Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation
(Proceedings of the Vienna Symposium, August 1991) IAHS Publ. no. 203, 1991.

SOME CHARACTERISTICS OF SEDIMENT TRANSPORT IN THE LOWER YELLOW RIVER

ZENG QINGHUA & ZHOU WENHAO
Institute Of Water Conservancy & Hydroelectric Power,
Research (TWHR), Beijing, China

ABSTRACT The Yellow River is famous for its extremely high sediment load. The average sediment concentration in the Lower Yellow River is 33 600 mg l^{-1}. The tremendous sedimentation on the floodplain and in the channel results in the river bed rising at a rate of 0.10-0.15 m $year^{-1}$. The main channel of the river often shifts from one side to the other, threatening the safety of the embankments. Consequently, flood prevention has become consistently the most important problem of the Lower Yellow River. This paper briefly illustrates the main features of the sediment transport and fluvial processes operating in the Lower Yellow River.

GENERAL CHARACTERISTICS OF THE LOWER YELLOW RIVER

The Yellow River Basin has a drainage of 75 x 10^4 km^2 with a total length of 5464 km. The annual rainfall is 478 mm and the annual runoff is 46.4 x 10^9 m^3 with an annual sediment load of 1.56 x 10^9 t (Huayuankou Station). The Lower Yellow River from Mengjing to the estuary has a total length of 800 km. The reach upstream of Gaocun is a wandering river with a wide, shallow, and braided channel. The distance between the embankments ranges from 5000 to 20 000 m and the channel ranges from 1000 to 3500 m with a longitudinal slope ranging from 1.72 to 2.65%. The channel downstream of Gaocun is gradually transformed into a meandering river with an embankment distance ranging from 450 to 8500 m, a channel width ranging from 400 to 1600 m, and slope ranging from 1.01 to 1.48%. In the braided reach, the maximum difference between the ground inside and outside the embankments reaches 10 m and the channel is much more unstable. Thus, the safety of the embankments is threatened.

In the meandering reach, due to the increased channel siltation, the flood conveyance capacity declines and the channel bed is raised, increasing the risk of overtopping and flood disaster. Ensuring the safety of the flood-prevention works therefore is still a long-term and formidable task.

RUNOFF AND SEDIMENT LOAD INPUTS

Less water, more sediment load and high sediment concentration

The water discharge of the Lower Yellow River is one-twentieth of that of the Yangtze river, while its sediment load with an average concentration of 33 600 mg l^{-1} is three times that of the Yangtze River. The annual sediment load of the Brahmaputra River at Bahadurabad Station in Bangladesh is 499 x 10^9 t and the average sediment concentration is 810 mg l^{-1}. The average sediment concentration of the Colorado River in USA is 27 500 mg l^{-1}, but its annual sediment load is only 0.135 x 10^9 t. Therefore, the Yellow River is an extreme in terms of both its sediment load and the average sediment concentration.

Different sources of runoff and sediment load

The Upper Yellow River (upstream of Hekouzhen) has a drainage area accounting for 49% of the total area of the Yellow River Basin. The runoff inputs to this reach account for 54% of the total runoff of the river, but the sediment input accounts for only 9% of the total sediment load. This area therefore is the main source of runoff for the Yellow River. The drainage area of the Middle Yellow River from Hekouzhen to Tongguan accounts for 17. 5% of the total river basin. The runoff inputs to this reach account for 14% of the total, whilst the sediment load input represents 55% of the total load. Runoff input to the reach between Longmen and Tongguan represents over 22% of the total and the sediment load input accounts for 34% of the total. This indicates that the area of the Middle Yellow River is the main source of sediment load. Two Tributaries, the Yilou and the Qing Rivers, are located downstream of the Sanmenxia Reservoir. Their runoff and sediment loads account for 11% and 2% of the totals, respectively. The runoff from upstream of Hekouzhen and from the Yilou and Qing rivers dilutes the highly concentrated flow from the reach between Hekouzhen and Tongguan.

Non-uniform distributions of runoff and sediment load

Runoff and sediment load exhibit periodic variation, reflecting wet and dry periods, with an 8 to 10 year cycle. The annual distribution of runoff and sediment load also is non-uniform. The runoff during the flood season (July to October) accounts for 60% of annual runoff. and the corresponding sediment load is 85% of the annual total. Furthermore, the sediment load is particularly concentrated in some floods. For example, the maximum 5-day runoff accounts for 4.4% of the annual runoff, while the maximum 5-day sediment load accounts for 31% of the annual sediment load.

