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Hydrodynamic Behaviour Change at Rambai River Outlet, Juru River Basin, Penang

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ABSTRACT

Rambai Valley is a partially urbanized and flood prone coastal plain located in the State of Penang. The valley is drained by Rambai River and its tributaries. Rambai River water level flux is subjected to daily tidal oscillation as the river is connected to the sea through the Juru River. During heavy rainfall events, the interactions between tidal intrusion and peak-flows in this coastal floodplain caused floods to occur. Tidal intrusion prevents effective outflows resulting in the accumulation of water that results in severe flooding. As a result, several flood management measures have been taken to mitigate floods. One of the most significant structural measures undertaken was the modification of the Rambai River outlet. This outlet, originally a small culvert was replaced with a large open channel in early 2003. The effectiveness of the new open channel in flood mitigation is examined and evaluated. The results of this research found that the new open channel may not be an effective flood mitigation measure and it may even aggravate future floods.

ABSTRAK

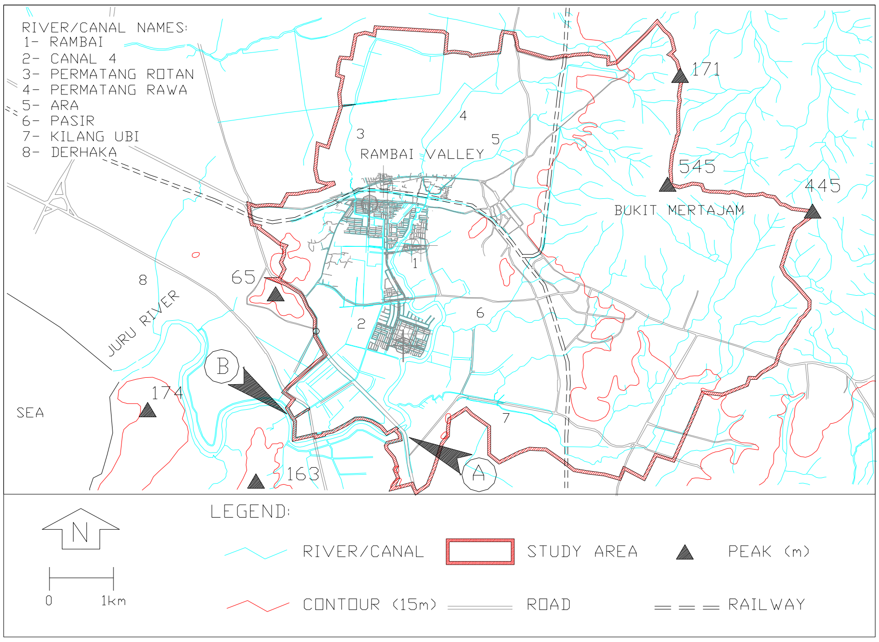
Lembah Rambai ialah sebuah dataran pinggir pantai separa terbandar yang sering dilanda banjir. Lembah ini disaliri oleh Sungai Rambai dan cawangan-cawangannya. Fluk aras air Sungai Rambai ditentukan oleh osilasi pasang surut harian kerana sungai ini dihubungkan dengan laut oleh Sungai Juru. Semasa hujan lebat, interaksi antara kemasukan air pasang dan aliran puncak di dataran pinggir pantai ini menyebabkan banjir. Kemasukan air pasang menghalang pengaliran keluar air secara berkesan menyebabkan pengumpulan air dan seterusnya banjir besar. Hasilnya, beberapa langkah pengurusan banjir telah diambil untuk mengurangkan banjir. Satu daripada langkah tebatan struktur yang telah dilakukan adalah modifikasi terhadap laluan keluar Sungai Rambai. Laluan keluar ini yang asalnya adalah sebuah kalvert telah diganti dengan sebuah bukaan laluan yang besar dalam tahun 2003. Keberkesanan bukaan laluan baru ini dalam mitigasi banjir telah diperiksa dan dinilai. Hasil kajian ini mendapati bahawa bukaan laluan baru itu bukanlah satu langkah

mitigasi banjir yang berkesan malah mungkin boleh memburukkan lagi keadaan banjir di masa hadapan.

INTRODUCTION

The Rambai Valley is located within the Juru River Basin (5° 17' N to 5° 25' N and 100° 22' E to 100° 30' E) in the State of Penang (see Figure 1). It is about 43.0 sq. km. in size. The Rambai Valley is a flood prone area just like many low-lying areas in Peninsular Malaysia (JICA 1978).

Floods occur every year since 1984, usually from September to October. This period coincides with the inter monsoon period which typically brings heavier rainfalls to the north-western region of Peninsular Malaysia (Chan 1985). The most recent flood occurred on 4th October 2003. The occurrence of floods in the Rambai Valley is caused by a combination of convectional storms, urbanization, topography and tidal effects.



