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Sediment measurement in the Yellow River

LONG YUQIAN & XIONG GUISHU
Institute of Hydraulic Research, Yellow River Conservancy Commission, Zhengzhou, China

ABSTRACT This paper provides a general review of the development of sediment measurement networks on the Yellow River. Long term systematic data collection has provided information on the location of the main source area of sediment yield and on the quantity of sediment transported, deposited and diverted. Particular features of sediment laden flow at hyperconcentration are noted. A network of basic hydrometric stations together with a number of experimental stations were used to study the sediment problems. Systematic sedimentation surveys in reservoirs and in the Lower Yellow River have been used to study the fluvial processes. The aggradation and the rapidly changing pattern of the alluvial channel of the Lower Yellow River have exerted an important influence on the measuring techniques and the data processing. This paper discusses the main features of the sediment measuring techniques and a preliminary analysis of the reliability of the data.

Mesure du transport solide du Fleuve Jaune
RESUME Cet article expose l'organisation des observations du transport solide dans le Fleuve Jaune. D'après des observations à long terme, on a trouvé les zones d'origine du transport solide et les masses de sédiments transportés, déposés et échappant au lit principal et on a déterminé les caractéristiques de l'écoulement chargé en sédiments avec une très haute concentration en sables et limons. Pour étudier le problème des sédiments une approche efficace consiste à établir des stations hydrométriques de base auxquelles sont associés un certain nombre de stations expérimentales, et, à effectuer systèmatiquement des mesures topographiques dans les réservoirs et dans le Fleuve Jaune lui même pour en étudier les variations du lit. Le chenal sur le cours inférieur du Fleuve Jaune est facilement colmaté et il se modifie beaucoup et rapidement, les conditions de l'écoulement de l'eau et des sédiments sont très variables en fonction des saisons. Ceci a une très grande influence sur la technique des mesures et le traitement des données. Cet article discute les caractéristiques principales des mesures de sédiments et présente une analyse préliminaire de la validité des résultats.

THE HYDROMETRIC NETWORK

The Yellow River is well known throughout the world for its exceedingly high sediment content. Historical records show that people living in the Yellow River basin have long made observations on sediment concentration. In the historic literature of the Eastern Han Dynasty (25-220 AD), descriptions of sediment content such as "the silt occupied six tenths of the volume in one barrel of water sampled" have been recorded. In the Song Dynasty, about 900 years ago, the breaching of the levee was explained by the backing up of the water surface elevation due to excessive accumulation of sediment in the river reaches downstream.

It was, however, only 60 years ago that hydrometric stations based on modern scientific knowledge were established. After a rare flood which occurred in 1933, a number of hydrometric stations had been set up, however, prior to 1949, only 33 stations were collecting records. Not only was the number of stations far from adequate, but the records were also insufficient and inaccurate. Since the founding of New China, hydrological work has rapidly developed. At present, 456 hydrometric stations have been set up to make measurements all the year round. A network has been developed consisting of basic hydrometric stations supplemented by experimental stations. A great deal of valuable data have been collected, providing an important basis for the development and management of water resources as well as the development of our national economy.

The Yellow River drains an area of 752 000 km^2, and the main stem is 5464 km in length (Fig. 1). Total annual runoff at the

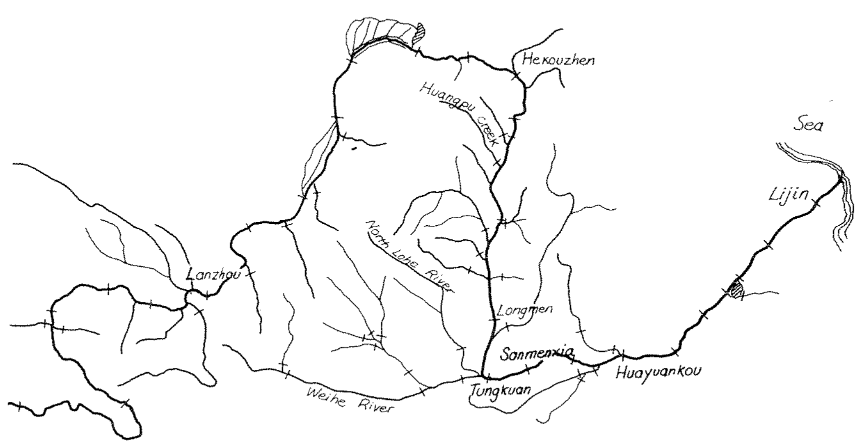

Fig. 1 The Yellow River drainage basin.