The maximum sediment concentration for floods in the tributaries of the Middle Yellow River range from 1 to 1.5 x 10^6 mg l^{-1} and the maximum sediment concentrations at Longmen and Sanmenxia Stations were 9.33 x 10^5 (July, 1966) and 9.11x 10^5 mg l^{-1} (August, 1977), respectively.

Rapid rising and falling of floods

Floods of the Lower Yellow River are generated by rainstorms. As a result, the flood peak rises and falls sharply in a few days or even in several hours.

The influence of reservoirs in the upper and middle reaches

The runoff and sediment load inputs are strongly affected by the regulation associated with the reservoirs built on the Middle and Upper Yellow River. For example, after the Longyangxia and Liujiaxia Reservoirs were impounded, the runoff input from the upstream area with low sediment concentration has been reduced during the flood season and increased during the dry season. With the operation mode of "retaining the clear water and releasing the muddy water" used for the Sanmenxia Reservoir, in the flood season, the reservoir water level is lowered and the muddy water is released, whereas in the dry season, the incoming water with low concentration is retained in the reservoir. The annual distribution of runoff and sediment load is changed, as compared with natural condition, as follows:

(a) In the dry season from November to June, the reservoir releases clear (sediment free) water and smooths the peak duration of the spring flood (March-April). The flood released from the reservoir is lower than 2000 $m^3 s^{-1}$ and less than that before the reservoir was impounded (2000-3000 $m^3 s^{-1}$). The reach from Tixian to Huayuankou therefore suffers from erosion.

(b) In the flood season with low water levels in the reservoir, the previous deposition may be flushed out of the reservoir. Meanwhile, the incoming water from the upper reach is decreased due to the impounding of the Longyangxia and Liujiaxia Reservoirs. Therefore, the water released from the Sanmenxia Reservoir has higher concentrations than before and the possibility of hyperconcentrated flood flows in the Lower Yellow River is enhanced.

(c) Due to the limited capacity of the flood outlets of the Sanmenxia Reservoir, floods higher than 5000 $m^3 s^{-1}$ are retained by the reservoir. Flood peaks higher than 10 000 $m^3 s^{-1}$ would be reduced by 30 to 40%. The sediment deposited in the reservoir during the dry season is flushed by moderate and low discharges, often causing large amounts of sediment to be carried by low to moderate or low flow. An unsuitable relation between runoff and sediment load therefore occurs.

(d) Hyperconcentrated floods can be conveyed through the reservoir with unchanged sediment concentration. Sometimes, the concentration of the outflow is even higher than that of the inflow. The peak discharge of the flood, however, is reduced by the reservoir as mentioned above.

CHANNEL SEDIMENTATION

Generally, the Lower Yellow River is an aggrading river due to the high sediment loads. An interesting problem is to estimate the sediment carrying capacity, and to determine under which conditions the channel may be in equilibrium. As shown in Fig. 1, with a long-term annual runoff of 46.4 x 10^9 m^3 and an annual sediment concentration from 20 to 25 000 mg l^{-1} (i.e., the annual incoming sediment load is 1.0 x 10^9 m^3), the channel equilibrium of the Lower Yellow River could be maintained. However, as mentioned above, the long-term mean sediment concentration is 336000 mg l^{-1}. As a result, the Lower Yellow River is aggrading and channel bed is rising at an annual rate ranging from 0.01 to 0.15 m. (Zeng and Zhou, 1989). The water levels corresponding to a discharge of 3000 $m^3 s^{-1}$ at three stations along the river showed a gradual increase over the period 1950-1982, with the exception of 1960-1963 when the channel was scoured by the clear water released from the Sanmenxia Reservoir (Fig. 2).

Since the completion of Sanmenxia Reservoir, the annual pattern of channel deformation has changed. Formerly, the channel aggraded during the dry season, but now the channel is eroding during the 8-month dry season releasing about 0.1 x 10^9 t of sediment. In the flood season, the channel still aggrades. According to available evidence, annual channel deposition has decreased and currently ranges from 0.02 to 0.03 10^9 t since the reservoir operation scheme of "retaining the clear water and releasing the muddy water" was adopted.