Notes: A – Rambai River outlet; B – Canal 4 outlet

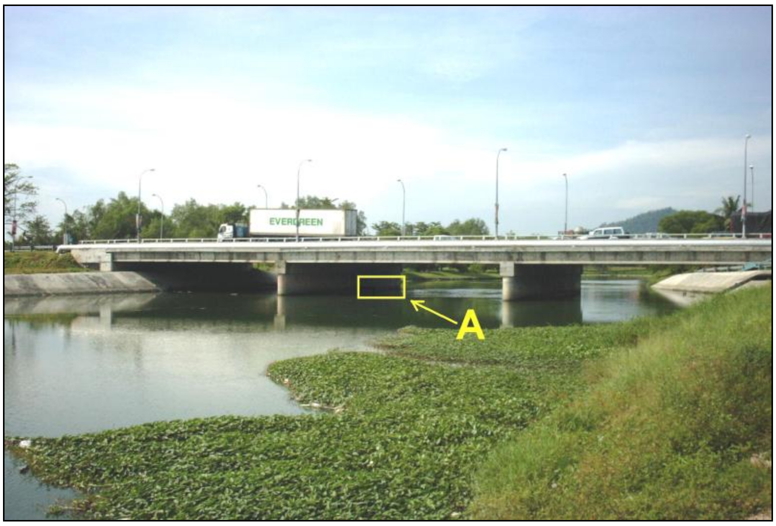
Figure 1. Rambai Valley, Juru River Basin, Penang

Rambai Valley is lodged between steep isolated hills succeeded almost abruptly by narrow depositional lowlands. It is drained by the Rambai River (75 percent of the total area) and Canal 4 and their tributaries. Both channels flow into Juru River, which connects this valley to the Penang Straits about 8.1 km away. Both river, i.e. Juru River and Rambai River, are inside the lowlands. Hence, a large part of this river basin is susceptible to the effect of daily tidal oscillations in the Penang Straits. Consequently, these daily tidal intrusions impede upstream flows which in turn could cause the floodplain channels to overflow resulting in floods during heavy rainfalls (Sathiamurthy & Goh 2001; Sathiamurthy 2004). This tidal effect was previously attenuated by the presence of a large mangrove swamp in this valley, which acted as a natural flood retention area. However, this swamp has been largely reclaimed for housing and industrial projects since 1980.

Since this natural retention area has been lost to urbanization, the high peak flows generated by present rapid urbanization coupled with steep highland topography need to be discharged off immediately (De Vries 1980). However, as explained earlier, tidal intrusion prevents effective discharge resulting in the accumulation of large volumes of water that eventually cause floods (Shuy 1989). Furthermore, high surface runoff from the mid-valley area itself, now densely built-up, is trapped aggravating the situation. This situation becomes even more complex when the effects of human induced flow regulation (e.g., canalization, tidal gates, etc.) are considered.

Apart from the flood factors discussed above, the past flood events are also associated with extreme weather conditions. One of worst flood event was caused by heavy rainfalls induced by the Super Typhoon Ryan on 17-19 September 1995 (JTWC 1995). As a result of this extreme rainstorm, meteorological stations in Penang recorded very high rainfall of between 250 mm to 350mm in less than one day (DID 1995).

One of the stations closest to Rambai Valley, i.e. Simpang Ampat, recorded very high rainfalls on 18 September 1995. It recorded a total amount of 218 mm of rainfall in 12 hours and subsequently 352 mm in 24 hours. This rainfall depth and duration has a return period of 50 years (Sathiamurthy 1998). In other words, it was an extreme event according to the rainfall records for this region. The floods that have occurred caused huge spending on mitigation projects. One of the most significant structural mitigation projects recently was the construction of the new Rambai River outlet. This paper focuses on the change of hydrodynamic behaviour in the Rambai River due to the replacement of the old outlet which was a box culvert with an open channel (see Figure 2). The effectiveness of this new outlet is examined and evaluated.



