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Flume Experiments on Channel Morphology at a Tributary Junction

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하천 합류점의 하도형상에 관한 수로실험

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Abstract : Flume experiments are conducted to describe the channel morphology at a tributary junction and to examine the influence of channel arrangements and hydrologic conditions on the channel morphology. When flow momenta of two tributaries are equal, a receiving stream tends to align with an axis bisecting junction angle. It causes lateral migration of a receiving stream according to an initial channel arrangement. As a result, the post-confluent channel morphology varies with plan geometry of a confluence such as symmetry, transition and asymmetry. Bed scour is the most notable morphology within a junction site. Its shape is characterized by steep walls which are primarily influenced by junction angle. Key control of scour dimension is also junction angle. Although the principle of accordant junction has been undoubtedly accepted, discordance is commonly developed at model and natural stream confluences. Unit discharge ratio of confluent streams is the most crucial factor because both discharge and sediment concentration ratios have an effect on discordance at a junction.

Key Words : flume experiment, tributary junction, channel morphology, bed scour, discordant junction

요약 : 하천 합류점의 하도형상을 파악하고 하도형상에 영향을 미치는 요소를 조사하기 위해 소형 수로실험을 실시했다. 합류하는 두 수류의 모멘트가 동일하면 합류후 하도는 합류각도를 이분하는 방향으로 늘어서기 때문에 초기하도의 배열에 따라 하도의 측방이동이 일어난다. 그 결과 합류후 하도의 형상은 합류의 평면형태 즉 대칭형, 점이형, 비대칭형에 따라 달라진다. 합류에 기인하는 가장 특징적인 하도형상으로 하상 세굴부를 들 수 있다. 급경사의 양벽으로 둘러싸인 합류점의 세굴부는 기본적으로 합류각도에 의해 지배된다. 하천합류는 전통적으로 협화적이라고 표현되어 왔지만 불협화적 합류도 빈번하게 발생한다. 합류의 불협화에는 합류하천의 유량비뿐만 아니라 유사농도비도 관여한다. 따라서 불협화를 일으키는 최대요소로는 두 비를 고려한 수면폭당 단위유량비를 들 수 있다.

주요어 : 수로실험, 하천 합류점, 하도형상, 하상세굴, 불협화적 합류

1. Introduction

A tributary junction represents a point of significant change in hydrologic, hydraulic and sedimentolgic conditions. The convergence and realignment of confluent flows generates the channel morphology characteristic of this site. The topography of channel bed at a junction is generally divided into tributary mouth bars with commonly steep avalanche faces, a confluence scour zone and post-confluent bars associated with separated flows(Bridge, 1993). Best(1988) and Biron *et al.*(1993) noted that the bed morphology is primarily controlled by flow and sediment transport patterns at a junction and vice versa. It is clear that key control of flow dynamics appears to be hydrologic conditions, such as the relative magnitude and synchroneity of confluent

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flows(Itakura, 1972; Best, 1988). Confluent channel arrangements also have influence on flow patterns and resultant sediment dispersal within a junction(Mosley, 1976; Best, 1986). Flume experiments with fixed bed, for example, demonstrated that flow patterns vary with junction angles(Itakura, 1972; Best and Reid, 1984). Roy *et al.*(1988) also found that a low junction angle simplifies flow patterns at a natural river confluence with coarse bed material. It implies that site-specific factors related to confluent planform yield discrepancies in the channel morphology at a confluence hydrodynamic zone(Kenworthy and Rhoads, 1995) where merging tributary flows must adjust to channel arrangements.

This paper reports the results of the flume experiments designed to describe the channel morphology at a tributary junction. It also examines the influence of plan geometric factors, such as confluent planform and junction angle of tributaries, and variations in incoming flow and sediment load conditions on the channel morphology at a confluence hydrodynamic zone.

2. Experimental Procedure

Two set of experimental runs were conducted in a small-sized tilting flume which was used in previous experiments(Kim, 1997). The flume was filled with a 40:1 mixture of sand and bentonite which was made to enhance the cohesiveness of bank material. The experimental material had a median diameter of 0.57mm and a Trask sorting coefficient of 1.23(Kim, 1997). It provided a straight, single-thread channel with cohesive and stable banks and an opportunity for the banks to be sufficiently undercut and eroded. Initial channels 6cm wide and 3cm deep were cut down after the mixture was compacted and graded into a desired surface slope of 0.015. After each experimental runs, the affected bed and bank material was removed and fresh material was added to ensure homogeneity in the experiments. The experimental runs were continued until the model stream reached a dynamic equilibrium state in the sense of Mackin's(1948) definition of grade. Run times were between 2.5 and 4 hours.