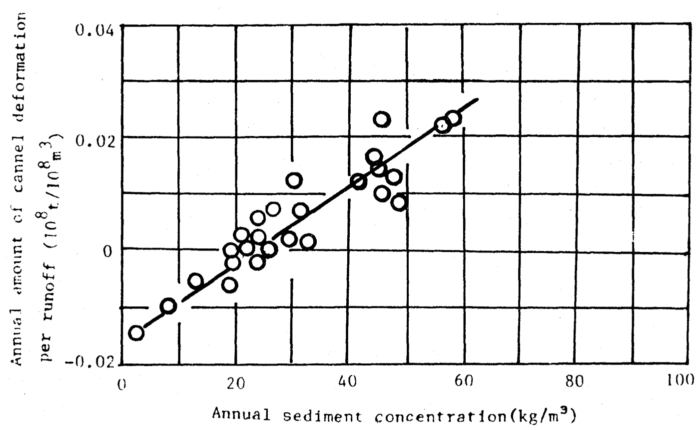

FIG. 1 Annual amount of channel deformation and annual sediment concentration (- erosion).

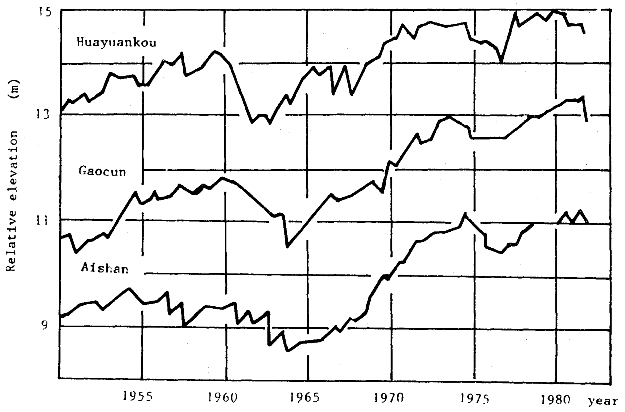

FIG. 2 Variation of water level for a discharge of 3000 m^3 s^{-1} along the river.

From November 1973 to October 1983, 0.156 x 10^9 t of sediment were deposited annually in the Yellow River. This represents only 43.2% of the total annual deposition of 0.361 x 10^9 t that occurred during the period 1950-1959. This reduction occurred mainly because the runoff inputs from the upper reach drainage were approximately the same as the long-term annual runoff, yet the runoff and sediment inputs from the Middle Yellow River were less than the long-term annual values.

FEATURES OF SEDIMENT TRANSPORT

Relation between median size and concentration

According to the observed data, the median size (D_{50}) of the sediment load increases with increasing sediment concentration (S) especially during hyperconcentrated floods. The universal linear expression for Sanmenxia, Huayuankou and Lijing Stations is

$$D_{50} = 1.15 \times 10^{-4} S + 0.009.$$

In the Lower Yellow River, about 70% of the deposition occurs on the floodplain and nearly 30% in the channel. Almost 50% of the deposited sediment has a grain size greater than 0.005 mm. Most of these coarse particles come from the sources of coarse sediment in the area of the Middle Yellow River. The floods from this area generally have average concentrations higher than 120 kg m^{-3}.

Sediment carrying capacity

The sediment transport rate in the Lower Yellow River increases with increasing discharge. In addition, the sediment transport rate is also related to the sediment concentration. The higher the incoming sediment concentration, the greater is the sediment transport rate. The sediment carrying capacity of the Lower Yellow River can be expressed as follows:

$$Q_s = K\, S_{up}{}^{\alpha} Q_s{}^{\beta}$$

where, Q_s is the sediment transport rate for suspended load (t s^{-1}), S_{up} is the suspended sediment concentration of the upstream station (mg l^{-1}), and Q is the discharge (m^3 s^{-1}). For Huayuankou Station, K is 1.04; α is 0.858; and β is 1.053.