Note: The box labelled 'A' is the approximate size of the culvert that was replaced by the new large open channel beneath the bridge. Notice their relative difference of size

Figure 2. Rambai River Outlet (Juru Bridge)

METHODS

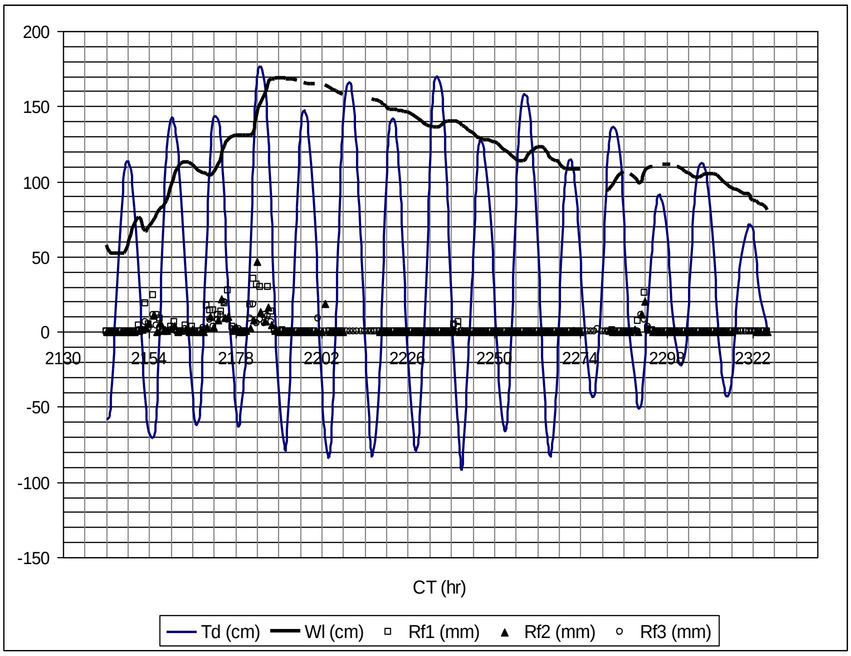
First, the effects of tidal inflows on the Rambai River hydrological behaviour are examined by focusing on their contribution to the occurrence of floods. For this purpose, past tidal records and a past flood event are studied. This is to verify the influence of tidal inflows on the channel system. Second, past and recent flood events are compared with the purpose of examining the effectiveness of the open channel. This procedure follows a simple deductive approach. If the open channel is effective in mitigating floods, then at best, floods should not have occurred after its construction. At least, if floods do occur again, the open channel should be able to attenuate the peak stage with due consideration to the past and present rainfall events, tidal boundaries and land cover. Third, the changes in the hydrodynamic behaviour of Rambai River outlet is examined by studying the impact of channel modification of gauged stage at the outlet. This is to identify whether the tidal inflow peak has increased or not as a result of a larger open outlet. An increase in tidal peak would indicate that greater tidal inflow has been permitted by the new structure which could sustain the peak stage or impede outflows in the channel system. Fourth, the past and present river stage is simulated under similar rainfall and surface conditions but with their respective outlet type. This is to conclude whether the open channel performed better than the demolished box culvert in attenuating flood peak given the same rainfall, tidal boundary and surface condition. Simulation is done by using XP-Storm (one dimensional dynamic wave model).

EFFECTS OF TIDES ON RAMBAI RIVER

Hourly rainfall depths, stages and tidal levels for the period of 26 July 1999 to 24 April 2001 were analyzed. Rainfall data were taken from the Juru (at Rambai River outlet), Prai, Simpang Ampat and Sungai Kulim stations (near to Rambai Valley). River water level or stage records were taken from the Juru telemetric station located at the outlet of Rambai River. As for tidal levels, the records were taken from the Penang Island station. In total, 15533 data points for tide, stage and rainfall were analyzed.

The results of tidal and stage peaks analysis (under dry periods) indicated that the lag time between tidal peak and stage peak is between 3 to 4 hours for both tidal conditions (i.e. neap and spring tides). This implied that when a high tide occurs in the Penang North Channel (tidal current flows southward in the Penang Channel during high tide), the stage in the Rambai River would rise 3 to 4 hours later. The results also indicated that the high tidal peaks changed approximately 1.9 times more than stage peaks for both tidal conditions. Both results implied that during high tides, stages in the Rambai Valley would rise to 51 percent of the tidal level after 3 to 4 hours. The same is assumed to apply to tidal recession period since the tidal pattern is symmetrical. The stage would recede to 51 percent of the lower tidal level and its recession is slower than tidal recession. These results indicate that tidal intrusion and recession caused significant changes to stage in the Rambai River.

The results of tidal and stage peaks analysis (under wet periods) indicated that for both tidal conditions, the stages were higher than the expected stages under dry period conditions. The stages were higher because of the combined effect of tidal inflows and upstream outflows in the Rambai Valley. The results also showed that rainfalls that occurred after the tidal lag time (about 2 to 3 hours after the lag period) caused the stage peaks to rise further instead of dropping to the expected stages under dry period conditions. These results implied that the drop of stages during tidal recessions was compensated by upstream outflow. It was further noted that when heavy rainfalls (above 30 mm/hr) coincided with high spring tides during the tidal lag period, the stages would rise much higher than the former case. These could be caused by larger tidal inflows and high upstream outflows coinciding in the Rambai Valley. These conditions could cause floods, as the stages are much higher than in case of rainfalls occurring after the tidal lag or during high neap tide.



