CHAPTER 4

RESULTS AND DISCUSSION

4.1 Analysis of observed data

The observed data can be separated into 4 parts:

1) The geometries of river cross-sections are measured by depth and width in the spring tide, because they are at the maximum depth and width.
2) Water levels are determined by 2 parameters: Tides (spring and neap tides) and distance from the sea, which are represented by stage hydrographs.
3) Discharges at each station are represented in the form of discharge hydrographs. Loop rating curves can be shown by the relative of water level and discharge.
4) Velocities at each station are represented in the form of velocity isovel contours and velocity profile.

1) Geometries of river cross-sections.

The main factors to control the hydrodynamic processes in a tidal stream are tides from the sea, river flow from the upstream and distance from the river mouth. The Lower Chao Phraya is a flat plain with a bottoms slope of 1: 14,500 (Visutimeteegorn et al., 2007). The cross sectional shape such as the position of thalweg, depth and width of river, current velocity patterns can be collected by using ADCP, as shown in Figure 4.1.

1.1) Fort Chula Station (Samutprakan Province): this area is connected between the seawater and the river flow. The geometry shape of the river at Fort Chula station is shallow and wide. The maximum depth is 12 m measured from the left bank 250 m the average depth is 7.2 m and width is 920 m. Therefore, approximate cross sectional area computed by ADCP is 6,600m^2. They can be measured in maximum water level of spring tide. The large wide of cross-section is helping rapidly drain fresh water to the sea.

1.2) PakkredStation (Nontaburi Province) has the maximum depth 16 m measured fromthe left bank 160 m. The average maximum depth is 11 m and width is 280 m. Therefore, approximate cross-sectional area computed by ADCP is 3,500m^2. The station is located at 70 km from the Chao Phraya Estuary.

1.3) Bang Sai station(Ayutthaya province) has the maximum depth of 25 m measuredfrom the left bank 280 m. The average maximum depth is 12.3 m and width is 450 m. Therefore, the approximate cross-sectional area computed by ADCP is 5,500 m^2. The station is located at 112 km from the Chao Phraya Estuary.

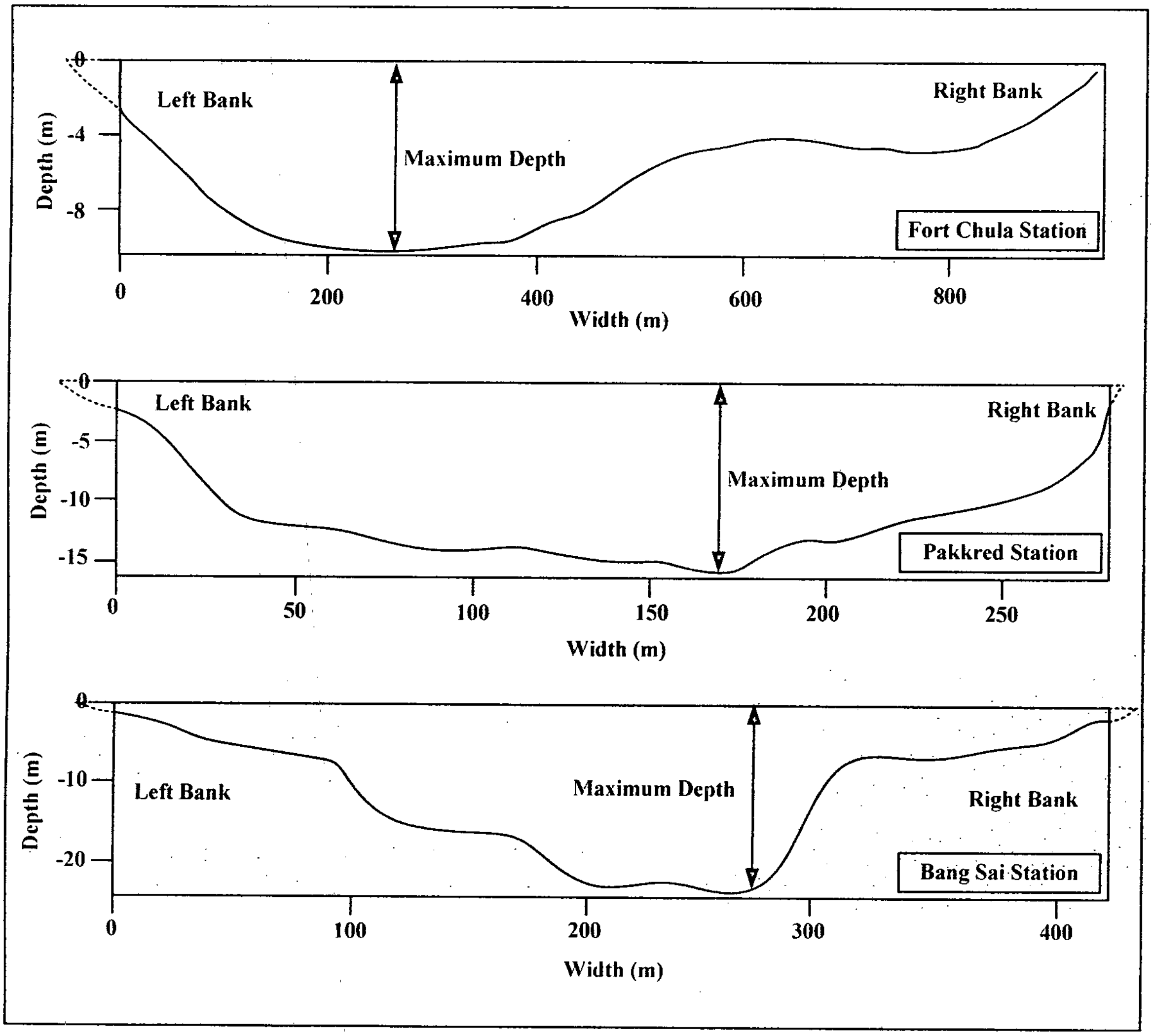

Figure 4.1 Cross-sectional shape at Fort Chula, Pakkred and Bang Sai Stations.

2)Water level

Water levels aredetermined by 2 parameters: tides and distance.

- Tides: the tides in The Upper Gulf of Thailand are mixed tides, as described in section 2.1. They causerises and falls in water levels in the Chao Phraya River in a similar fashion. The mixed tides have two unequal high water levels and two unequal low water levels each tidal day. That can be divided into 2 cases; spring tide and neap tide.

The rise and fall of the water surface in the spring tide is higher than in the neap tide because of astronomical force. The tidal ranges are determined from the highest water level to the lowest water level of tidal loop as shown in Figure 4.2, and the tidal ranges of each station are shown in Table 4.1.

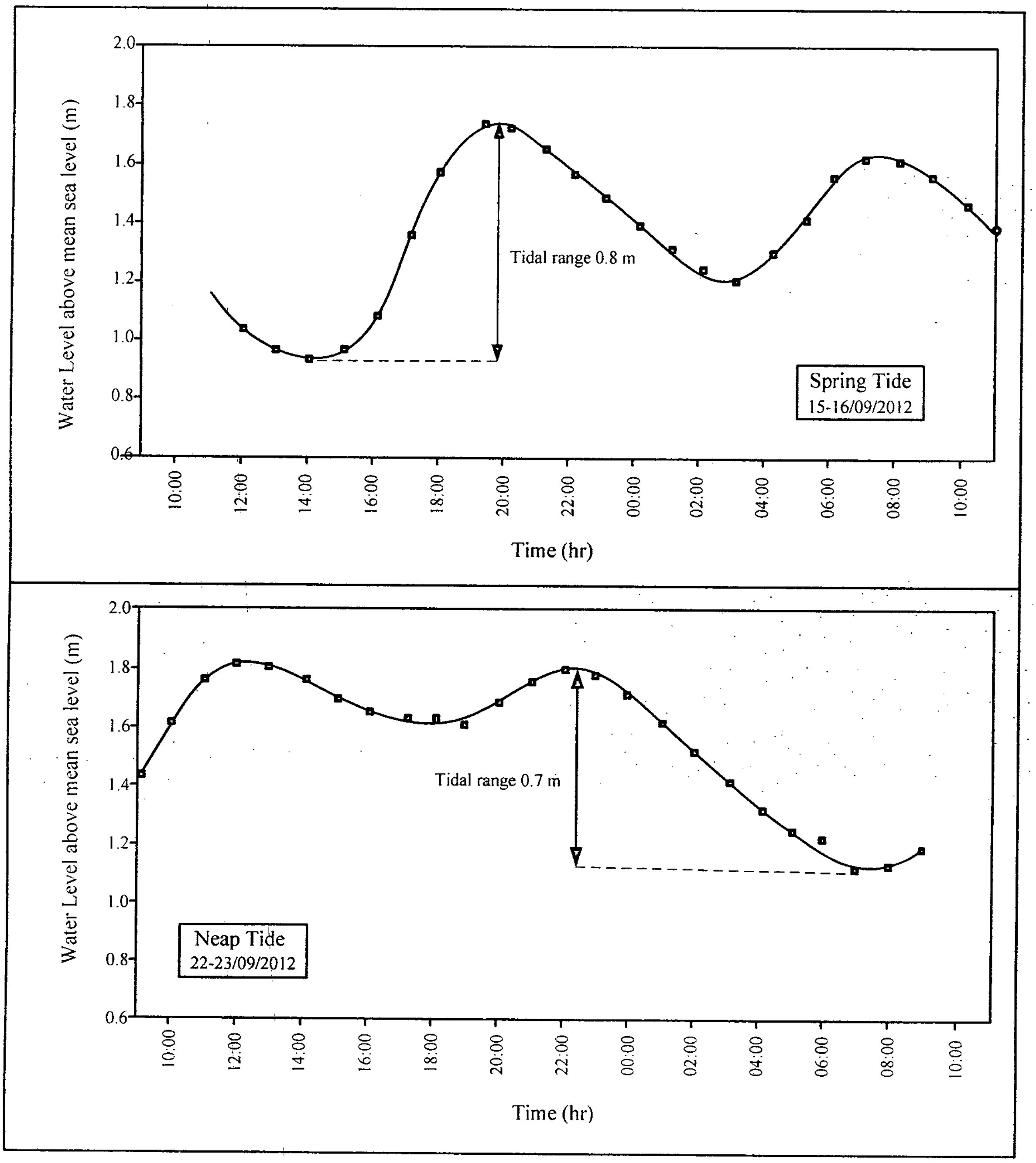

Figure 4.2 Tidal range in spring tide and neap tide at Pakkred Station (September 2012).

Table 4.1 The tidal ranges of each station in 2012.

Station	Spring tide			Neap tide		
	Date	Tidal ranges (m)	Average (m)	Date	Tidal ranges (m)	Average (m)
Fort Chula	13-14/10/2012	1.70	1.70	8-9/9/2012	2.00	2.00
Pakkred	15-16/9/2012	0.80	0.75	22-23/9/2012	0.70	0.70
	29-30/9/2012	0.70		-	-	
Bang Sai	1-2/8/2012	1.20	1.15	25-26/7/2012	0.80	0.85
	18-19/7/2012	1.10		27-28/6/2012	0.90	

- Distance: The distance from the sea to inland affectsthe patterns of the water level. The stations are located at 2 km, 70 km and 112 km from the sea respectively. The character of the rise and fall of water surface are similar to mixed tide, which are predominantly semi-diurnal at Fort Chula and Pakkred stations, and predominantlydiurnal at Bang Sai station as shown in Figure 4.3. In addition, the distance from sea effect on time of rising water level from low water to high water (flood tide). The travel time of the period of a cycle of water level at Fort Chula (13-14/10/2012) is about 7 hours. While those of water levels at Pakkred(15-16/9/2012) and Bang Sai (1-2/8/2012) are 5 hours.