Conveyance of hyperconcentrated floods

Hyperconcentrated floods often cause serious deposition due to the braided channel and overflow onto the floodplain when the flood passes through the river. According to the records, from 1951 to 1981, 18 floods occurred with a maximum concentration higher than 3.0×10^{5} mg l^{-1} at Sanmenxia Station. The total amount of deposition in the wandering reach upstream of Gaocun during the period 1951-1981was 6×10^9 t, and the deposition associated with the 18 floods with hyperconcentrations totalled 4.20×10^9 t, representing 67% of the total deposition from 1951 to 1981. In some years, such as 1977, almost all the deposition upstream of Gaocun was associated with hyperconcentrated floods.

The deposition caused by hyperconcentrated floods is much higher than that produced by ordinary floods. For example, the total runoff associated with the 18 hyperconcentrated floods was only one-third of the total runoff of the 36 ordinary floods that occurred from 1969 to 1981, yet the total sediment load was 1.31 times that of the latter floods, and the deposition upstream of Gaocun associated with the hyperconcentrated floods was 3.6 times that associated with the ordinary floods (Zhou & Zeng, 1983). As a result of the deposition, the sediment concentrations of hyperconcentrated floods decline sharply along the river and approach a constant value after some distance (Fig. 3). If the reach where the sediment concentration decreases markedly is named "the tremendous deposition reach," then its length is related to the peak discharge of the flood. Data indicate that when the discharge released from the Sanmenxia Reservoir is less than 9000 m^3 s^{-1}, the "tremendous deposition reach" is located upstream of Aishan. The deposition represents 61% of the incoming sediment load.

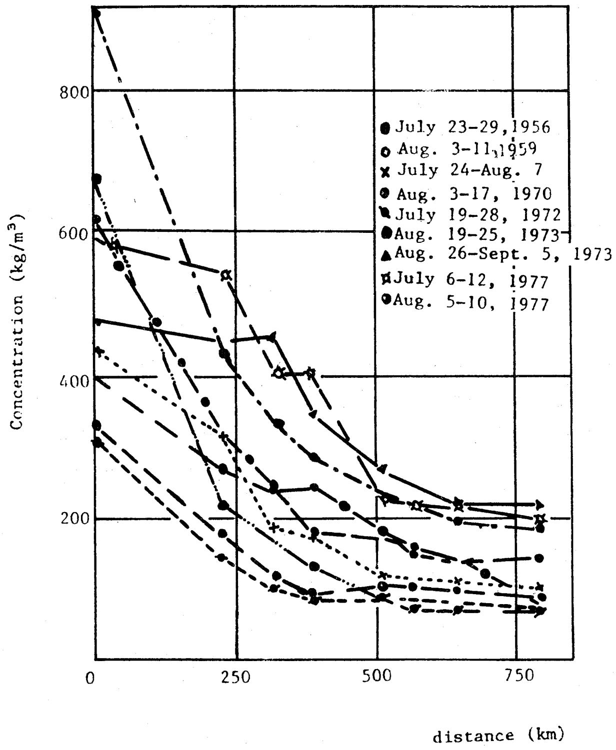

FIG. 3 Changes of maximum concentration along the river for hyperconcentrated floods.

Effects of high out-of-bank floods on fluvial processes in the Lower Yellow River

High out-of-bank floods play an important role in the fluvial-processes of the Lower Yellow River. Generally, when the flood level is higher than the surface of the floodplain, part of the flow in the main channel will spill over and sediment will be deposited on the floodplain. The Lower Yellow River has a configuration of alternating wide and narrow reaches. When the flow enters the wide reaches with wide floodplains, sediment concentrations in the overflow will decrease due to sediment deposition on the floodplain. Subsequently, flow returning from the floodplain to the channel with reduced sediment concentrations enters the main channel and mixes with the flow causing sediment concentrations to decrease in the main flow and erosion to increase in the main channel. Such transverse exchanges of water and sediment between the floodplain and the main channel result in a series of characteristic features of fluvial processes in the Lower Yellow River.

Scouring of the channel and deposition on the floodplain According to the data in Table 1, all the floods with peak discharges higher than 10 000 m^3 s^{-1} at Huayuankou, except the flood of August 1953, scoured the channel and deposited sediment in the floodplain simultaneously because of the high sediment concentrations (greater than 400 000 mg l^{-1}) showed scouring of the channel and deposition on the floodplain. Under certain conditions, the amount of erosion in the main channel from Huayuankou to Aishan was approx-

TABLE 1 Channel deformation caused by high magnitude floods in the Lower Yellow River ($10^9 t$).