Notes: Td – tidal level; Wl – stage; Rf – rainfall station
(1- Juru; 2 – Simpang Ampat; 3 - Prai).

Figure 3. 25 Oct. 1999 flood event

The flood that occurred on 25 October 1999 is a good example of the influence of tidal inflows in elevating and sustaining river stage which results in flood. With reference to Figure 3, the rainfall event occurred almost continuously for 36 hours with the intensity of 10 mm/hr to 45 mm/hr between 2154 hours to 2190 hours. They coincided with a spring tide period. As a result, the stage rose steadily from 0.51 m LSD (prior to 2154 hours) with some minor recessions to a flood causing level at 2184 hours and reached its peak at 2190 hours at 1.7 m LSD (0.3 m above flood threshold). The flood lasted for two days. The stage dropped very slowly because of spring tidal inflow. It took another 5 days to recede back to the normal level of 0.5 m LSD.

COMPARATIVE ANALYSIS OF PAST AND PRESENT FLOOD EVENTS

The Rambai River outlet was demolished after the Juru Bridge project was completed in the beginning of 2003. It was replaced with a large open trapezoidal channel. The dimensions of this new channel are given in Figure 4. The two vertical 'columns' are bridge abutments. The cross section height from channel bed is 5 m, top width 60.5 m, middle width 37 m and bottom width is 25 m. The cross section area is 199.4 m^2 while the channel length is 67 m. In comparison, the old outlet was a twin 2.7 by 2.7 m box culvert. In other words, the new channel has a cross section that is about 13.7 times larger than the demolished culvert.

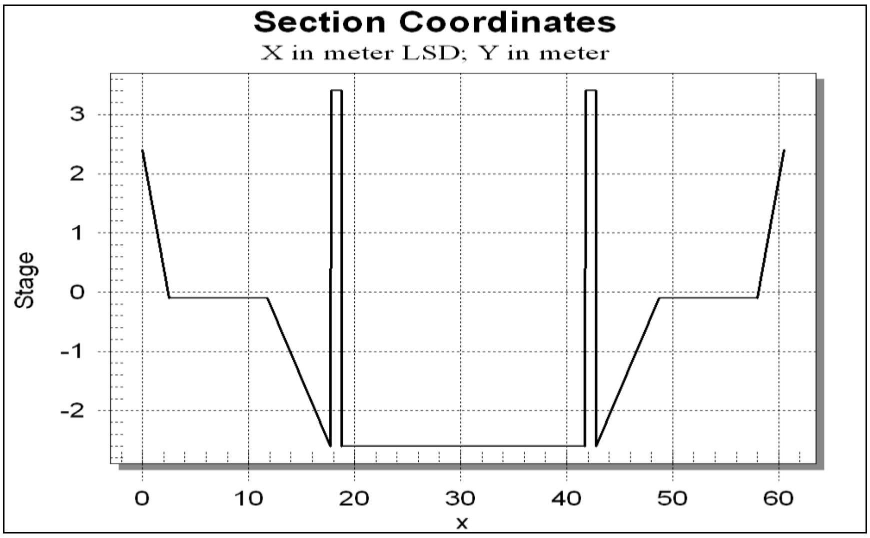


Figure 4. Channel cross section at Juru Bridge

The recent flood which occurred on October 2003 contains some important implications to this research. The new open channel was expected to attenuate peak stages and mitigate flood by lessening flow obstruction at the outlet of Rambai River. Nevertheless, a flood occurred from 4 to 9 October 2003. The rainfall and stage of Rambai River recorded by the Juru Telemetric station is shown in Figure 5.