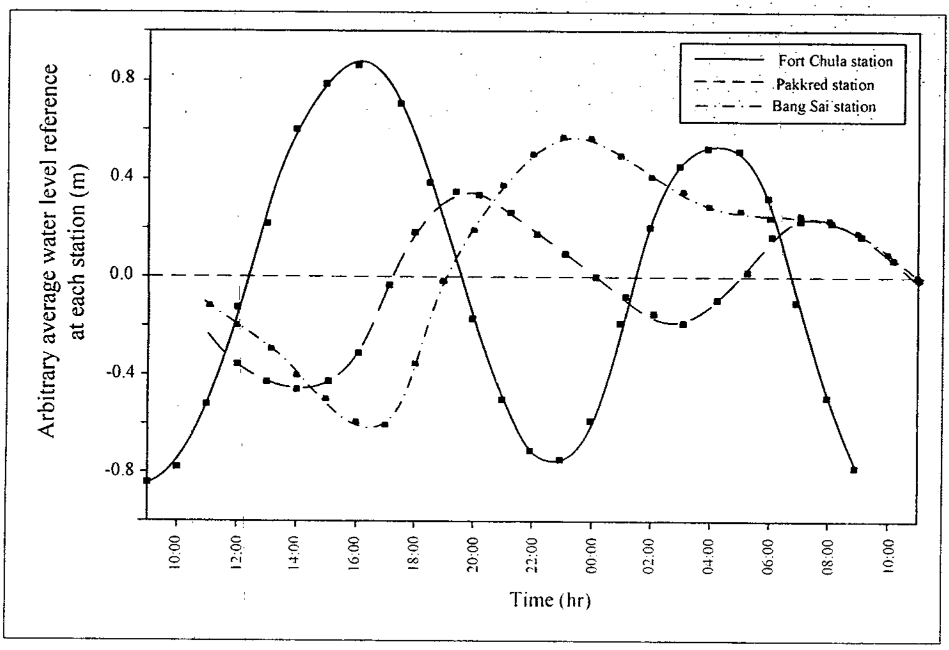

Figure 4.3 Typical tidal curves at any station during the spring tide (July- October 2012).

The friction between the water and the bed affects the variations in water level, especially during falling water level. This effect can be seen in slope of stage hydrograph (Figure 4.3), that the slope of rising water level (flood tide) is steeper than the falling water level.

3) Velocity

The current velocity can be calculated in the form of velocity perpendicular to the cross-section by using speed and direction data from the ADCP, as described inEquation 4.1:

$$V = \text{speed} \cos(\text{direction}) \qquad (4.1)$$

Then, the current velocity is represented in terms of non-dimensionalvelocity varying from 0 to 1(V/V_{max})where V is the velocity at any point of the cross-section and $V_{max}$is the maximum velocity. All data are considered from the largest loop of stage hydrographs at Fort Chula, Bang Sai and Pakkred stations along the river. The non-dimension velocity used to both isovel velocity contours and velocity profiles as shown inFigures4.4 and 4.5.

The current velocity depends on both water level and discharge variations. The rising (flood tide) and maximum water level periods have lower discharge than during the falling (ebb tide) and minimum water level periods, therefore the isovel velocity contours at close to the bottom zone arenegativeisovel lines (moving to upstream) and positiveisovel lines (moving to downstream) close to the surface. During the rising and maximum water level period, the salt water with higher density flow in the lower portion of the lower depth while the fresh water flows in the upper portion. In opposite, during falling and minimum water level periods, only flow from upstream to downstream is found.

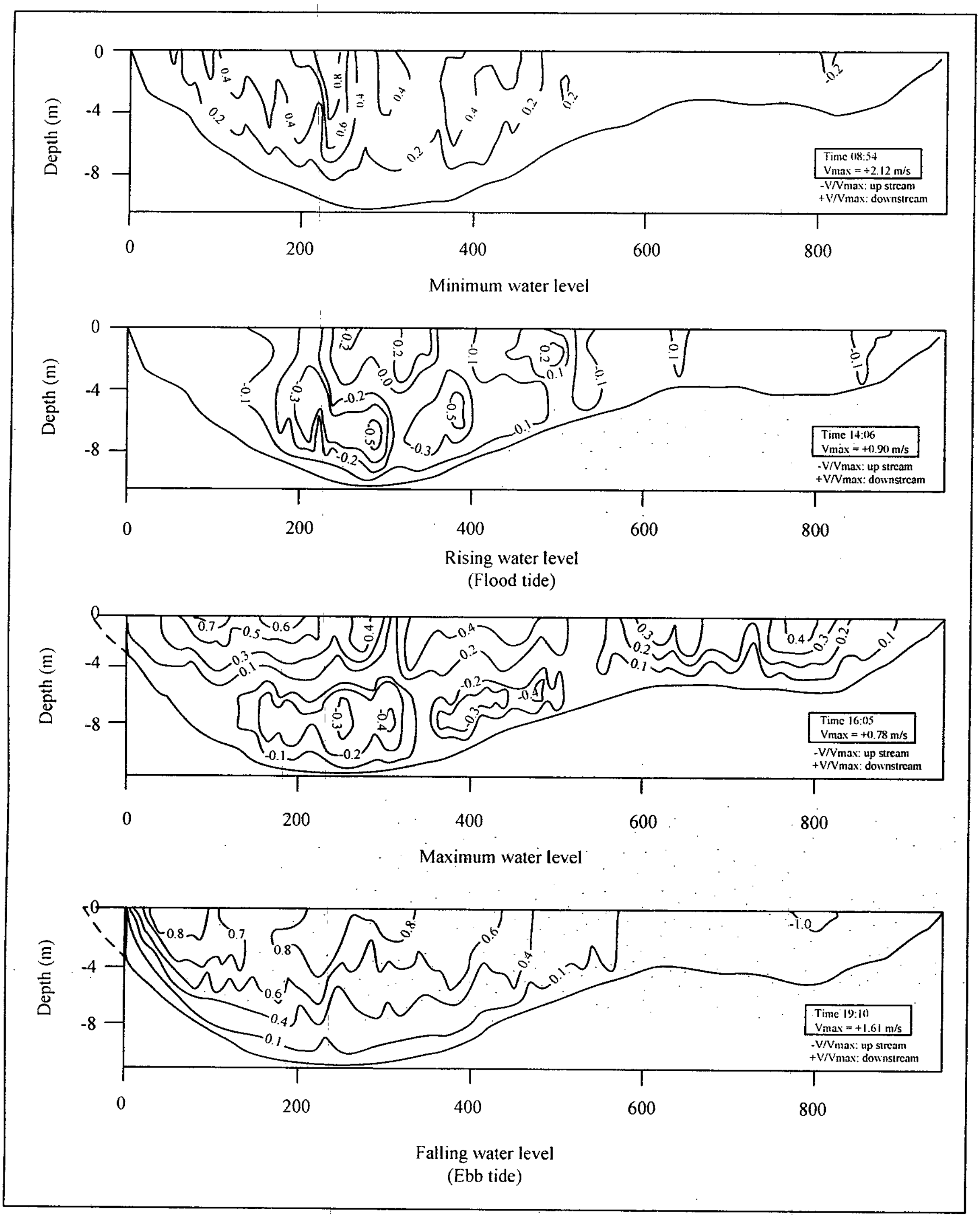

Figure 4.4 Channel section, isovels velocity contour at spring tide at Fort Chula Station (October 2012).

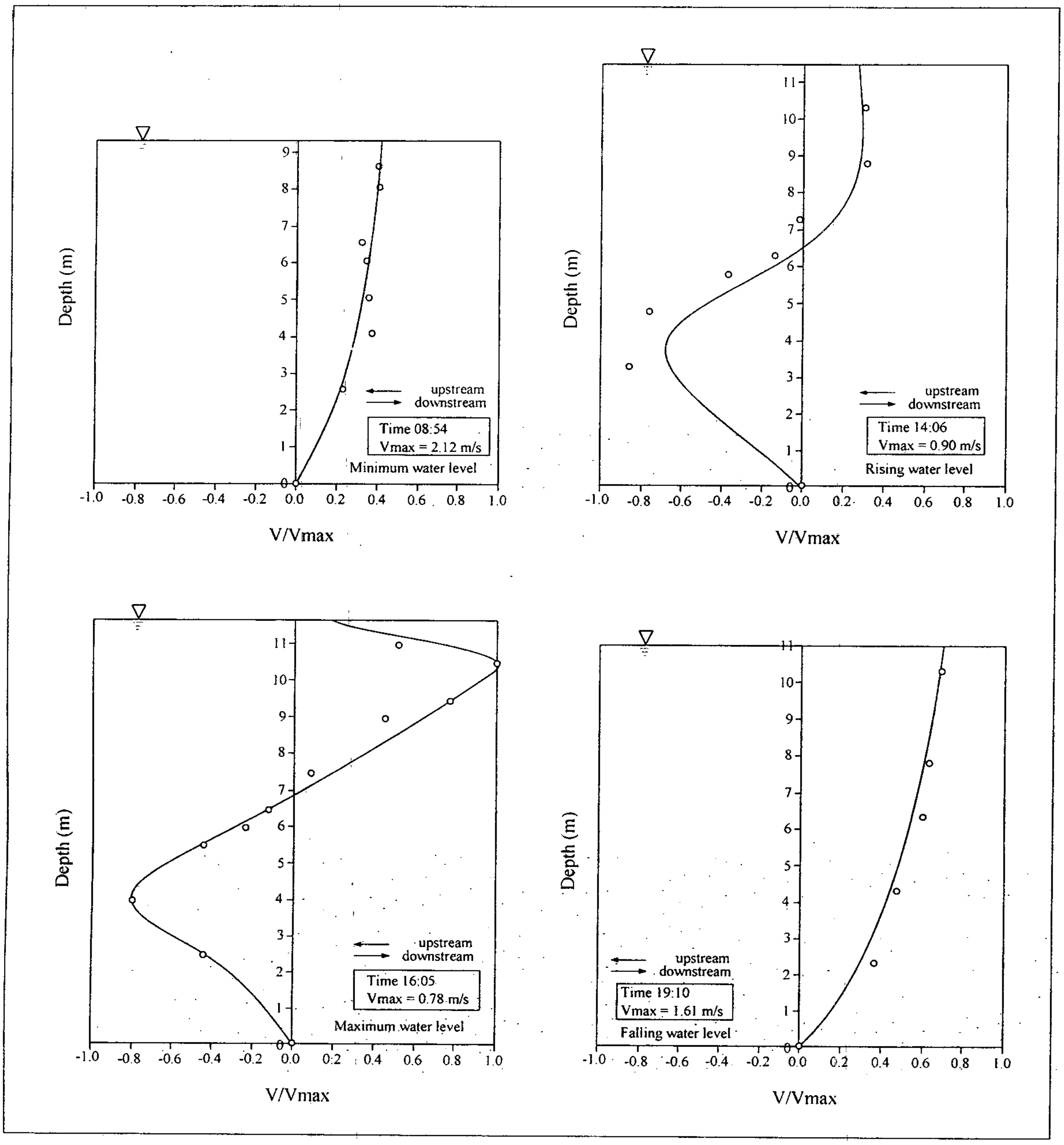

Figure 4.5 Water level and time variations of velocity profiles at the spring tide at Fort Chula Station(October 2012)

4) Discharge

Normally, the maximum discharge in the river was found during the maximum water level (but it was not in the case of river flow under the tidal effect). The maximum discharge under tidal effect is occurring when the sea water level is decreasing. So, the water level occur from striking between salt water and fresh water which makes water level life up to highest level giving rise to obstruck the discharge of fresh water to flow into the sea. This phenomena causes lag time between the stage hydrograph and the discharge hydrograph (Figure 4.6) as the stage hydrograph can be ahead of the discharge hydrograph at all stations. The lag time of Fort Chula, Pakkred and Bang Sai Stations are 4 hours, 7hours and 4hours respectively (Figure 4.7).