Confluent planform of initial channels was arranged in three ways because flow patterns at a junction are largely controlled by plan geometry of confluent channels(Best, 1986; 1988). There are two basic types of confluent planform; symmetry and asymmetry. The former is Y-shaped in plan geometry, whereas the latter defines that a receiving stream forms a linear downstream extension of a major tributary. The series Ⅰ runs were concentrated on effects of tributary arrangements on channel morphology. Haralick *et al.*(1985) extracted confluent planform from remote sensing images of drainage networks and found that natural river systems demonstrate a great variety of junction angles, even though these angles are inclined to be acute(Playfair, 1802; Horton, 1945). It is consequently required to consider obtuse angles as well as acute angles in the experiments. The natural plan geometry of confluences also exhibits a wide range between two basic types of confluent planform(Haralick *et al.*, 1985; De Serras and Roy, 1990). Thus, transitional arrangements which two confluent channels join at unequal junction angles were also simulated in the series Ⅰ runs. Twelve experimental runs, including symmetrical five cases, transitional three cases and asymmetrical four cases, were carried out to reflect a wide range of plan geometry, even though the number of runs was still insufficient to cover fully stream confluences in the natural environments (Fig. 1). Hydrologic conditions of two tributaries were held equal and constant at 175cm^3/s so that their flow momenta at a junction were kept equivalent throughout the series Ⅰ runs. Sediment load was also held constant at 2.7gm/s. On the other hand, the series Ⅱ runs were focused on

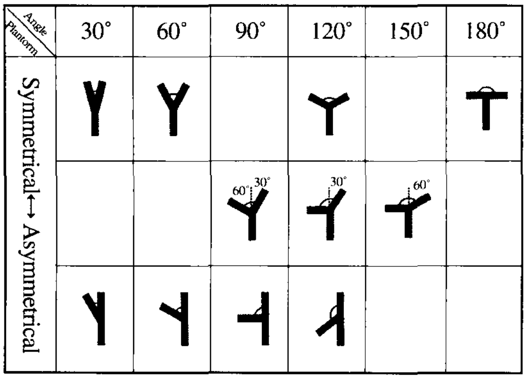

Figure 1. Varied arrangements of confluent channels simulated in the series I runs.

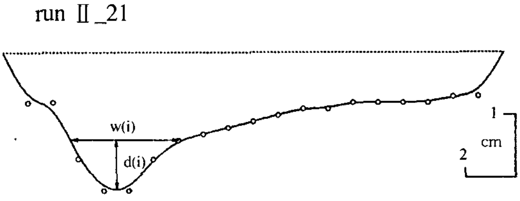

Figure 2. Recognition of bed scour. A scour pool was objectively recognized based upon the minimum width-depth ratio at channel cross-sections.

effects of variations in incoming flow regime and sediment conditions on channel morphology. The confluent planform was determined as a symmetrical Y-shape which could be considered more representative of plan geometry of tributaries. An initial angle of junction was kept constant at arbitrary 50°. Twenty-three experimental runs were conducted with varied amounts of discharge(150～500cm^3/s) and sediment load(2.3～6.7gm/s) of a major tributary. In all of runs, the discharge and sediment load of a minor tributary were held constant at 100cm^3/s and 1.9gm/s, respectively.

During the experimental runs, detailed measurements of channel cross-sections were made to describe bed scour at a junction. Five traverses were selected at longitudinal intervals of 5cm within this site. Bed elevations at each traverse were measured at every 1cm length. A set of transverse points defines each channel profile. Width and maximum depth were calculated at each transverse point of channel profiles(Fig. 2). A scour pool was objectively recognized based upon the minimum width-depth ratio. Wolman (1955) suggested that bankfull is the stage at which the form ratio is a minimum. The minimum value of form ratio was determined from the set of width-depth values at each transverse profile. The width and depth at this point defined the dimension of a scour pool. After desired run time, transverse and longitudinal water profiles were measured and vertical photographs were taken. Water flow and sediment feed were terminated before channel cross-sections were minutely measured at longitudinal intervals of 10cm. Six cross-sections were selected for each tributary and ten for a receiving stream.