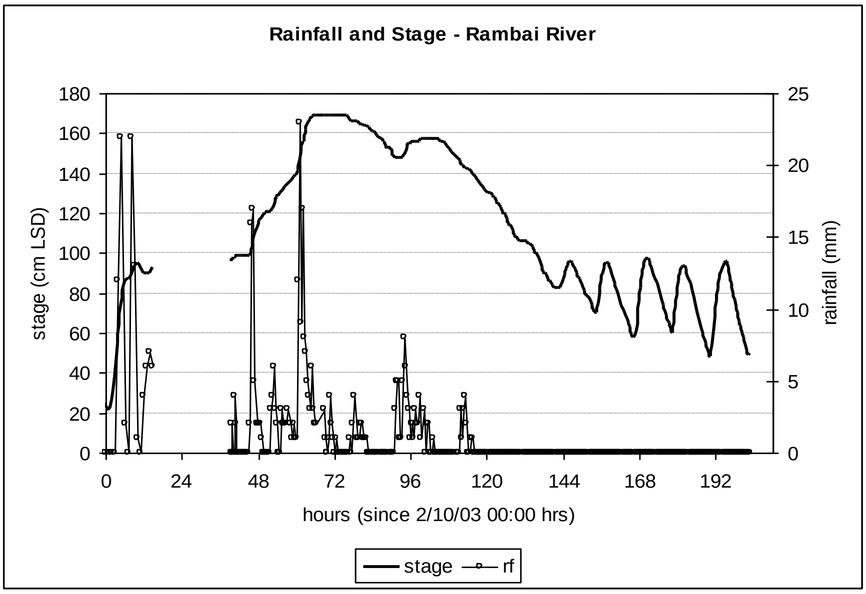


Figure 5. Rainfall and stage at Juru Bridge - 2 to 10 October 2003

With reference to Figure 5, there was no record between 2/10/03 16:00 hours and 3/10/03 15:00 hours because the station was temporally not in operation. However, there is enough record to show the progress of the flood. Heavy rainfalls occurred on 2 and 4 October. The Juru station recorded total rainfall of 397 mm in 5 days (not including Oct the missing record). The upper valley could have received heavier rainfalls resulting from orographic effect. The river stage reached the danger level (i.e. 1.4 m) on 4/10/03 at 12:30 hours following 2 days of prolonged rainfall. The danger level is set by the Drainage and Irrigation Department to indicate the beginning of a serious flood. The stage continued to rise offsetting tidal effects. The peak stage, i.e. 1.69 m, was reached 5.5 hours later. The peak level was sustained for about 11 hours. After that the stage started to recede gradually until 8/10/03 00:00 hours. After that, the stage began to oscillate as the outflows were no longer large enough to offset tidal effects thus indicating the channel system has returned to normal condition.

Table 1. Comparative analysis of gauged stage - past flood events (Event 1, 2 and 3) and the recent flood (Event 4)

Analysis:	Event 1	Event 2	Event 3	Event 4
Flood date	3/9/99	27/9/00	25/10/99	4/10/03
Gauged peak stage	1.630 m	1.100 m	1.690 m	1.690 m
Total time exceeding danger level (1.4 m) and percentage of difference compared to current event	35 hrs -36 %	Not relevant	46 hrs -16 %	55 hrs
Total rainfall depth during an event and percentage of difference compared to current event (Juru station only)	No record	Not relevant	380 mm -4.3 %	397 mm (456 mm)
Total length of rainfall period at Juru station during an event (Juru station only)	Not relevant	Not relevant	2.25 days	4.8 days
Average daily rainfall at Juru station during an event	Not relevant	Not relevant	168 mm/day	82 – 95 mm/day
48 and 24 hours rainfall prior to peak stage and percentage of difference compared to current event (Juru station only)	Not relevant	Not relevant	379 mm +35 % 292 mm +38 %	245 mm -35 % 181 mm -38 %

(456 mm) - The values of the nearest station (Simpang Ampat) is used to fill in the missing data

With reference to Table 1, the flood peaks of Events 1, 3 and 4 showed no significant difference. Nevertheless Event 4 differed from the other three events in several ways. Event 1 flood duration was significantly shorter than Event 4 (less by 16 %). Comparatively, Event 4 has the longest flood duration compared to Event 1 and Event 2. This could be due to the fact that Event 4 has a longer rainfall event which sustained the danger level longer.

The average daily rainfall of Event 3 was 1.9 times more intense than Event 4 but the rainfall period was shorter by 53 %. In other words, Event 3 was a shorter but more intense rainfall-runoff event compared to Event 4. Event 4 was a flood caused by prolonged but less intense rainfall. Comparatively, the stage hydrograph of this event is similar to the three past events especially the 25 October 1999 event (Figure 3 and Table 1). They showed a typical steady rise and a very gradual recession. This implies that the hydrologic system response or feedback to rainfall events has not changed significantly since the last three flood events which occurred prior to the construction of the open channel (i.e. year 1999 and 2000). Hence, although the replacement of the Rambai culvert with the open channel was the most significant modification done to the hydrological components of the Rambai System since 1999, it has not altered the Rambai System response to rainfall significantly as a whole. It should be noted that other factors or components that could have altered the system response like land cover and sub-system outlets have not changed considerably since 1999. Hence, the only change in the system's components that could have a significant impact on system response would be the installation of the open channel. However, the open channel has not impacted the hydrological system response significantly. This phenomenon could be attributed to one of the main components of the Rambai System which is tidal intrusions. The open channel does not only permit greater outflows but it also allows larger tidal inflows, which could have offset each other causing the system to display a response similar to the previous flood events.