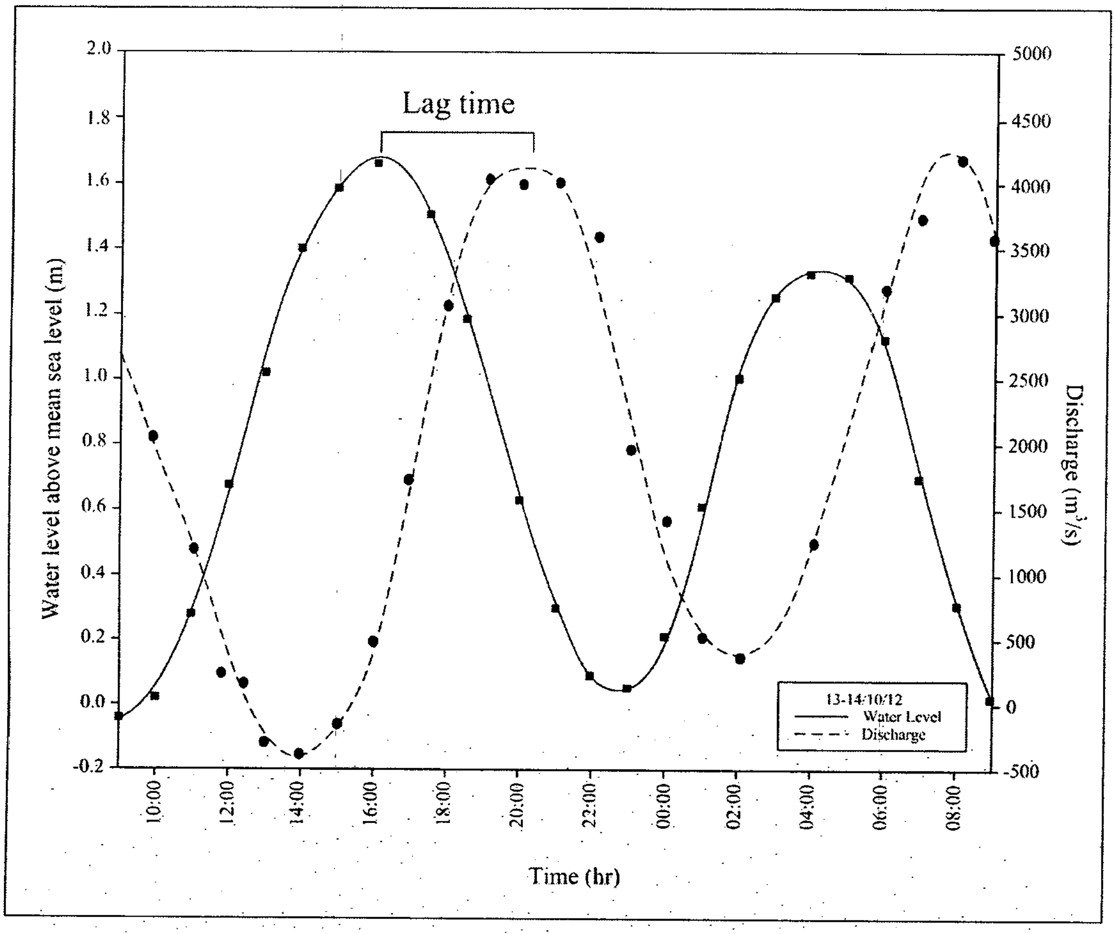

Figure 4.6 Lag time between stage hydrograph and discharge hydrographat Fort Chula Station at spring tide (October 2012).

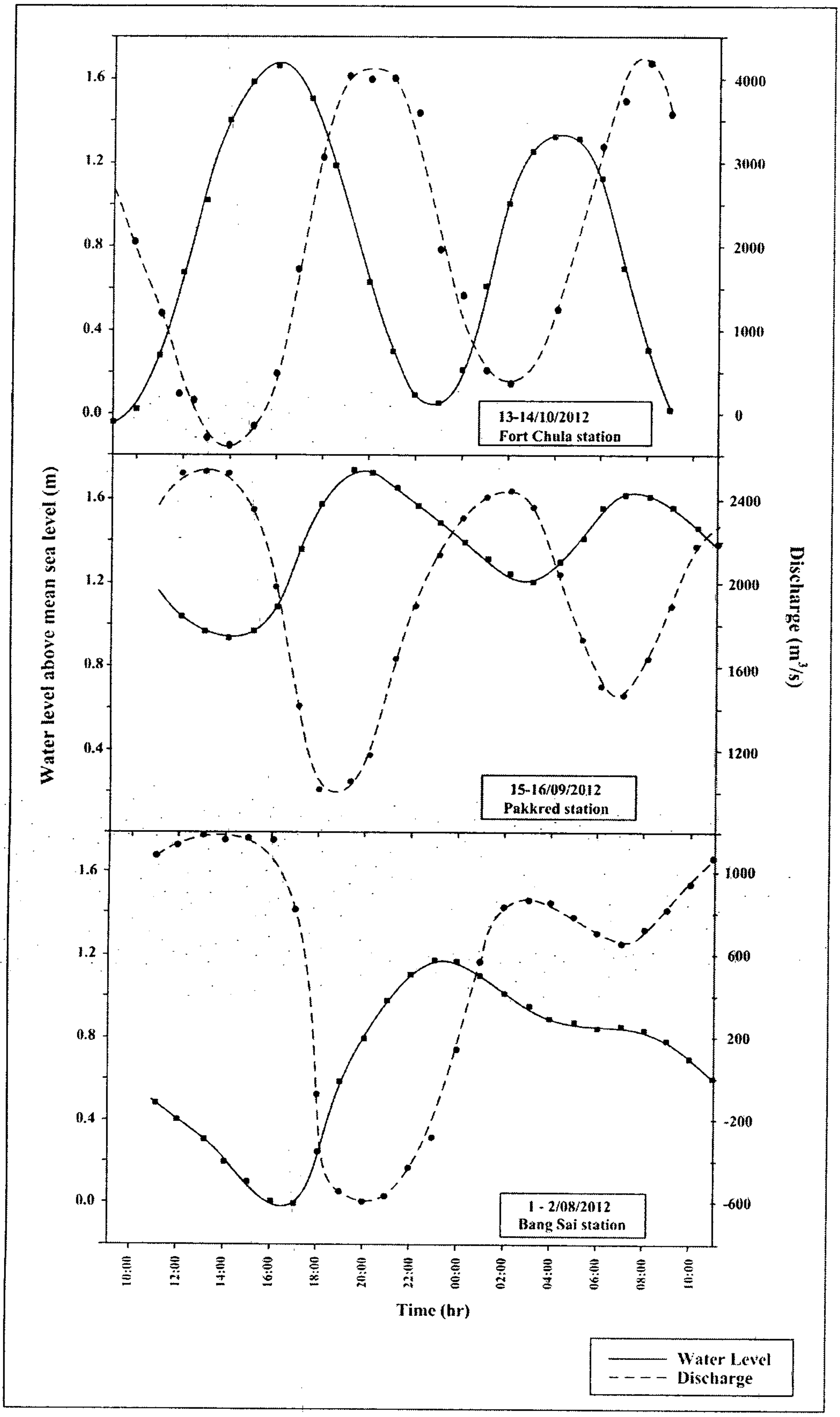

Figure 4.7 Lag time of stage hydrograph and discharge hydrograph at spring tide at Fort Chula, Pakkred and Bang Sai Stations (August-October 2012).

- Tides: generally, the rating curve is the direct relation between water level and discharge variation,whilethe river flow under the tidal effect case is presented in the form of the loop rating curve. The Chao Phraya River is mixed tide, that cause 2 loop cycles based on the rise and fall of water level in 24 hours as shown in Figure 4.8.The characteristic of loop rating curve in spring and neap tides have inclination angle with x-axis about 150° and the direction of loop cycle is clockwise as shown inFigure 4.9.The under line of loop is rising water level (flood tide) and upper line is falling water level (ebb tide). The length and width of loop cycle depend on discharge and water level, respectively. That cause the length and width of loop rating curve in neap tide to shorter and narrower than spring tide.

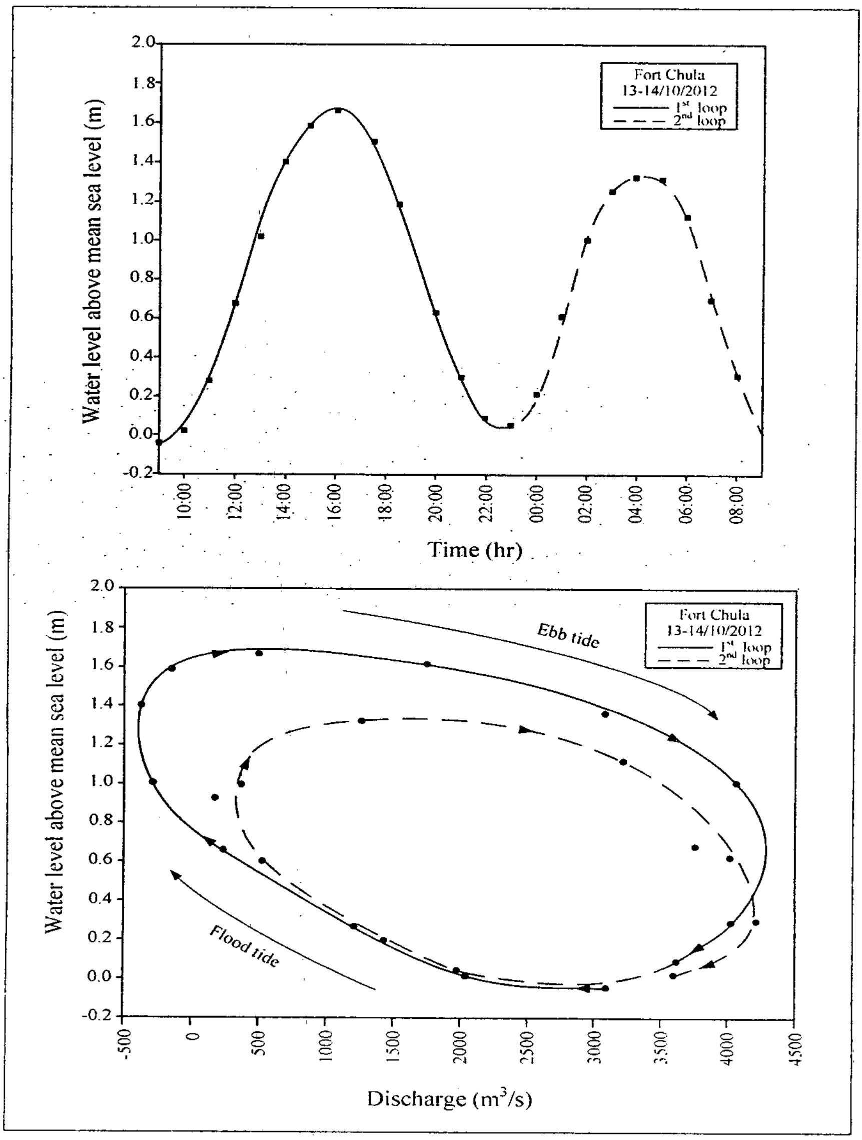

Figure 4.8 Stage hydrograph and loop rating curve at Fort Chula Station at spring tide (October 2012).