3. Results and Discussion

1) Post-confluent Channel Morphology

Figure 3a shows the typical channel morphology at a symmetrical junction which consists of two tributary mouth bars, a confluence scour and a mid-channel bar of a receiving stream. This morphology is very similar to those observed in other experiments(*e.g.* Mosley, 1976; Ashmore, 1982; Best, 1988), even though experimental conditions and materials are different. Smith(1973) and Roy *et al.*(1988) also reported similar morphology at natural river junctions, implying that this morphology seems to be a common feature developed at a Y-shaped junction. By contrast, Figure 3b exhibits the topography of channel bed at an asymmetrical junction. A post-confluent channel shows a curvature because a distinct side bar is developed immediately downstream of a junction. It indicates that the channel morphology at a junction varies with an

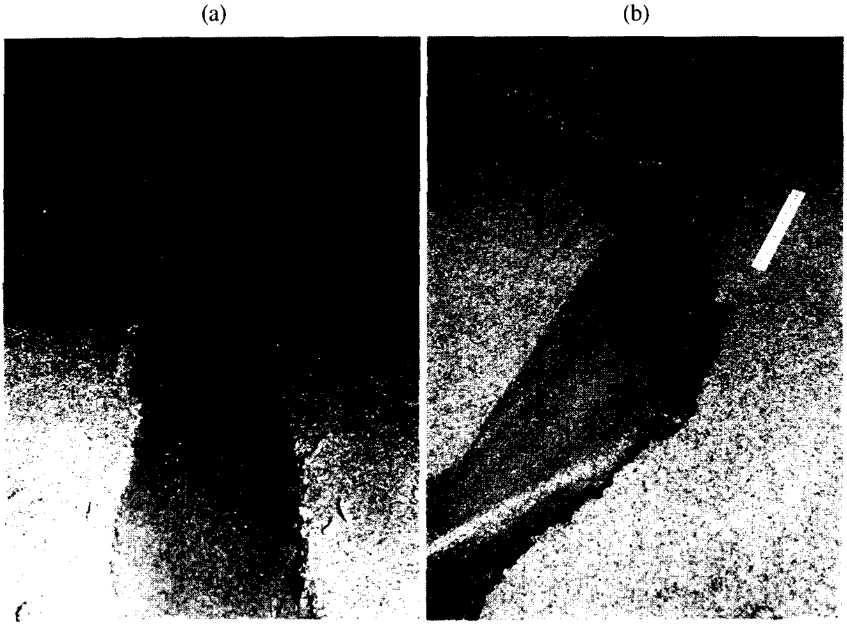

Figure 3. Oblique views showing the topography of channel bed at (a) a symmetrical junction and (b) an asymmetrical junction.

arrangement of confluent channels.

Because tributary flow momenta were held equivalent throughout the series I runs, the confluence scour aligned with an axis bisecting the angle of junction. A receiving stream also tended to align with the confluence scour. The differences in post-confluent channel morphology, as shown in Figure 3, result from the alignments of the confluence scour and the receiving stream which reflect an initial confluent planform. The receiving stream was initially placed in line with an axis bisecting the junction angle at a Y-shaped confluence(Fig. 1). The initial channel arrangement was unchangeable because the receiving stream did not migrate laterally. Sediment transport within a junction was concentrated at the confluence scour. Sediment transport capacity decreased downstream of the confluence scour because secondary currents responsible for the scour decreased in intensity. It generated deposition of sediment in a mid-channel bar and resultant widening of the channel downstream of a junction(Fig. 3a). The cross-sectional profiles of the post-confluent channel presented longitudinal variations in shape. However, it was generally symmetrical because the lateral shift of the channel did not occur(Fig. 4a).