Sanmenxia station amounts to 43.1×10^9 m^3, of which 58% comes from the upper portion of the basin above Hekouzhen. Large floods are mainly produced by rainstorms during July and August. The total annual sediment load averages 1.6×10^9 t and 90% of the total sediment comes from 40% of the total drainage area - the middle section of the Yellow River which is overlain by loess. The Yellow River is characterized by a very high sediment load and only a relatively limited volume of water.

The hydrometric network has been developed mainly for water resource development and is not uniformly distributed. In the middle portion of the basin, a density of five to seven hydrometric stations and 40-60 raingauges per 10 000 km^2 is found, while a density of only two to three stations and less than 10 raingauges per 10 000 km^2 is found in the upper basin. Sediment is measured at most of the hydrometric stations.

In the gullied hilly loess region of the Middle Yellow River drainage basin, the Chaba Gully experimental basin with an area of 187 km^2 has been chosen for a study of storm runoff and sediment generation. Within the basin, nine hydrometric stations have been set up. Measurements of runoff have also been made on 14 experimental plots within a 0.18 km^2 experimental area. Soil moisture, evapotranspiration, water balance and meteorological data have also been collected. All of these observations have provided valuable data for improving the understanding of the physical basis of soil erosion as well as surface runoff production within the study region.

In order to study rates of reservoir deposition, systematic reservoir surveys have been undertaken in a number of large and medium-sized reservoirs several times per year. The inflow and outflow of water and sediment are measured at hydrometric stations. Special phenomena such as density currents, bank stability, groundwater in the vicinity of the reservoir, density of reservoir deposits and flow conditions in the vicinity of the dam have also been observed. These provide a better understanding of the physical laws of sediment movement and deposition in reservoirs. According to the seasonal variation of water and sediment inflow and the boundary conditions of the reservoir, various strategies have been developed for the planning, design, operation and management of reservoirs built on sediment-laden rivers. These have proved important in the development of water resources in the Yellow River. As an example, the general layout of the sediment survey undertaken in the Sanmenxia Reservoir is illustrated in Fig. 2.

On the basis of the channel pattern, the Lower Yellow River may be divided into four sections, namely wandering, transition, meandering and estuary (Fig. 3). Eight hydrometric stations have been set up to measure the water and sediment discharge along the river course and 101 sections are surveyed repeatedly each year. Experimental stations have been established in order to study fluvial processes and the transport capacities within certain representative reaches. Hydrometric stations have also been set up at large canal headworks. Routine measurements are supplemented by reconnaissance investigations to determine the total quantity of water and sediment withdrawn for irrigation. Hydrological reconnaissance is an important supplement to the routine daily measurements made at fixed stations. It has been used extensively in the investigation of the distribution of rare storms, the peak discharge of rare floods, minimum flows, the detention effect of check dams, the use of irrigation water and erosion and sedimentation associated with structure failure.

In summary, for a better understanding of sediment processes,

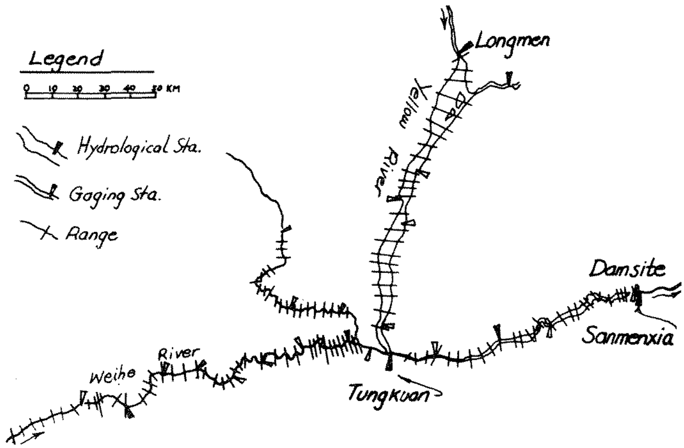

Fig. 2 General layout of observation network for the sediment survey of the Sanmenxia Reservoir.