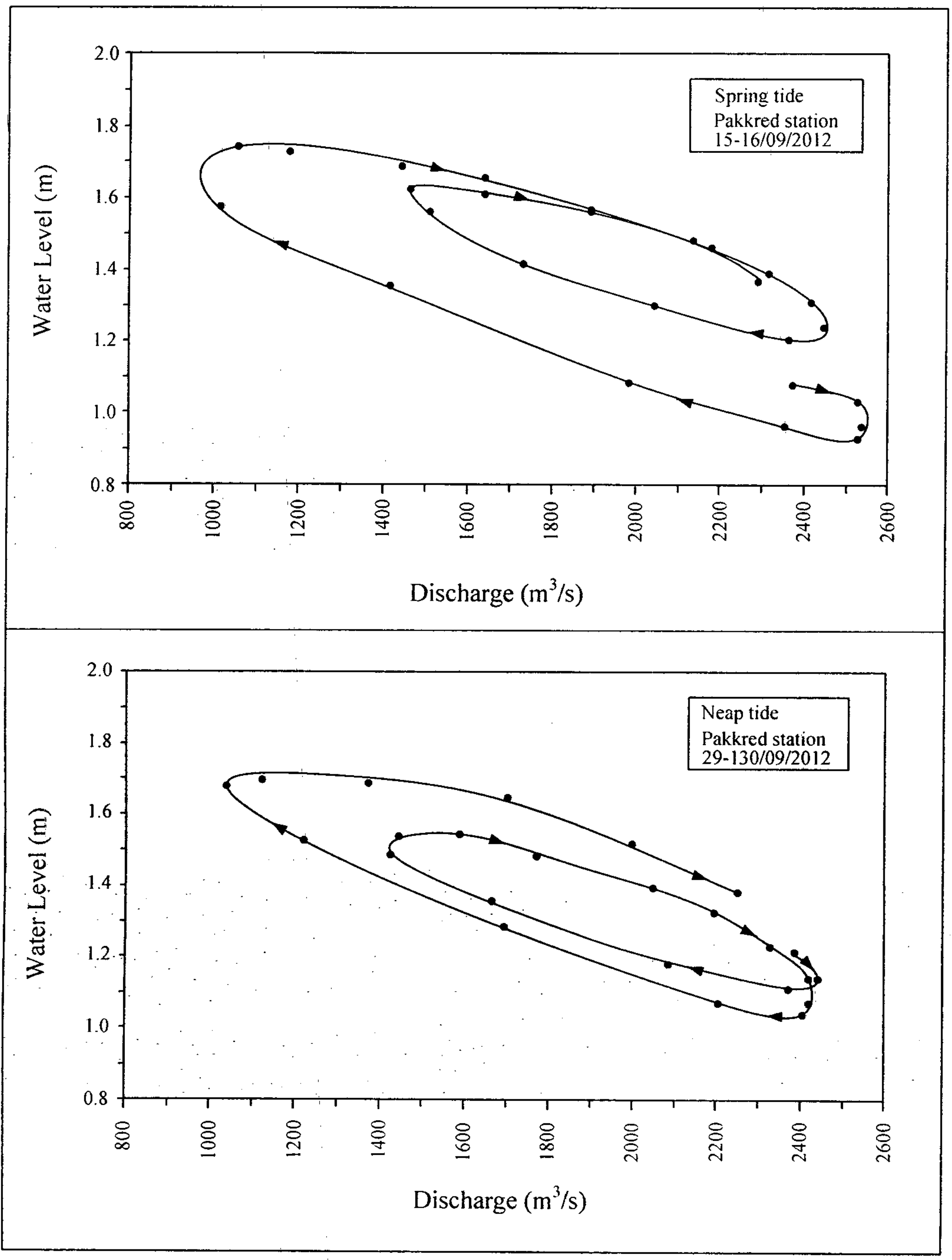

Figure 4.9 Loop rating curve atPakkredStation at spring and neap tides (September 2012).

- Distance: The distance from the sea affects the loop rating curve and the stage hydrograph patterns. The characteristic of the loop rating curve is narrowing gradually and effort to be change from 2 loops of cycle to 1 loop as follow the stage hydrograph as shown inFigure 4.10.

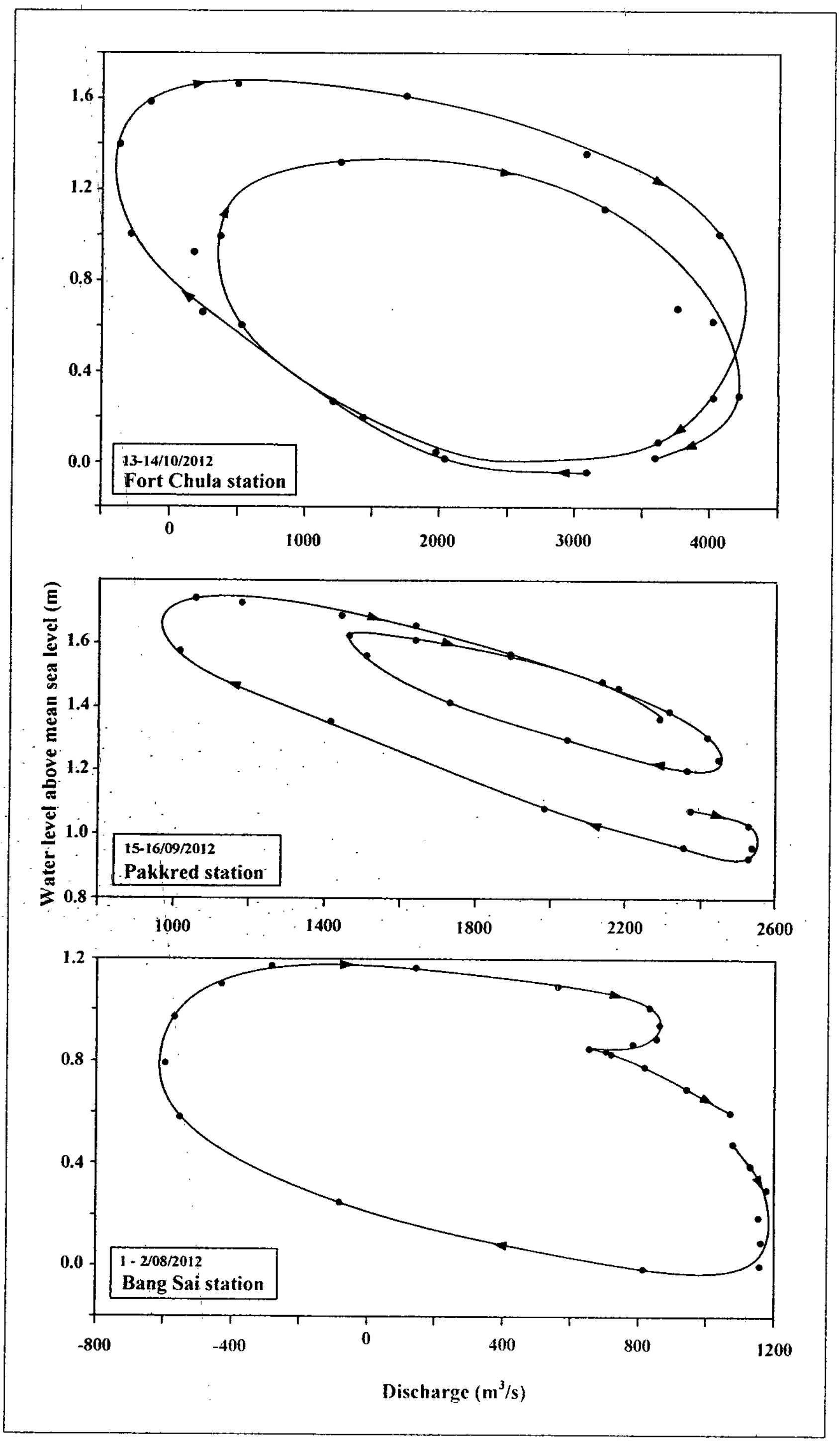

Figure 4.10 Loop rating curve in spring tide at Fort Chula, Pakkred and Bang Sai Stations (August-October 2012).

Sources of errors in the measured discharge in the river subsections in tidal rivers may include ADCP instrument error and flow variations in the river. Since the discharges in the top and bottom subsections are extrapolated from the measured subsections, discharge errors in the top and bottom subsections could be expected to be of the same magnitude as those for the measured subsections. Substantial error may occur when the boat is close to nearshore because of sudden changes in boat speed and direction, which is common at the start and end of transects in nearshore areas, particularly when stream velocities are high in those areas (Morlock, 1996).

4.2 Drainage discharge

The drainage pattern of the Lower Chao Phraya River has a cyclestarting from April with a minimum value. From May to August, the dischargegradually increases, while from August to October, the increase is more rapid, and reaches its peak in October. The discharge then decreases fairly rapidly during November and December, with the rate of decrease then slowing until minimum flow again in April. In this study, the duration of collecting data is from June to October,while are in the high discharge. The netdischarge of the spring tide at Fort Chula and Bang Sai stations has higher drainage potential than those in the neap tide because the water levels of spring tide has higher variable level than neap tide. But that is not occurs at Pakkred station because of the operation of Chao Phraya Barrier (from upstream).The total discharge of each station can be shown in Table 4.2.

Table 4.2 Total discharge of each station.

Station	Spring tide					Neap tide				
	Date	Q_{max} (m^3/s)	Q_{min} (m^3/s)	Q_{avg} (m^3/s)	Q_{total} (M. m^3/day)	Date	Q_{max} (m^3/s)	Q_{min} (m^3/s)	Q_{avg} (m^3/s)	Q_{total} (M. m^3/day)
Fort Chula	13-14 /10/2012	4210	-318	1,937	16.74	8-9 /9/2012	4,005	-279	1,674	14.47
Pakkred	29-30 /9/2012	2,440	1,031	1,912	16.49	22-23 /9/2012	2,726	1,340	2,114	19.24
	15-16 /9/2012	2,531	1,008	1.937	16.74					
Bang Sai	1-2 /8/2012	1,175	-597	540	4.67	25-26 /7/2012	899	-711	280	2.42
	18-19 /7/2012	1,136	-560	514	4.45	27-28 /6/2012	898	-690	308	2.66

The stage and discharge hydrographs can be applied tothe drainage system by using the lag time of the curve at each station (Figure 4.7). Table 4.3 shows the ratio of discharge average and maximum discharge average of each water level zone, the ebb tide especially falling water level has ability to drain the water. This study can be separated water levels in 4 zones; Rising, Maximum, Falling and Minimum water levels. The negative sign is the water flow backward to the upstream and positive sign is water flow to the downstream.