On the other hand, the receiving stream did not align with an axis bisecting the initial junction angle at an asymmetrical confluence(Fig. 1). The post-confluent flow was directed toward the left bank and caused erosion there, thus tending to bring the receiving stream into alignment with an axis bisecting the junction angle. The deposition of sediment in a side bar occurred on the right bank immediately downstream of a junction(Fig. 3b and 5). Both bank erosion and bar deposition continued throughout the experimental runs. It was expected that the whole receiving stream aligns with an axis bisecting the junction angle and the final confluent planform becomes Y-shaped. However, the expected planform was not finally developed in the experimental runs because the bank material was so cohesive and resistant that the flow was forced

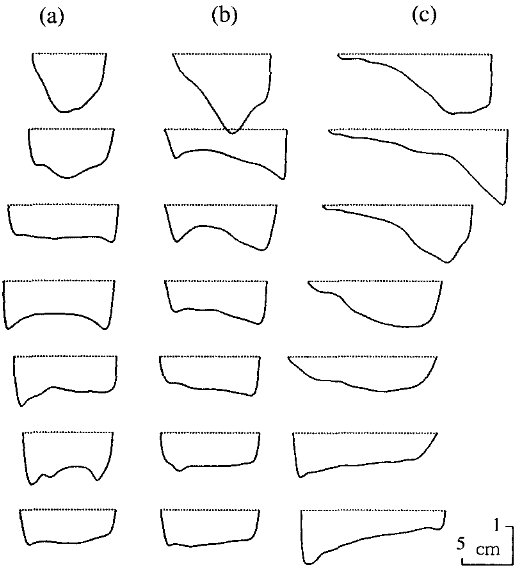

Figure 4. Longitudinal variations in cross-section of post-confluent channels with (a) a symmetrical junction angle of 60°, (b) a transitional junction angle of 90° and (c) an asymmetrical junction angle of 90°.

to turn. Thus, the channel immediately downstream of a junction exhibited a bend of a meandering stream. The transverse sections of the receiving stream were also asymmetrical(Fig. 4c).

A transitional confluence generally presented similar results to those of a Y-shaped confluence. However, a transitional confluence was considered as an intermediate type because it also indicated characteristics of an asymmetrical confluence. The receiving stream migrated laterally to align with the confluence scour and exhibited a slight curvature immediately below a junction(Fig. 4b). As a consequence, the post-confluent channel morphology can be classified into three types depending upon an arrangement of initial channels; symmetrical, transitional and asymmetrical.

2) Bed Scour at a Tributary Junction

The most notable bedform at a junction is a scour pool developed within the center of this site(Fig. 5). However, the confluence scour has received relatively meager attention from geomorphologists owing to difficulties in scour measurements at natural river junctions in spite of its notable morphologic feature(Ashmore and Parker, 1983). Figure 6 illustrates typical shapes of a scour pool transversely and longitudinally. The cross-sectional profile shows steep sidewalls indicating that the scour pool is maintained by strong secondary currents within itself(Mosley, 1976). The cross-sectional form of the scour pool changes with discharge ratios of two confluent channels. It becomes more symmetrical as discharges of the tributaries become equivalent. The longitudinal profile exhibits an elongate basin form with a relatively steep headwall. The longitudinal form varies with junction angles as well as discharge ratios; the headwall increases slope with increasing junction angle irrespective of confluent planform(Fig. 7a). Discharge ratios are also directly related to headwall slopes, even though the

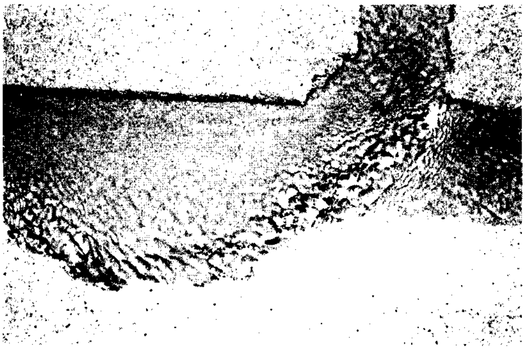

Figure 5. Vertical view of a junction with an asymmetrical angle of 90°.

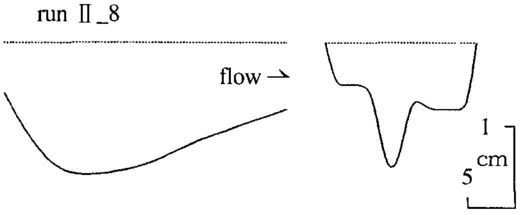

Figure 6. Longitudinal and transverse forms of a scour pool.