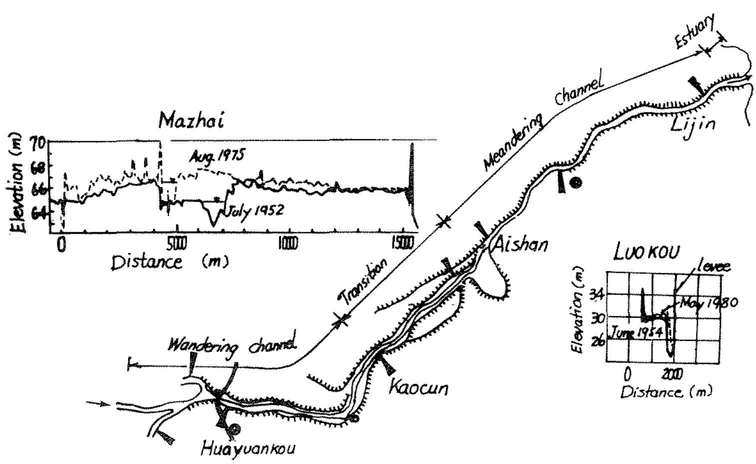

Fig. 3 Plan of Lower Yellow River and typical cross sections.

basic hydrometric stations should be accompanied by a number of experimental stations, and routine daily measurements at fixed points should be supplemented by reconnaissance investigations. This provides an effective approach to studying the sediment problems throughout the whole drainage basin.

MAJOR RESULTS OF OBSERVATIONS

According to the hydrometric data, 36% of the total sediment is on average greater than 50 μm in diameter and this coarse grained sediment has an important influence on deposition in the Lower Yellow River. Three-quarters of the coarse sediment originates from an area of approximately 100 000 km^2. As for the seasonal variation of the sediment load, some 50-90% of the total sediment may be delivered in 10 days during floods. This extreme spatial and temporal concentration of sediment transport is a significant feature of the Yellow River.

The Lower Yellow River exhibits an aggraded channel. The 1965-1974 data indicate that of the total sediment entering the Lower Yellow River, about 25% was deposited along the main course below Mengjin, 8% was extracted through irrigation, and 43% was deposited in the delta region. Only 24% passed through the delta region to be transported out to sea. As a result of the tremendous amount of deposition occurring each year, the river bed has been built up and the thalweg shifts frequently within the levee system. Control of floods and prevention of flood disasters are problems of vital importance. The variation of water and sediment discharge along the main stem of the Yellow River is shown in Fig. 4.

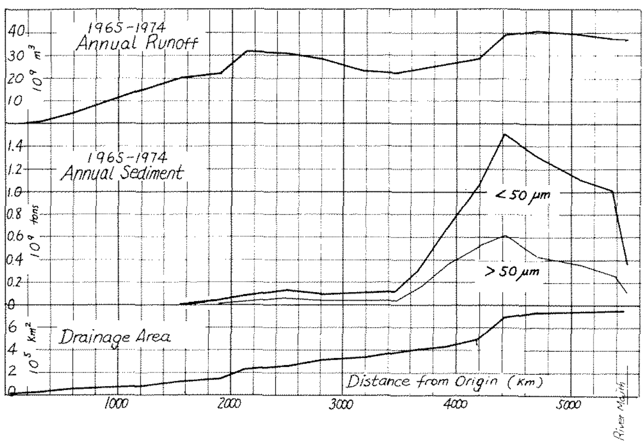

Fig. 4 *Variation of annual runoff and sediment along the Yellow River.*

Sediment yield

The severe soil loss in the gullied hilly loess area of the middle reaches of the Yellow River is the major source of sediment transported down the river. According to the data collected at the Zhezhou experimental station, the ratio of the average sediment yield of the area between the gullies (sloping surface) to that of the gullies is approximately 1:1.8. Because the total surface area of the land between the gullies is greater than that within the gullies, the ratio of the total amount of soil loss is approximately 1.6:1. These results are typical of the gullied hilly loess area, but may not necessarily be true for other physiographic regions. Erosion is primarily the result of severe storm events. In one storm event, the rainfall may exceed 10% of the total annual rainfall and short term intensities of 120 mm h^{-1} may occur. The soil loss during an individual storm may be 40% of the annual soil loss.

Under these conditions, surface runoff with hyperconcentrations of sediment may be generated even in the early stages of overland flow. Sediment concentrations may easily exceed 400 g l^{-1}. It is well known that the viscosity of the fluid associated with hyper-concentration of sediment is considerably increased and that the particle settling velocity is markedly decreased. The rheological properties of muddy water containing hyperconcentrations of sediment are very different from those of an ordinary Newtonian fluid which contains only a limited amount of sediment. The transport capacity of flow containing hyperconcentrations of sediment is largely influenced by its rheological properties. In the middle reaches of the Yellow River and its tributaries, flows with hyperconcentrations of sediment are frequently found. Sediment concentrations have reached as high as 1600 g l^{-1} in Huangpu Creek without noticeable deposition. Gong & Xiong (1980) have stated that the tributaries in the middle portion of the Yellow River drainage basin are essentially conveyance channels for sediment, and that the delivery ratio is close to one. Sediment produced either from the surface or from the gullies could eventually be conveyed to the main stem of the Yellow River.