There are two important implications that could be drawn from comparing Event 3 with Event 4. First, the large open channel that replaced the Rambai outlet which was a culvert could not attenuate the flood peak effectively. The flood peak remained the same as the previous major events (Events 1 and 3). Rationally, assuming the outlet was still a culvert, a less intense but prolonged rainfall event like Event 4 should produce a lower peak but a more sustained high stage compared to more intense but shorter event like Event 3. It was noted that the rainfall in the last 24 hours prior to flood peak for Event 4 was 38 percents less than in Event 3. The last 24 and 48 hour rainfall records indicate the rainfall amount that produced the peak stage. Moreover, in the case of Event 4, the open channel should permit greater outflows compared to the demolished culvert. In other words, the flow peak should have been attenuated. However, while the high stage was prolonged there was no significant attenuation of the flood peak even though the amount and intensity of rainfall received prior to the peak time was lesser than the previous event.

Second, the phenomenon above implies that the hydraulic modification of the outlet has altered the boundary conditions significantly. The introduction of a larger and open outlet enabled greater tidal inflows that enhanced the peak stage and sustained high stage. This viewpoint could be substantiated by examining tidal characteristics at the Rambai River outlet before and after the open channel was constructed. It also can be further substantiated by re-simulating a simulated past hydrologic event (e.g. Event 3, culvert outlet) under present condition (open channel outlet) and comparing its results with the simulated past event. Both will be discussed later.

CHANGES IN HYDRODYNAMIC BEHAVIOUR AT RAMBAI RIVER OUTLET

The stage data measured by the Juru telemetry station for the period of July 1999 to May 2001 are compared to the data measured between April 2003 and December 2003. The 1999 to 2001 data represent the period before the bridge construction and demolition of the Rambai culvert. The April to December 2003 data represent the present day where the bridge has been constructed and the culvert replaced with an open channel. The selected data are from dry periods only in order to examine the tidal characteristics without any significant influence from river outflows. The statistical analysis of the stages is shown in Table 2.

The data length for the dry period of 1999 to 2001 is longer than current data length. Hence there are more cases of stage exceeding 0.5 m for the dry period of 1991 to 2001 compared to the current data set. However, this does not affect the analysis greatly because tidal fluctuations are highly periodic and predictable. There are no data for stages below 0.5 m for the 1999 to 2001 period because the Juru station then did not measure stages below 0.5 m. Hence, a set of data representing stage above 0.5 m is selected from the 2003 dataset for the purpose of comparison.

From the frequency distribution of stages for 1991-2001, there were no cases out of 9010 cases which are above 0.7 m before the culvert was demolished. Most of the cases, i.e. 78.7 percent are within 0.5 to 0.55 m. As for the period after the bridge was constructed, there were 28 cases above 0.7 m out of 375 cases. As for cases ranging from 0.6 to 0.7 m, 12.5 percent of the cases for 1991-2001 fell within this range whereas for 2003, 22 percent (i.e. increase by 9.5 percent). The low water between 1999-2001 and 2003 cannot be compared because there are no records below 0.5 m for the 1999-2001 periods as explained earlier. The mean value of stages above 0.5 m for 2003 is 0.65 m whereas for 1991-2001 is 0.54 m. The other statistical indicator such as quartile range also showed higher values for 2003. These indicators imply that the stages have generally become higher.

The statistical analysis implies that by replacing the culvert with a large open channel the frequency of high stages has increased. This implies that the open channel enables outflows to leave the system faster but at the same time it also enables freer tidal intrusions. Further examinations were made by simulating the present condition by using one of the past events as an example.