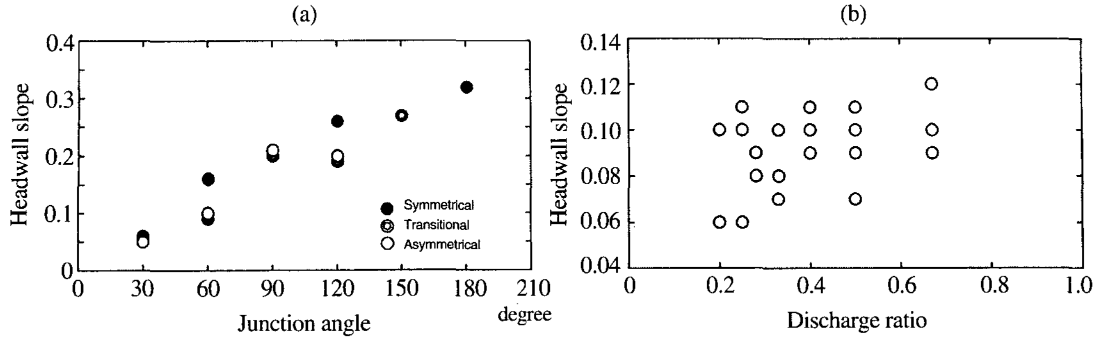

Figure 7. Relation of headwall slope of a scour pool to (a) junction angle and (b) discharge ratio of two tributaries.

relationship is not so strong(Fig. 7b).

Scour depth has been usually expressed as a function of the average depth of tributaries (Ashmore and Parker, 1983; Best, 1986). However, the dimensionless scour depth may be influenced by bedload transport which decreases tributary depths; a wide, swallow cross-section is favorable for transporting a high bedload sediment because this channel shape provides an appropriate hydraulics to increase stream competence (Morisawa, 1985). Thus, scour depth and width were directly defined from measurements in that there was few suspended sediment in the experiments.

The relationship between scour depth and discharge ratio of tributaries is plotted in figure 8a. This plot shows no specific association between the two variables, even though it is expected that discharge ratio is positively related to scour depth in that turbulence at a junction is largely dependent on the relative strengths of two confluent flows. Because water discharge of a minor tributary was held constant in the series Ⅱ runs, a decrease in discharge ratio implies an increase in total discharge which also influences turbulence. When the relative flow condition of tributaries is equal, an increase in total discharge causes higher turbulence at a junction. Thus, opposite changes in discharge ratio and total discharge exert an effect on the bed scour simultaneously and result in no specific tendency to change. Figure 8b illustrates that total sediment concentration is inversely related to scour depth. Bedload materials are largely transported through a scour pool downstream of a junction. It indicates that scour depth decreases as more sediment load is transported through the scour pool. However, sediment concentration ratio of tributaries has no effect on the scour pool.

On the other hand, Figure 8c shows that a strong relationship exists between scour depth and junction angle. The best-fit regression gives the equation with correlation coefficient of 0.92

$$d_s = 18.7 * \mathrm{Log}A - 21.5$$

where d_s and A denote scour depth and junction angle, respectively. Compared to other factors, junction angle exhibits a systematic linear relationship with scour depth noted by Mosley (1976); scour depth increases rapidly at junctions of acute angle and slowly at junctions of obtuse angle. This relationship does not depend on arrangements of initial channels. However, scour width shows a less distinct relationship with junction angle. It may be partly due to measurement errors associated with movable avalanche faces of tributary mouth bars.

The bed scour results from turbulence and helicoidal flows closely related to flow dynamics within a junction(Mosley, 1976; Ashmore, 1982). It is clear that the discharge ratio of tributaries