The sediment yields from different physiographic regions are quite different, and some data on water and sediment yield are listed in Table 1 to demonstrate the influence of geological and geomorphological conditions.

Sediment transport

The middle and lower reaches of the Yellow River are alluvial channels. It is well known that an alluvial channel will adjust

Table 1 Mean annual sediment yields of representative stations in different physiographic regions of the middle portion of the Yellow River

Phsyiographic region	River	Station	Drainage area (km^2)	Depth of runoff (mm)	Average sediment concentration ($g\ l^{-1}$)	Sediment yield ($t\ km^{-2}\ year^{-1}$)
Gullied-hilly loess area	Yehe	Yean	3208	47.1	311	14400
Gullied loess plateau	Puhe	Bajiazui	3522	35.9	145	5190
Loess terrace	Zhuhe	Sujiadian	840	83.2	18.9	1400
Hilly loess area with forest	Huluhe	Zhangcunyi	4715	23.0	4.94	128
Rocky mountain with forest	Wenyuhe	Wenyuhe	1876	131	0.12	15.3
Hilly sandy area	Xiliugou	Longtouguai	1145	25.0	125	3130
Sandy grass land	Dusitu	Kushuigoukou	8321	1.5	10.0	15.9
Hilly grassland	Kundulun	Atashan	879	16.2	56.9	917

Table 2 Deposition and erosion within the Lower Yellow River during typical floods

Period	Hyayuankou station		Total sediment load coming into lower river during flood (10^6 t)	Sediment deposited in Lower Yellow River (10^6 t)		
	Peak discharge ($m^3\ s^{-1}$)	Ratio of Sed. conc. to discharge		Main channel	Flood plain	Total
15/8/53- 1/9/53	11700	0.0376	857	149	94	243
12/7/57- 4/8/57	13000	0.0119	561	−433	527	94
13/7/58-23/7/58	22300	0.0095	639	−865	1020	155

its transport capacity to conform with the incoming water and sediment load, by adjusting its bed composition, longitudinal slope and transverse bed forms. Under the particular conditions of the Yellow River, with the abundant supply of sediment, this adjustment is large. Figure 5 shows the changes of bed composition occurring at the Tungkuan hydrometric station during floods. It should be noted that the changes take place in response to changes in the incoming sediment load. Thus, in studying the relationship between water and sediment discharge, the sediment concentration at the upstream station is often used as a parameter. This response referred to as "the more the sediment flows in, the more it can be conveyed" is an important characteristic of sediment transport in the alluvial stretches of the Lower Yellow River (Mai *et al.*, 1980).

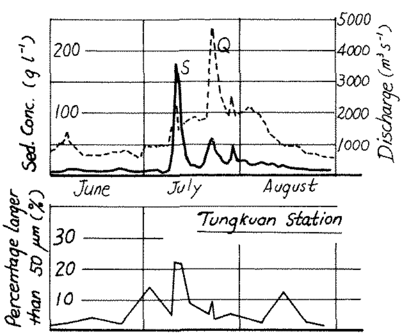

Fig. 5 Variation of bed composition during a flood event.

The quantity of sediment transported during floods is enormous. When floods with moderate concentrations overtop the flood plain, deposition will take place on the flood plain and the main channel will be eroded. On the other hand, when the sediment concentration is high, deposition will occur in both the flood plain and the main channel (Table 2). During floods with hyperconcentrations of sediment, large amounts of sediment will be deposited in shoals and bars, but the main channel stem could still be eroding. In consequence, the bed configuration will be narrow and deep. Table 3 shows how the hydraulic parameters change after a flood with a high sediment content.