Date	Huayuankou Station		Huayuankou-Aishan			Aishan-Lijing			Huayuankou-Lijing		
	Peak discharge ($m^3 s^{-1}$)	Average sediment concentration ($\times 10^5 mg l^{-1}$)	Main channel	Flood plain	Total	Main channel	Flood plain	Total	Main channel	Flood plain	Total
1953.7.26-8.14	10700	1.198	-0.179	0.22	0.04	-0.121	0.083	-0.038	-0.30	0.303	0.003
1953.8.15-9.1	11700	4.399	0.106	0.103	0.209	0.043	0	0.043	-0.149	0.103	0.252
1954.8.2-8.23	15000	1.455	-0.334	0.343	0.266	-0.091	0.147	0.056	-0.208	0.49	0.282
1954.8.23-9.9	12300	2.091	0.217								
1957.7.12-8.14	13000	1.785	-0.323	0.466	0.143	-0.11	0.061	-0.049	-0.433	0.527	0.095
1958.7.13-7.23	22300	2.119	-0.71	0.92	0.21	-0.150	0.149	-0.001	-0.86	1.069	0.209
Total			-1.223	2.052	0.829	-0.429	0.440	-0.011	-1.652	2.492	0.840

Negative values reflect scour and positive values denote deposition.

imately 70-80% of the deposition on the floodplain. In the extremely high flood of July 1958, the erosion in the main channel from Huayuankou to Aishan was 0.71 x 10^9 t, while deposition on the floodplain was 0.92 x 10^9 t. During this flood, the erosion occurred in the main channel downstream of Huayuankou Station over a distance of more than 100 km. In places, the main channel was scoured by more than 1 m (Table 1).

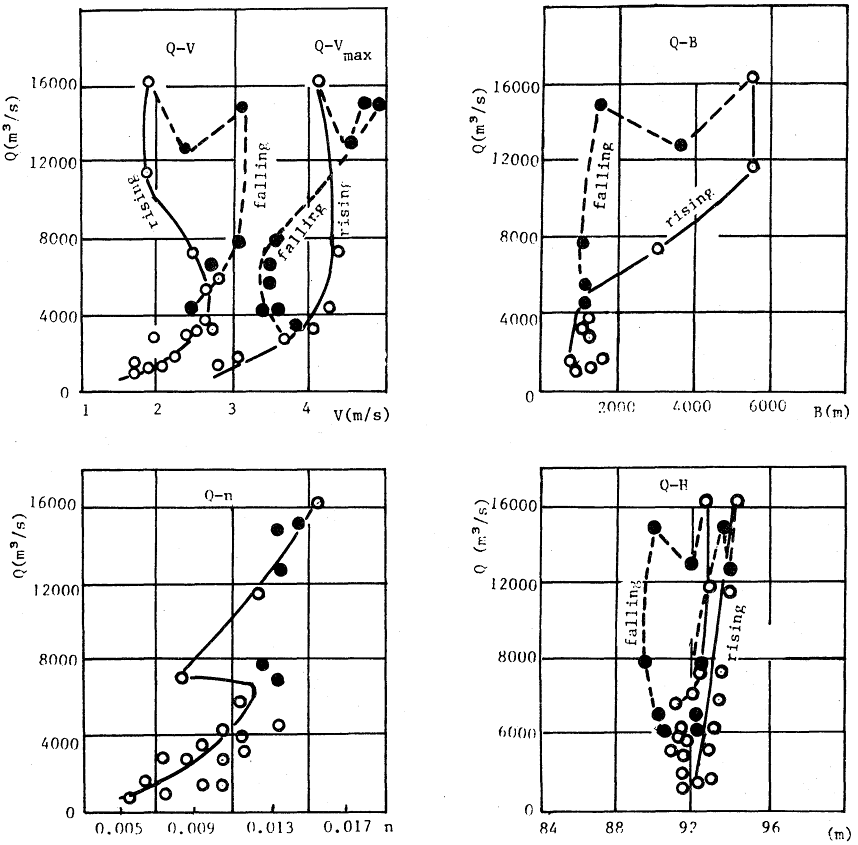

FIG. 4 Changes in hydraulic factors before and after out-of-bank flooding at Huayuankou Station