Table 4.3 The ratio of average discharge at each water level zone.

Station	Flood tide		Ebb tide	
	Rising	Maximum	Falling	Minimum
Fort Chula	-0.13	0.25	1.0	0.25
Pakkred	0.60	0.50	0.90	1.0
Bang Sai	-0.33	-0.67	1.0	0.83

4.3 Discharge estimation

Chen and Chui (2002) proposed a method to estimate the discharge on tidal effect, which is based on constant ratio of mean to maximum velocities. This method is applied from the velocity area principle as:

$$Q=\bar{V}A \tag{4.2}$$

where Q is the discharge (m^3/s)

A is the cross sectional area (m^2)

$\bar{V}$ isthe mean velocity (m/s)

By assuming that

$$\frac{\bar{V}}{V_{\max}}=\phi \tag{4.3}$$

$$Q=(\phi V_{\max})A \tag{4.4}$$

where ϕ is the constant ratio of cross-section, that is not affected by the dischargeor the water level.

$V_{\max}$ is the maximum velocity depicted on the Y-axis.

The method of discharge estimation can be separated into 2 parts:mean velocity estimation and area estimation. The field measurement data used for discharge estimation separated into 2 groups; 80% of all datawere used for calibration and 20% for verification. The steps of each part are shown in Figure 4.11 and can be described as follows.

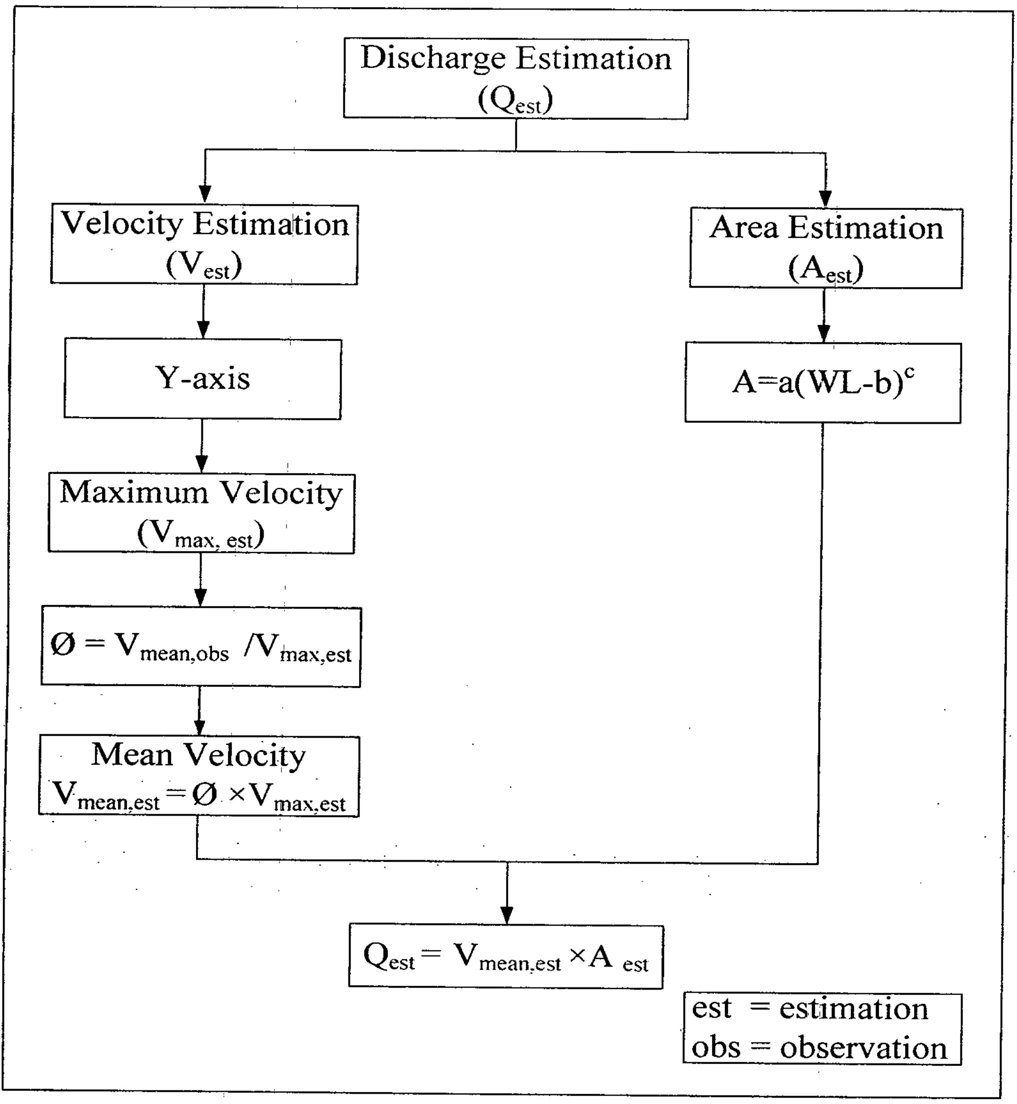

Figure 4.11 Flow chart of discharge estimation.

1) Estimation of mean velocity

Velocity determination in the river under the tidal effect is difficult. However, the velocity is important to determine the river discharge. The mean velocity is the product of ϕ and maximum velocity. When relation between mean and maximum flow velocities are plotted, the maximum velocity at a river cross section can be found the Y-axis and ϕ is the slope of graph between maximum and mean velocity. The step to determine the Y-axis and ϕ can be described as follows.

1.1) The Y- axis is the vertical line pass the maximum velocity isovel contour ofthe cross section.Normally, the Y-axis is located at the middle of the river cross section if the channel is straight and symmetrical cross section. In the natural channel, the maximum velocity is located nearby the maximum depth of thalweg zone. Its location is not variable with water level and discharge variation, as shown in Figure 4.12 and Table 4.4.

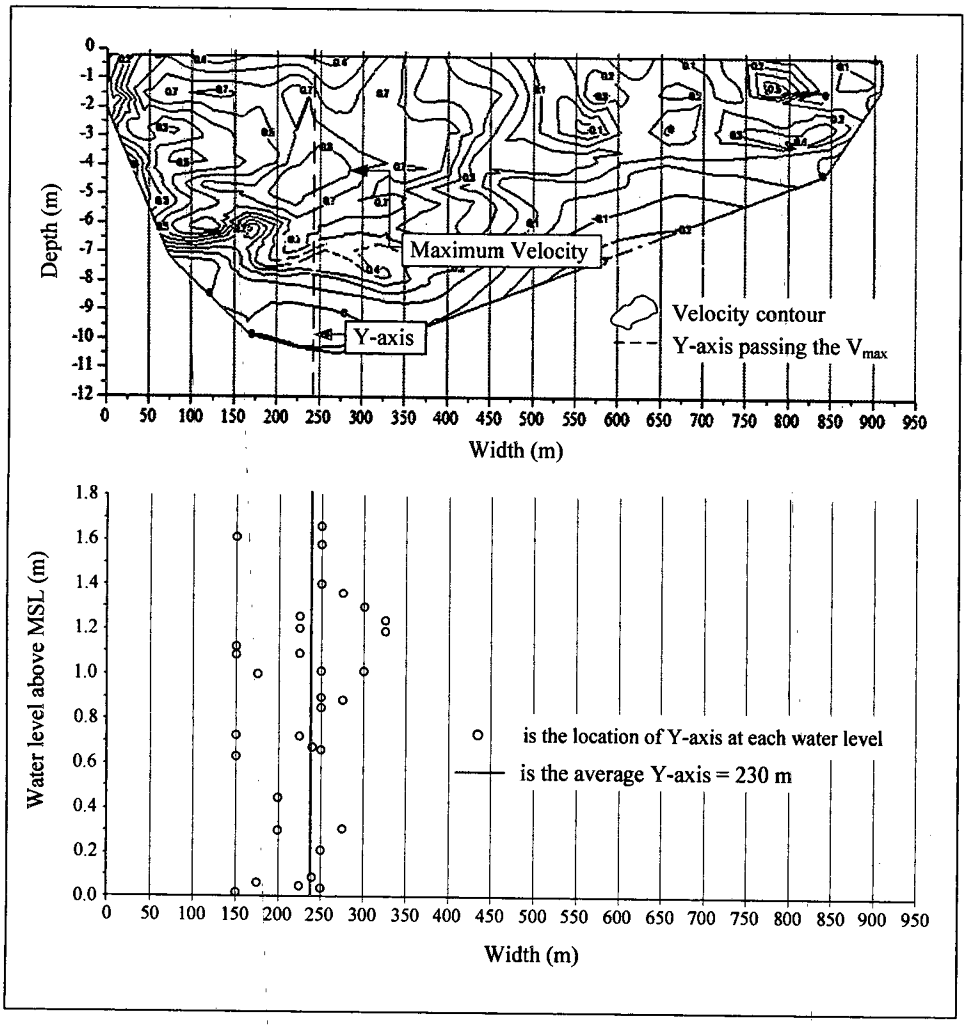

Figure 4.12 The Y-axis ofFort Chula Station.

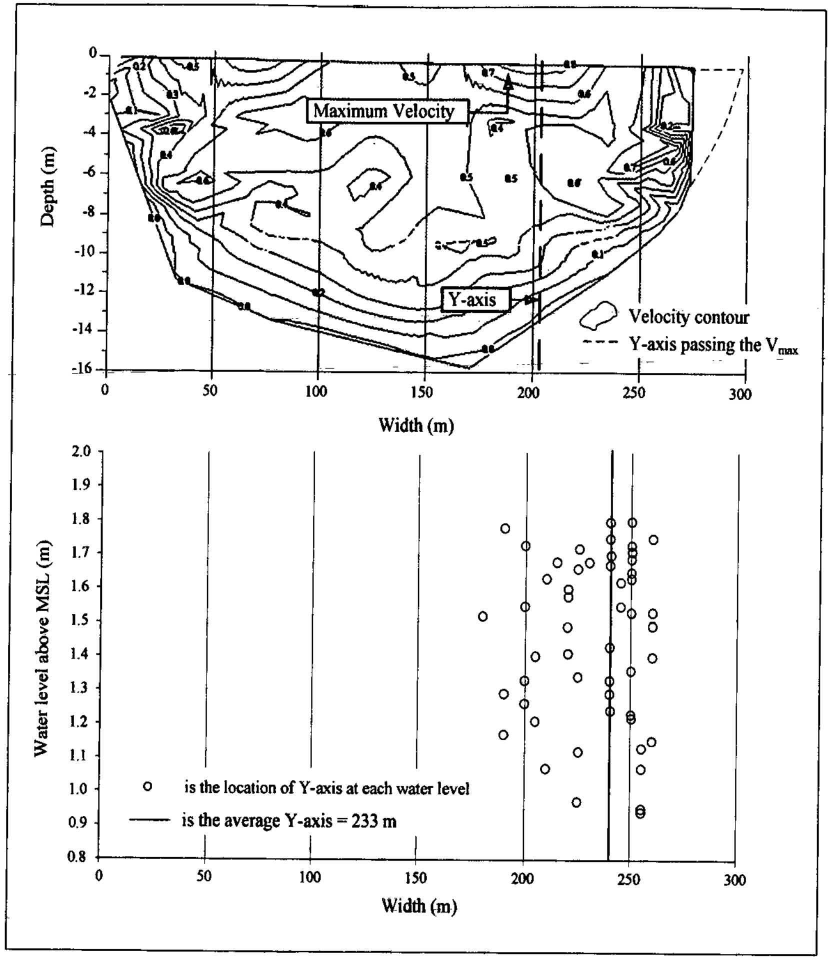

Figure 4.13 The Y-axis of PakkredStation.

