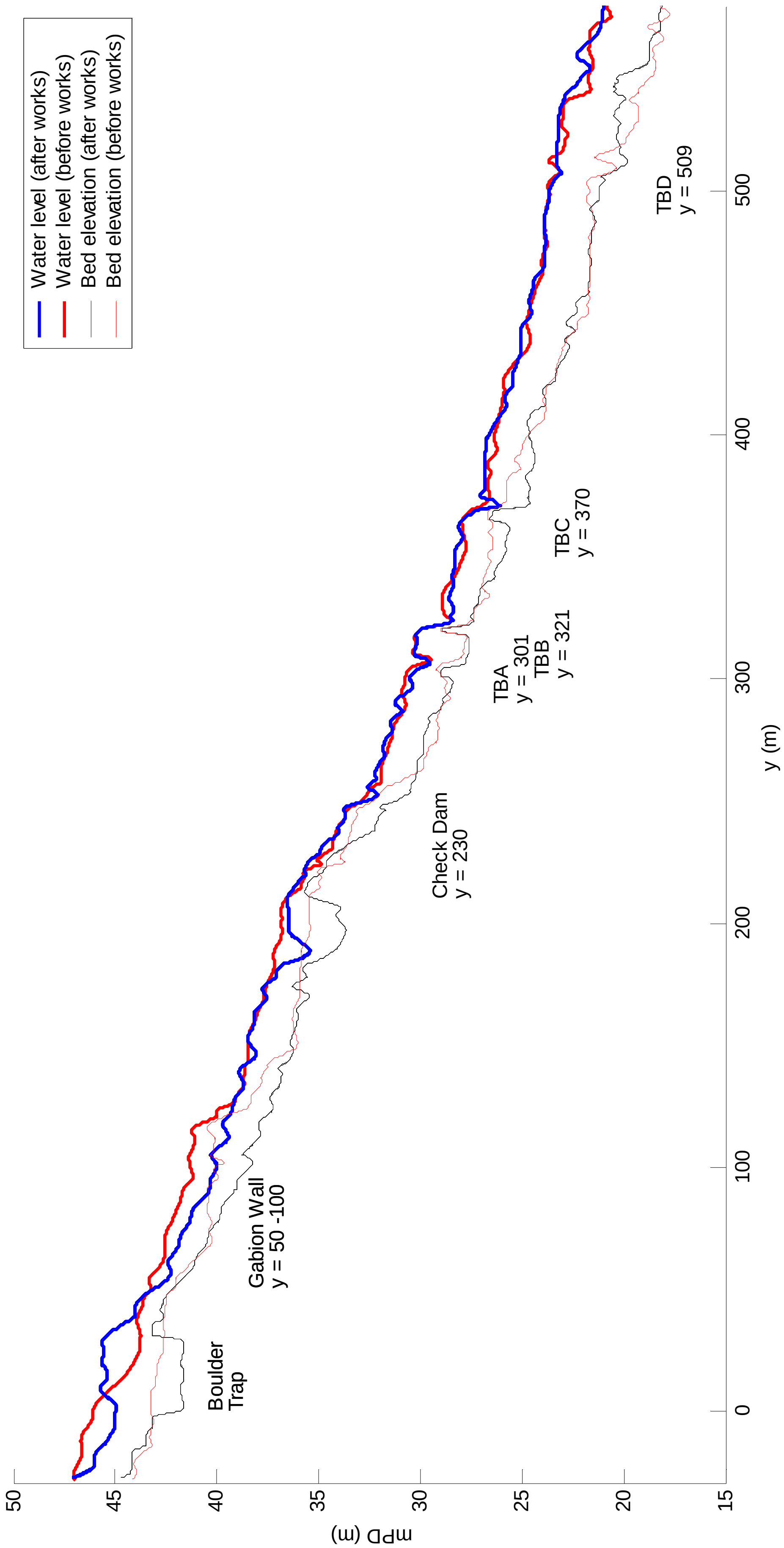


Fig.C6 Predicted water level along main (central) branch of Tai Po River