Increasing the flood conveyance capacity and decreasing the channel deposition The change in hydraulic factors during the extreme flood of 2-28 July 1958 is shown in Fig. 4. It indicates that after the flood spilled out of the channel and the main channel was eroded, the channel width was considerably decreased, the water level for the same discharge decreased and the velocity abruptly increased. For example, at a discharge of 12 000 m^3 s^{-1}, the width on the falling stage was 4200 m less than on the rising stage, the velocity increased from 1.6 to 3.0 m s^{-1} and the water level fell by some 4.5 m. Therefore, after the major flood, the flood conveyance and sediment transport capacity of the main channel would be increased due to erosion of the main channel, and thus the overall deposition would be decreased.

Deposition on the floodplain during the flood season and in the channel during the dry season are interrelated Erosion of the main channel by a major out-of-bank flood creates favorable conditions for deposition in the main channel during the subsequent dry season and deposition in the main channel during the dry season increases the opportunity for overflow onto the floodplain during the flood season. Such mutual restriction causes both the main channel and the floodplain to rise at equal rates maintaining a difference between the elevation of the main channel bed and the floodplain. This is the main reason why the Lower Yellow River was characterized by a difference in elevation between the main channel and the floodplain over a long period of time.

In addition, high magnitude out-of-bank floods causes the blocking of channel branches so that channel configuration becomes smoother and straighter after major floods.

Since the completion of the Sanmenxia Reservoir, the opportunity for major floods to overflow onto the floodplain has decreased and more sediment has been deposited in the main channel, the width has increased and the elevation difference between the channel and the floodplain has decreased. Therefore, it is necessary to regulate the channel under moderate discharges to accommodate the requirement for transporting hyperconcentrated flow.

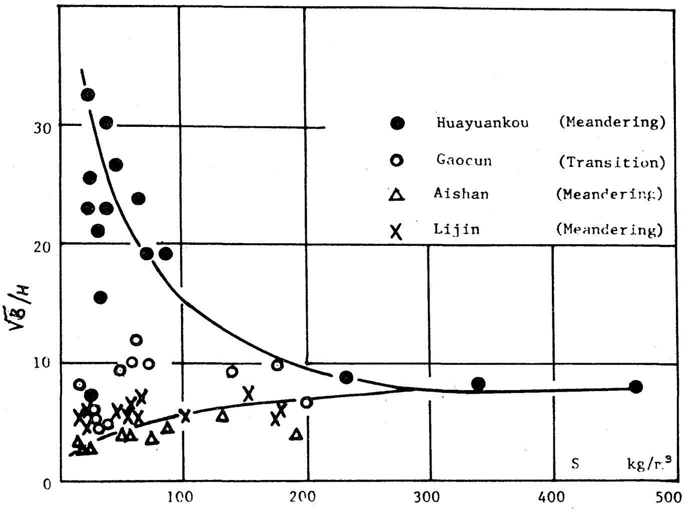

FIG. 5 $B^{0.5} H^{-1}$ *versus sediment concentration (S).*

Cross-sectional morphology effects on sediment transport

Changes of cross-sectional morphology represent part of the automatic self-regulation of alluvial rivers. Its result is to adjust the sediment transport capacity to the runoff and sediment input through regulation of boundary conditions (mainly the bed material composition), cross-section and longitudinal slope. Due to the small variation of bed material in the Lower Yellow River and the shortage of data, the effect of bed material is not taken into account. Considering the maximum and most rapid channel deformation occurring during flood periods, the relation between sediment concentration and its corresponding morphological parameter at bankfull discharge is shown in Fig. 5. It can be seen that for the wandering reach, such as Huayuankou Station, with a decrease of $B^{0.5} H^{-1}$, i.e., the cross-section is narrower, the sediment concentration rapidly increases with an increase in velocity. For the transitional reach, the situation lies between the above two conditions.

It should be pointed out that, for the wandering, meandering, and transitional reach, sediment concentrations approach a similar value when $B^{0.5} H^{-1}$ is about 8. This implies that when the morphological parameter, $B^{0.5} H^{-1}$, at bankfull discharge for the Lower Yellow River is equal to 8, the sediment carrying capacity at the cross-section reaches its maximum value. This is significant for training work on the channel for medium and minor flows in the Lower Yellow River.

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