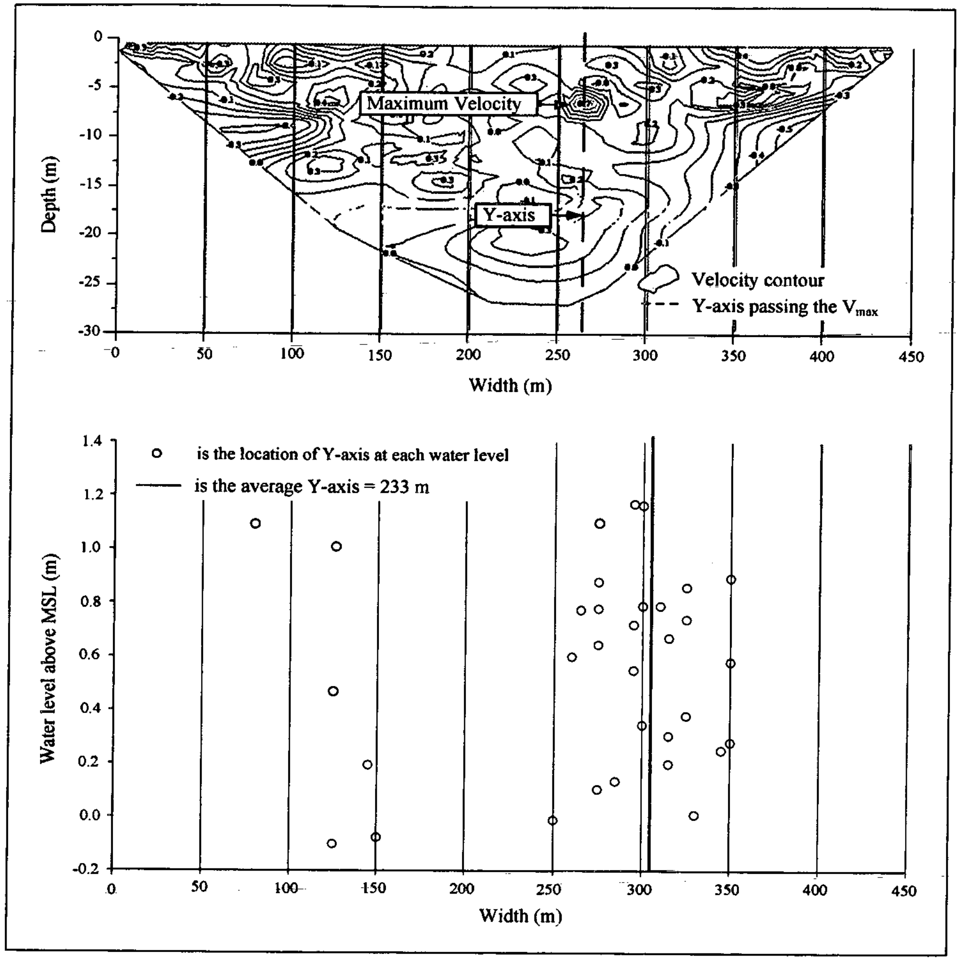

Figure 4.14 The Y-axis of Bang Sai Station.

Table 4.4 The position of average Y-axis of each station.

Station	The position of average Y-axis from the left bank (m)	Average top width of the river (m)
Fort Chula	230	920
Pakkred	233	280
Bang Sai	309	450

1.2) The average Y-axis can be used to estimate the maximum velocity of a cross- section becausethe slight shift of the Y-axis will not have much effect on the maximum velocity (Chen and Chui, 2002). Therefore the maximum velocity can be estimated at the mean location of Y-axis. The Root Mean Square Error (RMSE) of maximum velocity by ADCP observation and maximum velocity by average Y-axis as shown in Table 4.5.

Table 4.5 Accuracy and reliability of maximum velocity by ADCP and Y-axis.

Station	Maximum velocity (m/s)	Calibration		Verification	
		RMSE (m/s)	R^2	RMSE (m/s)	R^2
Fort Chula	2.760	0.463	0.91	0.493	0.89
Pakkred	1.381	0.275	0.74	0.296	0.69
Bang Sai	0.793	0.229	0.95	0.251	0.88

1.3) The ϕ is the constant ratio of the mean velocity and the maximum velocity of the cross-section (Equation 4.3). It is the characteristic of each cross section and is not affected by water level and discharge variation (Chen and Chui, 2002). The ϕ can be determined by the regression method.

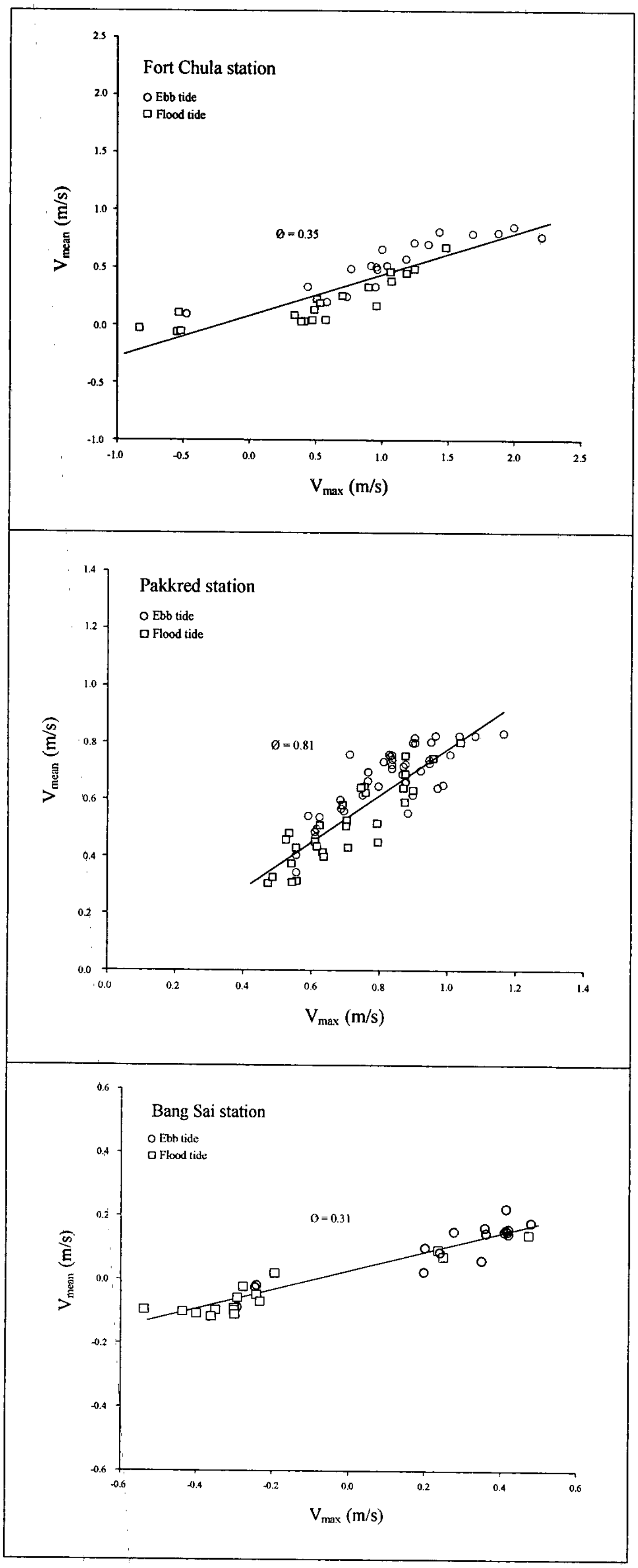

Figure 4.15 The relation between mean velocity and maximum velocity.

The ratio of mean and maximum velocity at the ebb tide is higher than those at the flood tide. The water level of ebb tide is falling, therefore it causes high discharge and high velocity as well (Figure 4.15).

1.4) The mean velocity of the cross-section can be estimated by using ϕ and the maximum velocity at average Y-axis (Equation 4.3). The RMSE between the estimated mean velocity and the observed mean velocity of each station can be shown in Table 4.6.

Table 4.6 Accuracy and reliability of estimated mean velocity and observed mean velocity.

Station	Observe mean velocity (m/s)	Calibration		Verification	
		RMSE (m/s)	R^2	RMSE (m/s)	R^2
Fort Chula	0.860	0.164	0.80	0.185	0.74
Pakkred	0.832	0.080	0.75	0.120	0.71
Bang Sai	0.244	0.050	0.91	0.094	0.87

Tables 4.5 and 4.6show the RMSE of maximum and mean velocity.The RMSE of mean velocity is less than that of the maximum velocity.

2) Estimation of area

The ADCP calculates the cross-sectional area at2 differentwater depths of subsection and widths of subsection. The cross-sectional area causes the summary of the subsection area.Assuming that the stable channel is without sediment and erosion, the cross-sectional area and water level are related in form of power regression as:

$$A=a(WL-b)^c \tag{4.5}$$

where WL is the water level above the mean sea level (m. MSL), a and c are coefficients that can be determined from the data, b is the water level of effective zero area. The cross-sectional area equation can be obtained from the power regression method, as show in Figure 4.14 and the accuracy of estimated cross-sectional area is shown in Table 4.7.