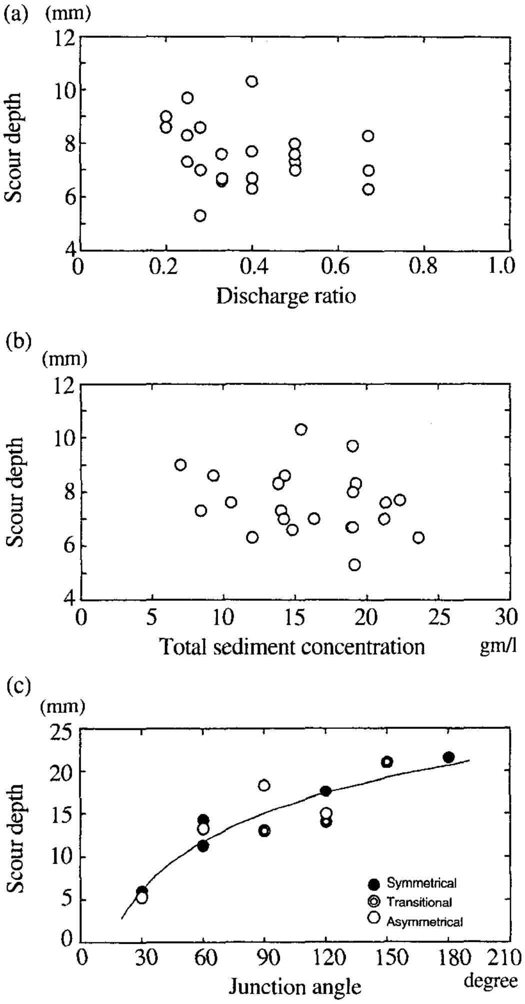

Figure 8. Relation of scour depth to (a) discharge ratio, (b) total sediment concentration and (c) junction angle of two tributaries.

controls flow patterns within a junction. Best(1986) and Roy *et al.*(1988) described flow patterns at a junction, but their models exhibited a difference in the existence of separation and stagnation zones. Because this discrepancy is attributable to different junction angles, the bed scour is thought to be controlled by confluent channel arrangements. The size of a scour pool is basically considered as a function of turbulence and shear stress at a junction. Within the limits of the experiments, junction angle is the most influential factor of the scour dimension. Discharge ratio, total discharge and total sediment load of tributaries have relatively minor effects on the bed scour.

3) Discordant Junction

A tributary junction has been accepted as being morphologically accordant since Playfair(1802) who pointed to accordance at a confluence, even though some geomorphologists referred to a discordant junction(*e.g.* Morisawa, 1964). However, Kennedy(1984) defined six types of junctions as accordant, hanging, barred, impeded, disrupted and disturbed and noted that junctions between channels of roughly comparable sizes may be really accordant. Increased, yet still insufficient, attention has been recently paid to non-accordant junctions. Best and Roy(1991), for example, simulated a confluence of unequal depth channels in a fixed bed flume. Biron *et al.*(1993) also surveyed a discordant junction and described a different morphology from that of an accordant junction.

A typical discordant junction is clearly seen in figure 9, even though bedform is slightly modified as water flow was terminated. The mouth bar of a minor tributary appears to be placed on the bed of

Figure 9. Oblique view of a non-accordant junction.

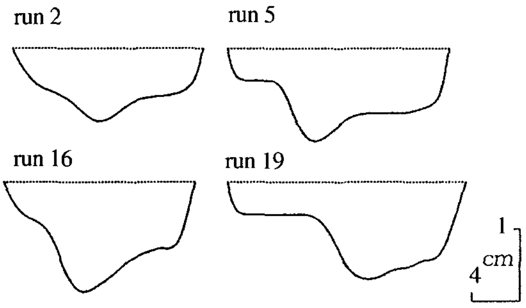

Figure 10. Cross-sectional profiles showing discordant junctions.

a major tributary at a junction. An elevation difference between two tributary beds is remarkable. Discordant junctions were commonly observed throughout the series Ⅱ runs, indicating that discordance at a confluence is not an unusual feature. Figure 10 shows cross-sectional profiles across junction sites of runs 2, 5, 16 and 19. It clearly illustrates that the tributary bed is higher than that of the main channel except run 2 with higher discharge ratio of two tributaries. Assuming that water surfaces of confluent flows at a junction are accordant, an elevation difference between the tributary and the main channel beds simply indicates the degree of discordance. Thus, a discordance index(D) was estimated for all runs as

$$D = (d_{major} - d_{minor})/d_{major}$$

where d is the mean depth at each tributary mouth and the subscripts major and minor define the major and minor tributaries, respectively.