The geomorphological changes of the river bed during floods in the Lower Yellow River are characterized by their high

Table 3 Change in hydraulic parameters after a flood with very high sediment concentrations (Huayuankou station 1977)

Date	Stage (m)	Discharge ($m^3 s^{-1}$)	Top width at water surface (m)	Average depth (m)	Average velocity ($m s^{-1}$)
7 July	92.24	2290	1470	1.00	1.56
16 July	90.82	2000	623	1.93	1.67
28 July	91.00	2320	541	1.92	2.23

intensity and their speed. The flow boundary is very sensitive to adjustment to conform with the incoming water and sediment load (Qing & Chow, 1965). This is not only a basic feature of sediment transport in the alluvial river, but drastic changes of the river course will also introduce difficulties in making hydrometric measurements.

Deposition and diversion

Before the construction of the Sanmenxia Reservoir, only very small amounts of deposition occurred along the alluvial valleys above the dam site. Most of the sediment was deposited in the delta and along the nearly 800 km lower course of the river. After the impoundment of the Sanmenxia Reservoir in September 1960, most of the sediment was deposited in the reservoir and the Lower Yellow River underwent a period of erosion by the clear water released from the reservoir. The eroded material was deposited in the delta region. Since the reconstruction of the Sanmenxia Reservoir project, sedimentation in the reservoir has been reduced to a minimum and the lower river has resumed its aggradational nature. Table 4 shows the deposition that occurred above and below the Sanmenxia Reservoir during different stages of operation (Zhang & Long, 1980). According to the analysis, the most severe deposition in the Lower Yellow River is due to floods coming from the coarse grained sediment source area. Over the past 30 years, water stages for the same discharge (3000 $m^3\ s^{-1}$) at various places in the main channel have been raised by 1.6-2.2 m as a result of aggradation.

More than 140 large and medium-sized reservoirs with a capacity greater than 10 x $10^6\ m^3$ have been built on the main stem and tributaries of the Yellow River. Sedimentation in the reservoirs is a serious problem. Some of the reservoirs are operated in such

Table 4 Deposition in the Sanmenxia (SMX) Reservoir and the Lower Yellow River before and after impoundment

Type of operation	Period	Deposition in SMX Reservoir ($10^9\ m^3$)	Sediment entering Lower Yellow River (10^9 t)	Deposition in Lower Yellow River (10^9 t)	Deposition in delta region (10^9 t)
Before impoundment	July 1950–June 1960	–	17.95	3.68	9.48
After dam construction					
During impoundment	Sept. 1960–March 1962	1.75	0.14	−0.98	0.90
Flood detention period					
Before reconstruction	April 1962–June 1966	1.97	3.50	−0.65	3.87
First stage reconstruction	July 1966–June 1970	1.59	7.45	1.43	4.35
Second stage reconstruction	July 1970–Oct. 1973	0.10	5.88	1.83	1.82
Storage in nonflood season, low head operation in flood season for sluicing	Nov. 1973–Oct. 1978	0.05	6.80	1.27	3.89
Subtotal	Sept. 1960–Oct. 1978	5.46	23.77	2.91	14.83

a way that the outflow of sediment as well as the water can be regulated according to the seasonal variation of the incoming sediment. Water storage capacity can be preserved by means of a mode of operation known as "storing the clear water and disposing of the muddy water". Multipurpose benefits can be developed to a certain extent.

In addition, sediment laden water has been withdrawn from along almost all the main course of the Yellow River and its tributaries for irrigation or warping. Large amounts of sediment have thereby been removed from the river. For the Lower Yellow River alone, this removal is estimated to be more than 200 x 10^6 t annually.

Control of soil loss from both sloping land surfaces and gullies by means of various soil conservation measures, the regulation of both the water and sediment outflow from reservoirs, and diversion of water for irrigation have had a major influence upon the sediment yield, transport and deposition in the whole drainage basin. An important function of the hydrometric network is to study the influence of these measures upon the hydrological processes.

METHODOLOGY AND ACCURACY

Analysis of the long term data provides an insight into the inherent nature of sediment yield, transport capacity and the deposition process. The knowledge should serve as a guide to the development of measurement strategies. The relationship between average sediment concentration or size gradation, obtained from detailed sediment discharge measurements, and that of a single sample is used for converting the daily routine measurements of sediment concentration or size gradation made using single samples to the average sediment concentration or size gradation for the cross section. The converted value is then multiplied by the discharge to obtain the sediment discharge. It is clear that the accuracy of the sediment measurement depends largely upon the method used for taking the single sample, the closeness of the relationship between the concentration of the single sample and that of the average for the cross section, and the reliability of the discharge measurement.