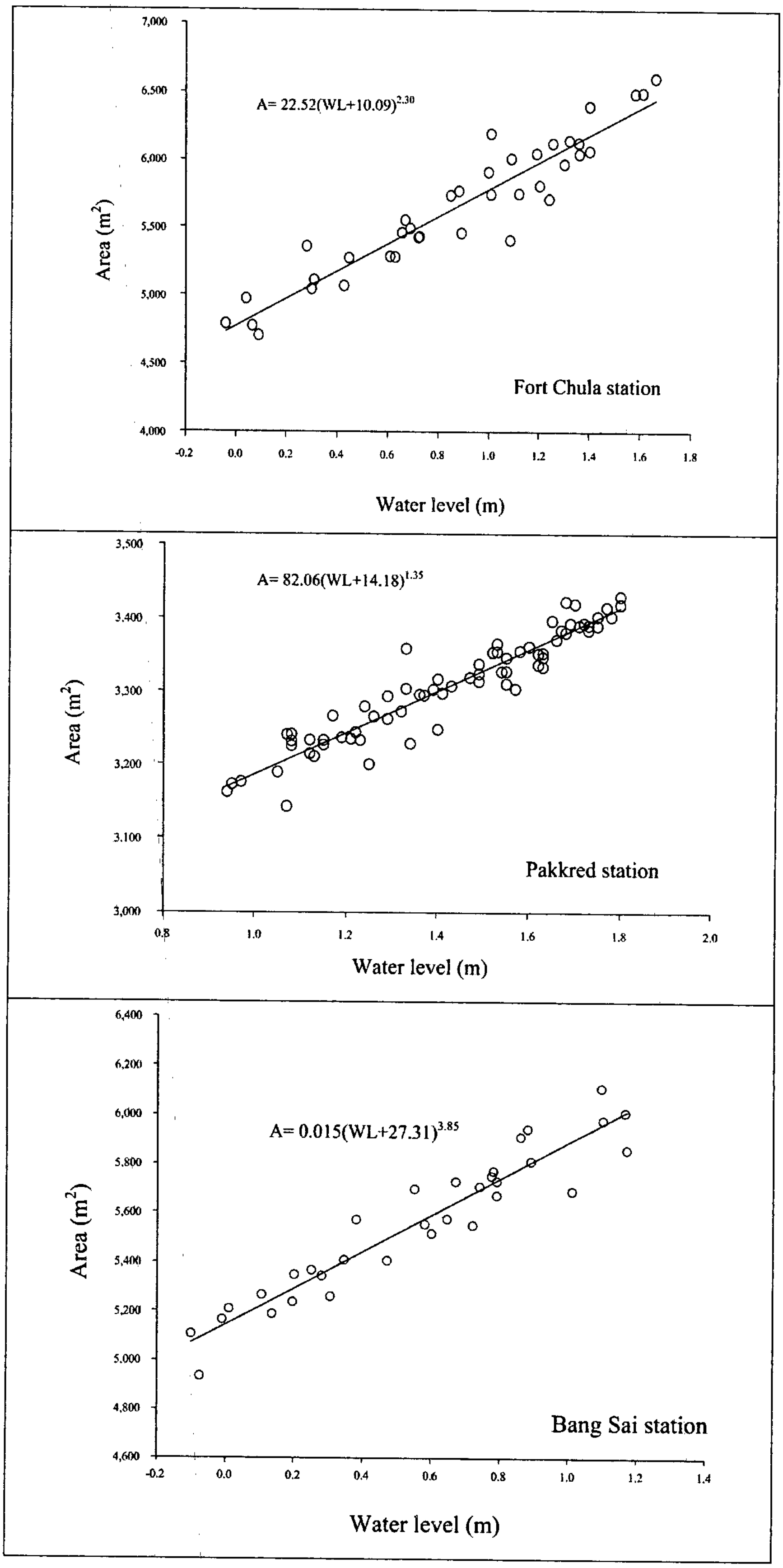

Figure 4.16 Area estimation.

Table 4.7 Accuracy and reliability of estimated and observedcross-sectional areas.

Station	Maximum area (m^2)	Calibration		Verification	
		RMSE (m^2)	R^2	RMSE (m^2)	R^2
Fort Chula	6,598	186.8	0.91	201.8	0.91
Pakkred	3,430	23.1	0.90	30.1	0.89
Bang Sai	6,108	77.8	0.93	81.8	0.93

3) Discharge estimation

The discharge estimation can be computed by using the locations of the Y-axis, which are 230 m, 233m and 309 m from the left bank at Fort Chula,Pakkredand Bang Sai Stations, respectively. The location of Y-axis can be used for measurement the maximum velocity in the field. The constants ratio of cross section (ϕ) are 0.35,0.81 and 0.31 of Fort Chula,Pakkredand Bang Sai stations, respectively. The water levelsare measured from the staff gages in the unit of meter above mean sea level. Therefore, the equation of discharge estimation can be expressed as Equations4.6-4.8. The limitations of water level above mean sea level (m, MSL) of each equation are -0.1 to 1.7, 0.9 to 1.8 and -0.2 to 1.2 respectively.

Fort Chula Station : $$Q = (0.35V_{max})\,[22.52\,(WL + 10.09)^{2.30}] \quad (4.6)$$

PakkredStation : $$Q = (0.81V_{max})\,[82.06\,(WL + 14.18)^{1.35}] \quad (4.7)$$

Bang Sai Station : $$Q = (0.31V_{max})\,[0.015\,(WL + 27.31)^{3.85}] \quad (4.8)$$

The accuracy and reliability of the proposed equations are shown in Figures4.17-4.18 and Table 4.8. The estimate discharges iscompared with at obtained by the conventional method.

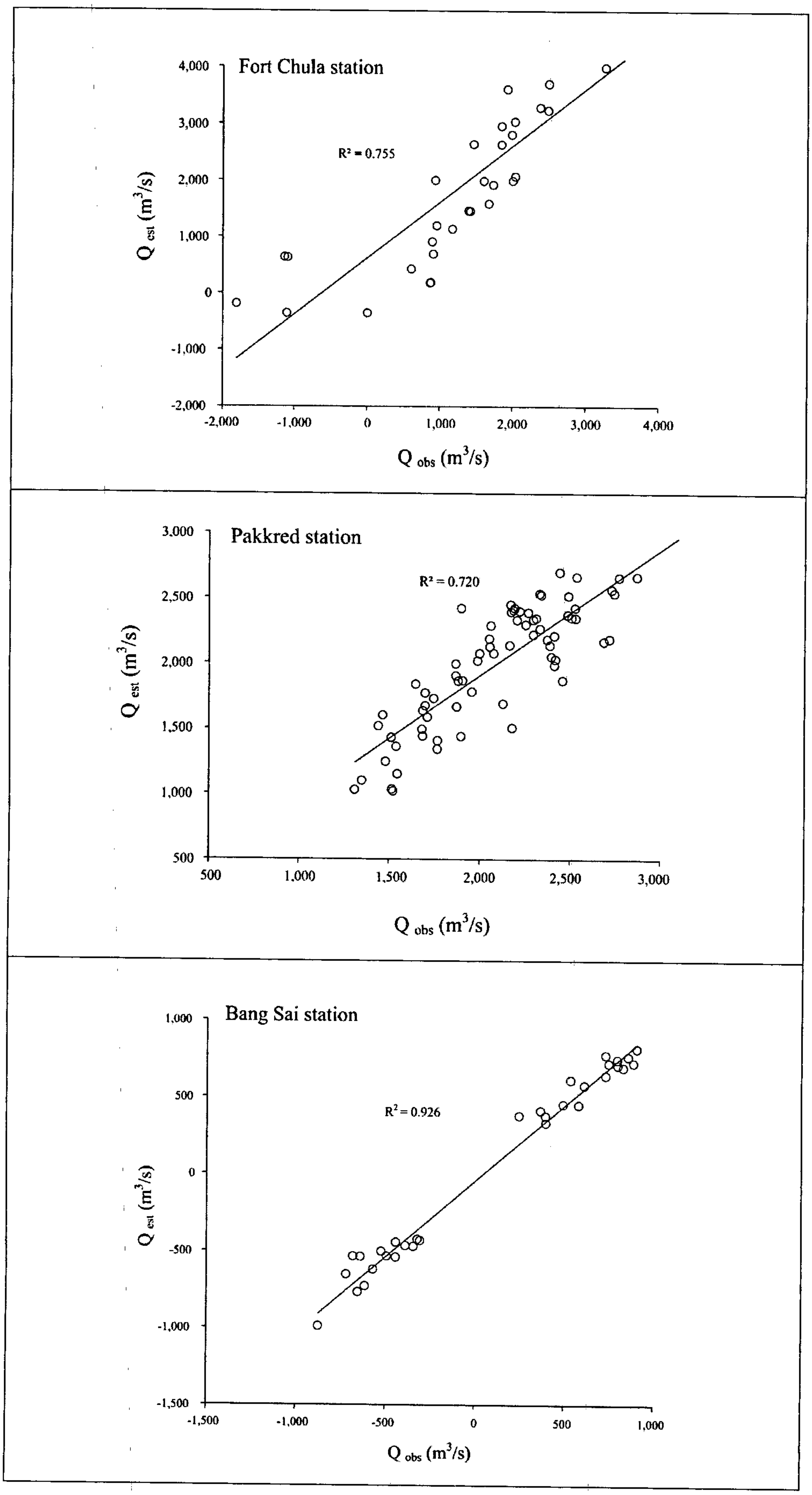

Figure 4.17 Accuracy of estimated discharge.

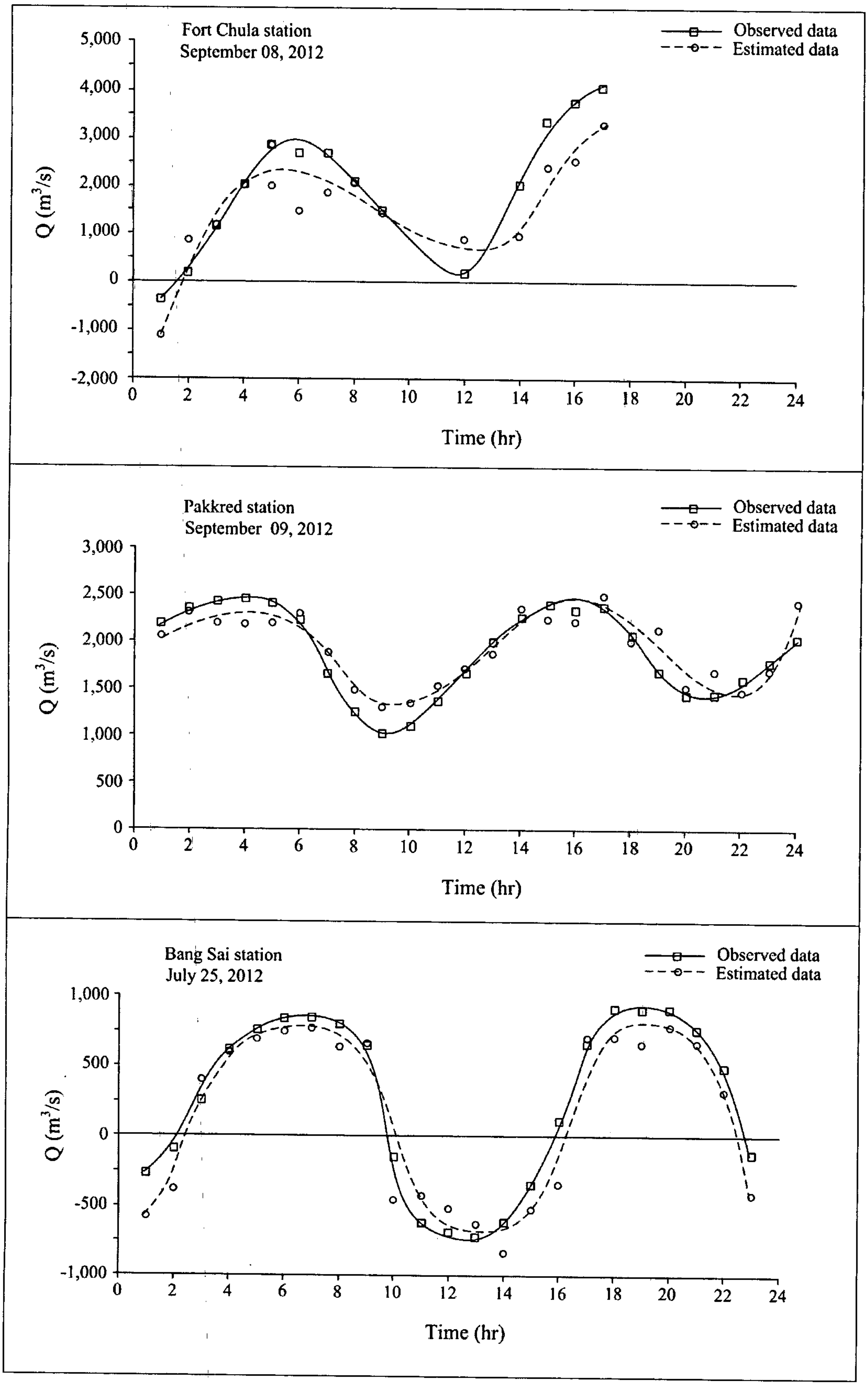

Figure 4.18 Observed and estimated discharge hydrographs of the Lower Chao Phraya River.