The most probable control of discordance at a junction can be intuitively considered the relative magnitude of confluent discharges. When discordance is plotted as a function of discharge ratio of tributaries, a clear inverse relationship emerges(Fig. 11a). Discordance is also plotted against sediment concentration ratio of tributaries because channel depth is strongly influenced by sediment load(Kim, 1997). Figure 11b illustrates that discordance is positively related to concentration ratio, with considerable scatters. It indicates that these factors exert an effect on discordance in opposite directions. Using unit discharge, defined by discharge per unit channel width, as an independent variable, scatters in the relationships with discordance are considerably reduced(Fig. 11c); discordance is primarily controlled by unit discharge ratio of tributaries because unit discharge reflects effects of both discharge and sediment load on channel depth at a tributary mouth. Kennedy(1984) demonstrated that differences in rock type and sediment caliber may modify the nature of the basic relationship between accordance and flow regimes of confluent streams. It is clear that sediment discharge, as well as channel boundary resistance, is largely dependent on lithological condition. The series Ⅱ runs confirmed that discordance is usually developed at

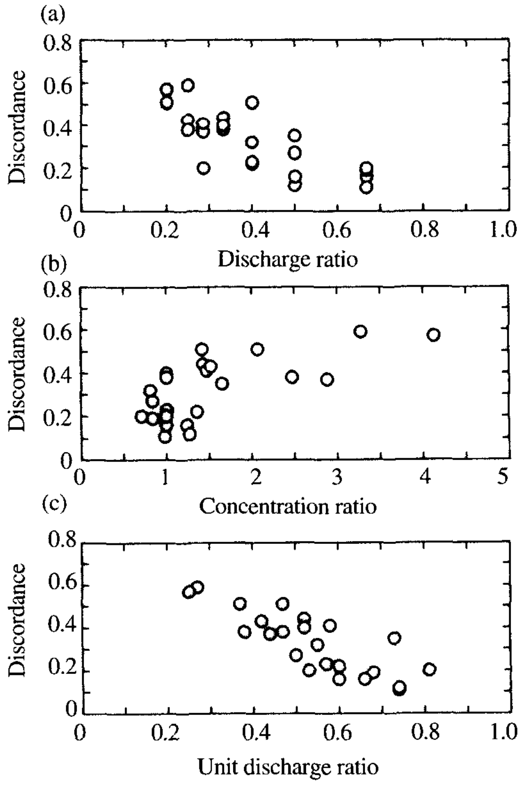

Figure 11. Relation of discordance to (a) discharge ratio, (b) sediment concentration ratio and (c) unit discharge ratio of two tributaries.

a tributary junction, implying that Playfair' s law of an accordant junction is not the clearest description of confluent river channels as noted by Kennedy (1984).

4. Conclusions

A tributary junction presents the channel morphology characteristic of complex three-dimensional flow patterns generated by merging flows. Flume experiments were conducted to describe the channel morphology and to examine some factors to which the channel morphology is subject. When the relative strengths of confluent flows are equivalent, a post-confluent flow tends to align with an axis bisecting junction angle. It results in three types of the post-confluent channel morphology reflecting an initial channel arrangement of symmetry, transition and asymmetry. The most notable bedform at a junction is a scour pool with steep sidewalls which are related to helicoidal vortices within this site. Scour dimension is largely controlled by junction angle irrespective of confluent planform. Discharge ratio, total discharge and total sediment load of two tributaries have relatively minor effects on the bed scour. Discordance is commonly developed at natural and model stream confluences. The relative magnitude of confluent discharges is a key control of discordant junctions. In particular, unit discharge ratio, defined by a ratio of discharge per unit channel width of confluent channels, is the most crucial factor because it reflects effects of sediment load as well as discharge on channel depth at a tributary mouth.

The present experiments can be defined as analog model experiments(Chorley, 1967) or geomorphic experiments(Ikeda, 1988) because these experiments were not carried out using strict hydraulic modeling of a specific site. The results of analog model experiments should not be directly extrapolated to the prototype in natural systems owing to uncertainties in the relationship between the model and its prototype. In the experiments, for example, a model stream was regarded as the analog of a gravel-bed river. However, it was uncertain for a mixture of sand and bentonite to fully reflect properties of the prototype materials, even though it provided a straight, single-thread channel with cohesive and erodible banks. The analog model experiments are fundamentally concentrated on reproducing some significant aspect of the form and function of a natural phenomenon(Schumm *et al.*, 1987). Nevertheless, the experiments aided understanding of the channel morphology development at a junction through easy visualization. The experiments were also favorable to examine respective effects of variables concerned on the channel morphology by setting various initial and boundary conditions. Therefore, the results of these experiments provide insight into the influence of a tributary junction on channel morphology and its adjustments at this site.

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