The sediment transport characteristics of the main course and the tributaries of the Yellow River are different. For flow with hyperconcentrations of sediment, the vertical and transverse distributions of sediment concentration and size gradation are uniform. The relationship between the average sediment concentration in the cross section and that of a single sample is approximately a straight line at 45°. The method of taking single samples can therefore be simplified without introducing appreciable error. In the alluvial channel of the Lower Yellow River with its broad and shallow cross section, the bed composition and channel geometry change rapidly. The distribution of coarse sediment exhibits some gradient in the vertical direction. It is therefore necessary to select the method of sampling carefully if a representative sample is to be obtained. Figure 6 gives an

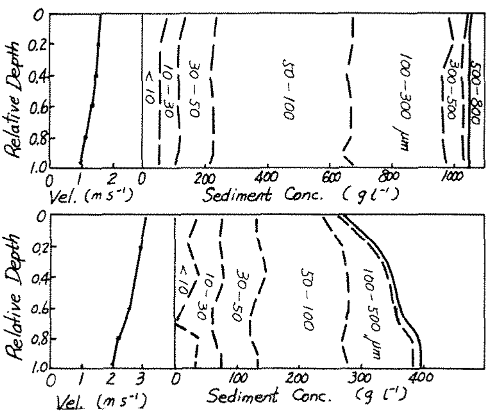

Fig. 6 Vertical distribution of velocity and sediment concentration.

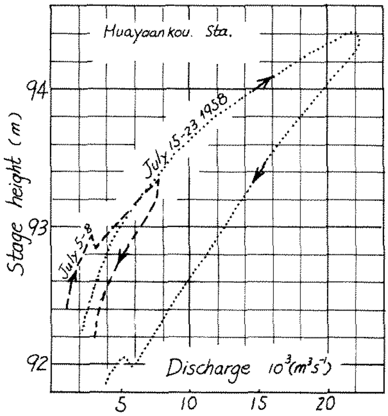

Fig. 7 Stage/discharge relationship during floods.

example of the vertical distribution of sediment.

Temporal variations of sediment load are also an important feature of the Yellow River. In order to study the total quantities of water and sediment involved it is necessary to make frequent measurements during floods. The stage/discharge relationship is usually determined at the same time. Satisfactory results can only be obtained with a sufficient number of measurement points. Figure 7 provides an example of the stage/discharge relationship during flood events.

As stated above, the correct timing of measurements and choice of appropriate methods are important. The problems are further complicated by the different transport characteristics of ordinary sediment-laden flows and those of flows containing hyperconcentrations of sediment. Since survey sections have been established almost all the way along the river, comparisons can be made between the amount of deposition or erosion occurring within individual reaches and the change in sediment discharge between the stations at each end of the reach. It is thus possible to assess the relative accuracy and reliability of the hydrological measurements.

For example, a study has been undertaken on a reach in the Sanmenxia Reservoir which extends approximately 120 km from Tungkuan to Sanmenxia. From September 1960 to October 1978 the measured volume of deposition calculated from 34 sections amounted to 2.89×10^9 m^3. The difference in sediment discharge between the two end stations, taking into account the estimated sediment yield of the intervening drainage basin, was equal to 2.18×10^9 t. Assuming an average density for the deposits of 1200 kg m^{-3}, the difference in the sediment discharge measurements could be considered to be 1.29×10^9 t too low. The total sediment discharge at Tungkuan for the period was 25.4×10^9 t, and a maximum error of 5% may therefore be assumed. For the same reach, comparisons between the volume of deposits and the difference in sediment discharge can be made at least twice a year, since the section surveys were conducted several times a year. The results of comparisons for the period October 1973 to

October 1975 indicate that errors between 7.8 and 15.2% may be expected for the dry season and between +0.8 and 1.1% for the flood season.

Another comparison has been made for a reach between Kaocun and Lijin, in the Lower Yellow River (Jinan District Office of Hydrological Bureau, 1978). Seventy four sections and a number of gauging stations had been set up. According to comparisons for the period 1951-1977, the average annual deposition rate for the main channel was 0.04-0.07 m, which is almost the same value as that obtained from analysis of the increase in water stage for the same discharge. The results obtained from analysis of the difference in sediment discharge evidence some deviations from the above value. The total quantity of deposition estimated by the section survey method amounted to 2.0×10^9 m^3 (of which 40% was in the main channel and 60% in the flood plain). This is equivalent to approximately 2.4×10^9 t, but the difference in sediment discharge was 1.42×10^9 t. A difference of 0.98×10^9 t is noted, which represents an error of 3.1% for the 31.3×10^9 t measured.

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