Table 4.8 Accuracy and reliabilityof estimated discharge.

Station	Maximum discharge (m^3/s)	Calibration		Verification	
		RMSE (m^2)	R^2	RMSE (m^2)	R^2
Fort Chula	4,316.8	761.7	0.72	793.7	0.68
Pakkred	2,716.8	263.6	0.76	271.2	0.71
Bang Sai	1,173.4	92.1	0.93	102.7	0.86

4.4) Application of the results

The results of research can be applied to water management in the Lower Chao Phraya River only during the wet season. They are:

1) Total discharge equation
2) Lag time curve

1) Total discharge equation

The step of discharge estimation, as shown in Figure 4.19,and the details of its can be shown as follows:

1.1) Install the ADCP at the bottom of the section in order to measure the maximum velocity. The distance from the left bank for the installation of the ADCP is 230, 233 and 309 m of Fort Chula, Pakkred and Bang Sai Stations, respectively.

1.2) Install the staff gauge at the river bank in order to measure the water level above the mean sea level.

1.3) The maximum velocity from ADCP and the water level from the staff gauge reading can be substituted into the total discharge equations: Equations 4.6, 4.7 and 4.8 for Fort Chula, Pakkred and Bang Sai Stations respectively. Then calculate the total discharge of fresh water drained into the sea.

Fort Chula Station : $$Q = (0.35V_{max}) [22.52 (WL + 10.09)^{2.30}] \quad 4.6$$

PakkredStation : $$Q = (0.81V_{max}) [82.06 (WL + 14.18)^{1.35}] \quad 4.7$$

Bang Sai Station : $$Q = (0.31V_{max}) [0.015 (WL + 27.31)^{3.85}] \quad 4.8$$

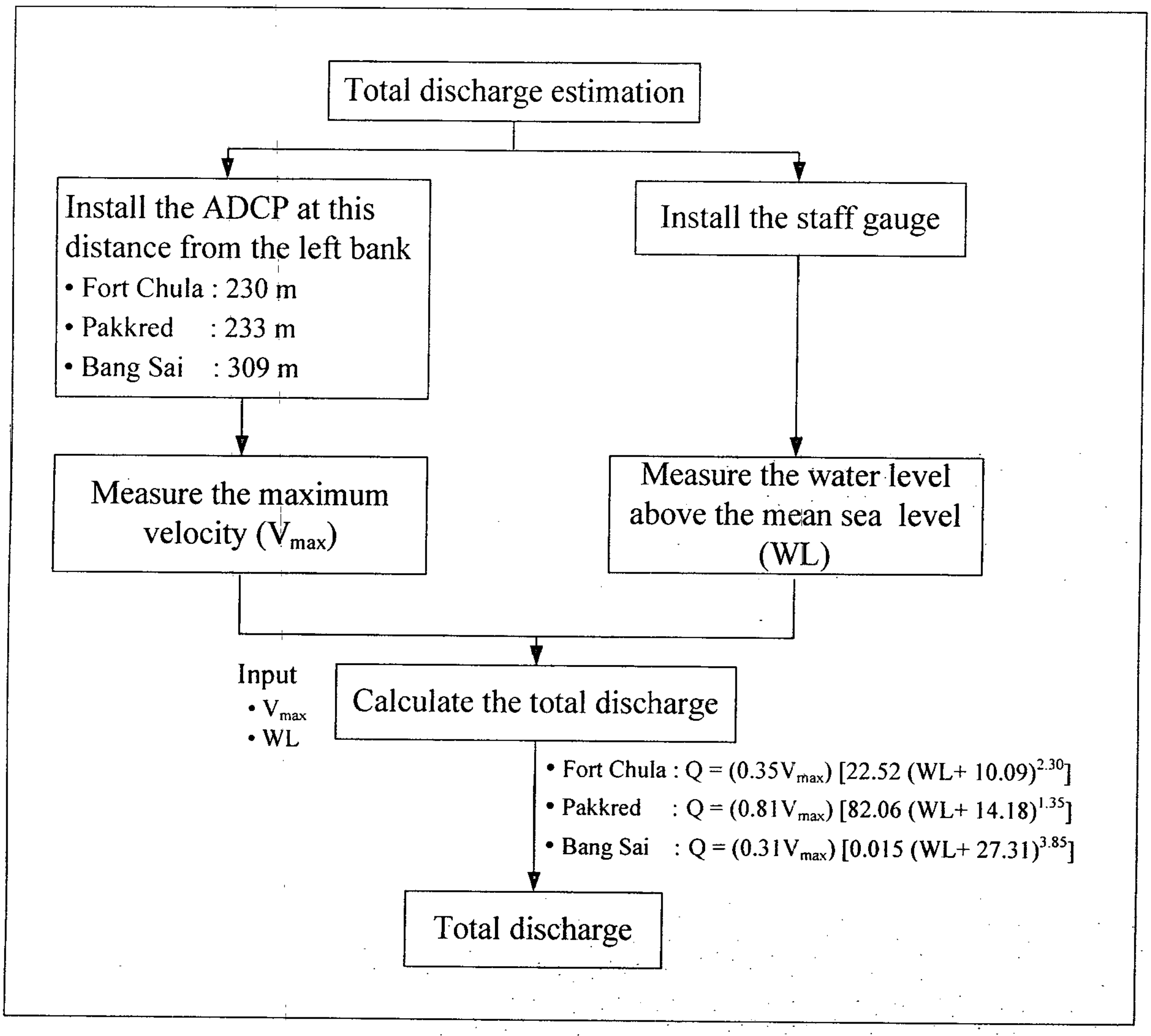

Figure 4.19 Step of discharge estimation.

An example of the application of the total discharge equation at Fort Chula Station is shown in Figure 2.20. The maximum velocity from ADCP is 2.12 m/s and water level from staff gage is -0.04 m above mean sea level, they can be substituted into total discharge equation of Fort Chula station as following;

$$Q = \quad (0.35x\ 2.12)\ [22.52\ (-0.04 + 10.09)^{2.3}]$$

Total discharge is:

$$Q = \quad 3{,}372.5\ m^3/s$$

At Fort Chula station, the total discharge of fresh water that can be drained into the sea is 3,372.5 m^3/s. Finally, the total discharge at each station can be used to analyze the drainage system.

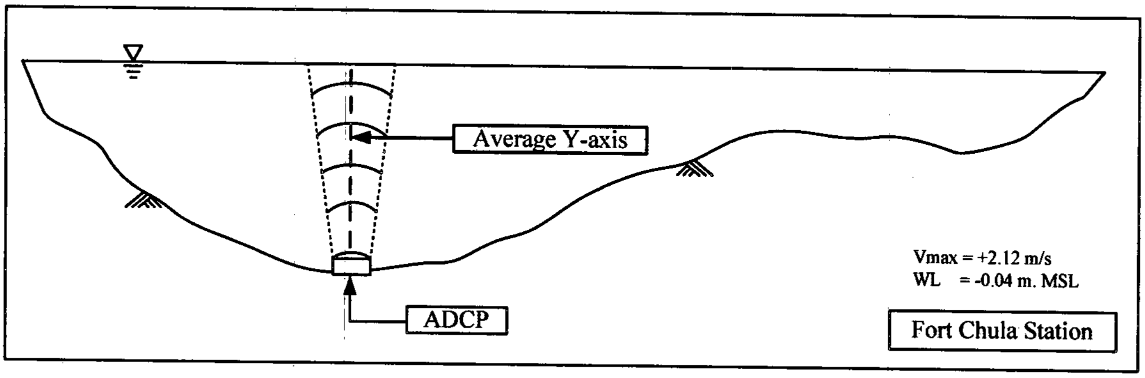

Figure 4.20 An application of discharge equation.

2) Lag time curve

The costs of ADCP and the installed system are too high and difficult to maintain. So, the lag time curve between water level and discharge can be applied to drainage system. The important criteria of drainage discharge by using lag time curve as shown in Figure 4.21 and the details of the criteria are as follows:

- The duration of rising water level can be used to operate the drainage system byclosing the water gate in order to obstruct the water flow up to the inland.

- The duration of the maximum water level to the minimum water level can be used to operate the drainage system by opening the water gate because this duration the total discharge flows out to the sea.

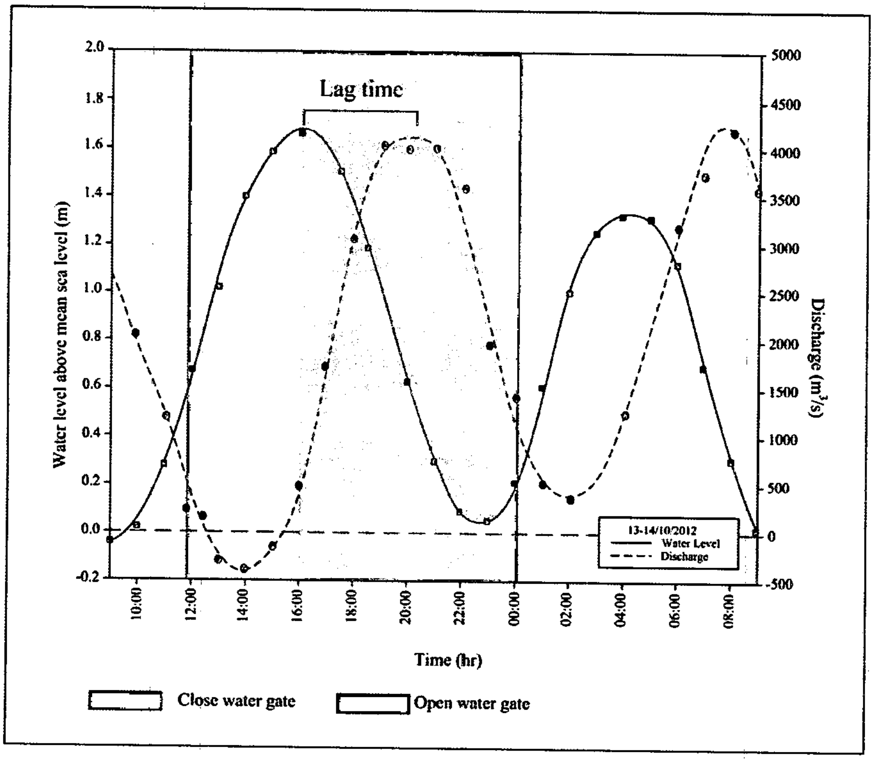

Figure 4.21 Application of the lag time curve of the drainage system.