Table 2. Statistical analysis of stages measured at Rambai River outlet

Year 2003 – Dry Period				
Frequency dist.	Count	Cumul. Count	Percent of Valid	Cumul % of Valid
-40.00 < x <= -20.00	0	0	0	0
-20.00 < x <= 0.0000	5	5	1.33	1.33
0.0000 < x <= 20.000	66	71	17.60	18.93
20.000 < x <= 40.000	154	225	41.07	60.00
40.000 < x <= 60.000	100	325	26.67	86.67
60.000 < x <= 80.000	34	359	9.07	95.73
80.000 < x <= 100.00	16	375	4.27	100
Year 1999 – 2001 - Dry Period				
Frequency dist.	Count	Cumul. Count	Percent of Valid	Cumul % of Valid
45.000 < x <= 50.000	0	0	0	0
50.000 < x <= 55.000	7093	7093	78.72	78.72
55.000 < x <= 60.000	791	7884	8.78	87.50
60.000 < x <= 65.000	667	8551	7.40	94.91
65.000 < x <= 70.000	459	9010	5.09	100
Year 2003 - Dry Period (above 0.5 m)				
Frequency dist.	Count	Cumul. Count	Percent of Valid	Cumul % of Valid
40.000 < x <= 50.000	0	0	0	0
50.000 < x <= 60.000	50	50	50	50
60.000 < x <= 70.000	22	72	22	72
70.000 < x <= 80.000	12	84	12	84
80.000 < x <= 90.000	12	96	12	96
90.000 < x <= 100.00	4	100	4	100
Dry Period of:	2003	2003 (>0.5 m)	1999 - 2001	
Valid N	375	100	9010	
Mean	38.25	65.12	54.19	
Confid. -95.0 %	36.18	62.56	54.10	
Confid. +95.0 %	40.31	67.68	54.29	
Median	36	60.5	52	
Minimum	-11	51	51	
Maximum	96	96	70	
Lower Quartile	23	55	52	
Upper Quartile	50	74.5	54	
Range	107	45	19	
Quartile Range	27	19.5	2	
Std.Dev.	20.34	12.92	4.54	

Notes: There are no data for stage below 0.50 m for the 1999 to 2001 period because they were not recorded. All measurements are in cm.

SIMULATED HYDROLOGICAL BEHAVIOUR OF RAMBAI RIVER: PRE AND POST-JURU BRIDGE CONSTRUCTION PERIOD

The change in stage, velocity and flow characteristics resulting from replacing the culvert with an open channel was examined by simulating Event 3 under three scenarios. Event 3 was selected because it resembles the flood event of October 2003. The scenarios are as stated below:

1. Open scenario: The open channel dimension is used. The boundary point is shifted from Rambai River outlet to Juru River mouth. The new boundary point is necessary because the open channel does not represent a distinctive boundary condition unlike the demolished culvert. The Juru River mouth is located about 8.05 km downstream from the Rambai River outlet.
2. Culvert 1 scenario: The demolished culvert is used together with the new boundary point. This is to compare this scenario with the first scenario under the same boundary upstream transmission rate. Pre-simulation test has shown that the boundary depletes about 2 percent for every kilometre. This is to examine the effect of channel modification without the effect of different boundary propagation.
3. Culvert 0 scenario: The demolished culvert and initial boundary point at Rambai River outlet is used. This is to compare the initial boundary scenario with the first and second scenarios in order to examine the effect of channel modification and boundary change.

The simulation result for each scenario is shown in Figure 6 and Table 3. With reference to Figure 6, the outline of the stage hydrographs is similar except for Culvert-0 scenario which shows significant fluctuations. The Culvert-0 scenario has lower stages than the Open and Culvert-1 scenarios but it has the highest peak flow and peak velocity. The receding limbs of the Open and Culvert1 scenarios are sustained higher than Culvert-0 scenario resulting from the modulating effect of a further boundary point. There is no significant difference in the overall stage levels between the Open and Culvert-1 scenario.

The Culvert-1 scenario has a higher peak stage than the other two scenarios (see Table 3). The peak flow of the Open scenario is 8.6 percent higher than the peak flow of Culvert-1 scenario but 20 percent lower than Culvert-0. This indicates that given the same boundary location the open channel is able to convey flow better than the culvert. Nonetheless, the peak velocity of the second scenario, which is 3.66 m/s, is 91 percent higher than the first scenario. This is because of pressure flow created by the box culvert in the second scenario. As a result, there is no significant difference between their peak stages although the open channel conveyed a larger peak flow.

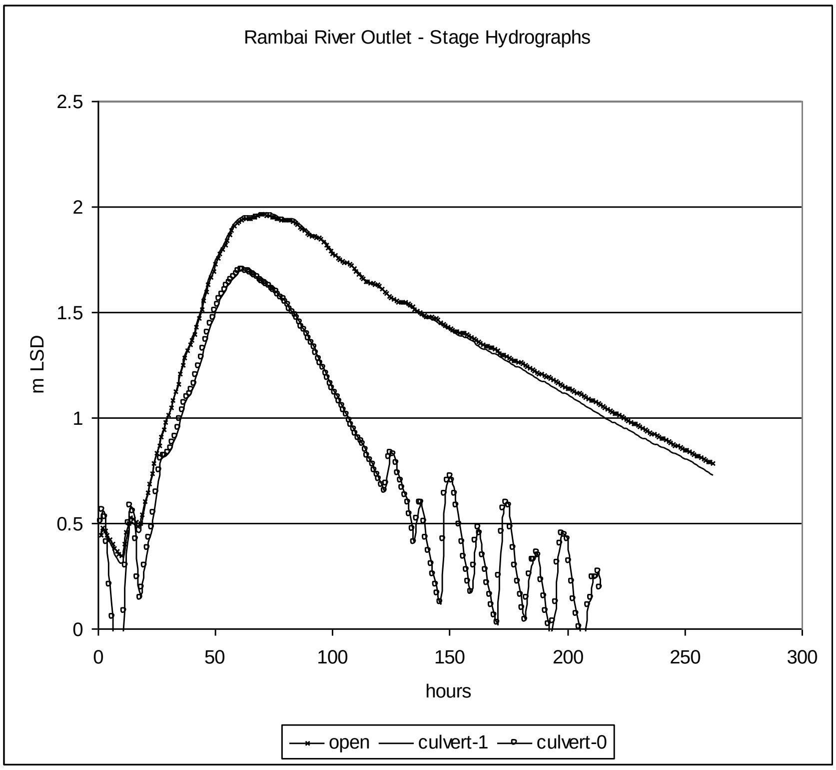


Figure 6. Comparative simulation of the effect of boundary modification

Table 3. Simulated flow results of the scenarios

Scenario	Peak Flow (cms)	Peak Velocity (m/s)	Peak Stage (m LSD)
Open	58.2	0.32	1.966
Culvert-1	53.6	3.66	1.975
Culvert-0	70.0	4.95	1.700

In comparison, the peak flow and peak velocity of Culvert-0 scenario (i.e. 70 cms and 4.95 m/s) are higher than the other two scenarios. As a result, it has a significantly lower peak stage compared the other scenarios. Its peak flow and peak velocity are much higher as a result of the wider stage range between upstream and downstream stages. The stage range is wider because the boundary condition is located immediately after the outlet unlike the other two scenarios where the boundary has been shifted downstream.

This implies that a further boundary could lower the flow rate and velocity because it allows a longer time for an outflow to gradually modulate itself against the boundary conditions. Its higher peak flow and peak velocity also indicate that the pressure flow caused by the culvert could have effectively reduced tidal intrusion compared to the open channel. This could be substantiated by the fact that it has a much higher peak velocity than the open channel scenario while having a much lower peak stage.

On the whole, the simulated results imply that the new open channel is not effective in attenuating peak stage. In theory, it could convey larger flows due to its larger cross section size. However, this may not be the case operationally due to greater tidal intrusion which reduces its flow velocity. This is indicated by its low simulated peak velocity and higher peak stage. This high stage-low velocity coincidence phenomenon is not uncommon for a tidal affected channel. The low velocity indicates the effect of freer tidal inflows offsetting outflows. The freer tidal inflows induce a higher peak stage.

DISCUSSION AND CONCLUSION

The hydrodynamic characteristics of Rambai River outlet have changed significantly as a result of replacing the old culvert with a new open channel. The past and present tidal characteristics was examined and discussed. The statistical analysis of tidal characteristics (gauged stage) from pre and post bridge construction period implies that the frequency of high water levels has increased after the culvert was replaced with the large open channel. In other words, while the open channel enables outflows to leave the system faster compared to the old culvert, it also enables freer tidal intrusions which could offset outflows resulting in an enhanced peak stage and sustained high stage. The demolished culvert on the other hand was a flow constriction point for both tidal inflows and river outflows. Consequently, the Rambai system response in Event 4 (October 2003 flood) was similar to past events that occurred in 1999 and 2000. The stage hydrograph produced by Event 4 was similar to the stage hydrograph of Events 1, 2 and 3.

The effect of replacing the old culvert with an open channel was further examined by re-simulating Event 3 under the present conditions.

Since the present Rambai River outlet is an open channel, the boundary conditions for the present condition cannot be assumed as an abrupt boundary like in the case of Events 1, 2 and 3 which were simulated under conditions before the open channel was constructed. Thus, the boundary point is shifted downstream to the estuary of Juru River for the purpose of simulating the present condition. The simulation results of the present condition indicated that the open channel reduces peak flow rate and peak velocity while it increases peak stage significantly. Consequently, the lower peak velocity caused flow volume to increase resulting in a higher peak stage. These results substantiate earlier conclusion that the open channel allows greater tidal intrusions which offset outflows.

In conclusion, it can be mentioned that the new open channel may not be effective by itself in mitigating floods compared to demolished culvert. Adversely, it may even aggravate future floods because it allows greater tidal intrusions. However, further simulations have shown that by enlarging the downstream sections of Rambai River and the whole stretch of Juru River all the way to its estuary by 50 % from their present width, this open channel could be an effective flood mitigation structure. This measure should be carried out hand in hand with the usage of pumps. At present, more pump stations have been planned for construction soon. The results of this research point to a simple thought that a flood mitigation effort should consider all the main factors that causes floods in a particular area.

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