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IMPORTANCE OF SEDIMENT RESEARCH IN GLOBAL WATER SYSTEM SCIENCE

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Abstract: The global production of suspended sediments to discharge into the ocean is estimated about 20 $\times 10^9$ t·y^{-1}, of which over 25% may be trapped by about 45,000 large dams constructed around the world. Both sediment production and reservoir trapping are increasing. Sediment production, transport, deposition and its temporal and spatial balance have a major impact on global landscape and upon water and nutrient circulation. These issues need major attention, but are, unfortunately, not well studied on a global basis. A proper sediment production function is not available. The detail global distribution of dam reservoirs, and therefore sediment trapping, is unknown. The USLE (Universal Soil Loss Equation) formula developed by USDA-ARS (Agricultural Research Service) for sheet and rill erosion is literally universally used around the world, including in mountainous regions where landslides and debris flows are the major sources of sediment production. After reviewing the current sediment production studies and information about the global distribution of large reservoirs, this paper introduces the Japanese land slides and debris flow prediction methods, the Soil-Rainfall Index and the Snake Curve. These methods would provide a new alternative for developing a better sediment production function applicable in orogenically active regions of the world. Due to the importance of sediment production and transport in the global water system science, it is concluded that the current GEOSS (Global Earth Observation System of Systems) and GWSP (Global Water Systems Project) plans should include the proper sediment study component as an observation target. The IAHS (International Association of Hydrological Sciences) PUB (Prediction in Ungaged Basins) initiative supports this target since sediment is one of the most important phenomena of ungaged hydrology.

Keywords: Large dams, Sediment trap, USLE, Soil-Rainfall Index, Snake Curve, GEOSS, PUB

1 INTRODUCTION

There are about 45,000 large dams with the total sum of storage capacity being about 7,000 km^3 in the world (Varma, 2002). The most often cited estimates of the global suspended sediment discharge to the ocean range between 15 t·yr^{-1}-20$\times 10^9$ t·yr^{-1} where the best estimate may be about 20$\times 10^9$ t·yr^{-1} (Walling and Webb, 1996), of which over 25% is considered to be trapped by dam reservoirs (Vorosmarty *et al.*, 1997). This creates a major impact on the global landscape and upon water and nutrient circulation. Nearly all sediments are trapped in upstream dams in the Nile and the Colorado rivers, resulting in a significant retreat of the river mouth and in the reduction of aquatic population. Due to the impacts of climate change and agricultural development, the sediment yield seems increasing. The balance between the sediment yield and trapping needs major attention considering its global impact. Unfortunately, however, sediment production is not sufficiently studied. It is incredible to see the USDA-ARS (United States Department of Agriculture, Agricultural Research Service) formula: USLE (Universal Soil Loss Equation) that should apply only for sheet and rill erosion in agricultural land with undulating topography is literally universally used around the world including in mountainous regions where landslides and debris flows are the major sources of sediment production. In Japan, the meteorological agency and local governments issue landslide and debris flow prediction for warning the public by using the Soil-Rainfall Index and the Snake Curve methods. Those methods have been used for more than a decade. Although the accuracy of predictions is still to be improved, the underlying concepts of these methods would be valuable for developing a sediment production formula applicable to the orogenically active regions of the world. This paper highlights the importance of studying global sediment production and trapping and the need of developing a sediment production function for landslides and debris flows in orogenically active regions around the world, including mountainous Southeast Asian countries.

2 SEDIMENT PRODUCTION

Walling and Web (1996) provide the following most up-to-date picture of the current knowledge on the global suspended sediment flux to the ocean:

(1) The most frequently cited global total sediment discharge is between 15 $t \cdot y^{-1}$-20×10^9 $t \cdot y^{-1}$. The most rigorous attempts made to estimate the global suspended sediment flux to the ocean is by Milliman and Meade (1983) and refined by Milliman & Syvitki (1992) who suggest 20×10^9 $t \cdot y^{-1}$.

(2) The specific sediment yield from basins larger than 100 km^2 ranges from less than 1 $t \cdot km^{-2} \cdot y^{-1}$ in Eastern Europe to $(10\text{-}30) \times 10^3$ $t \cdot km^{-2} \cdot y^{-1}$ in Southwestern part of Circum-Pacific Rim countries where the highest reported is 53,500 $t \cdot km^{-2} \cdot y^{-1}$ at Huangfuchuan, China.

(3) Walling and Webb (1983) and Lvovich *et al*. (1991) provide the estimated maps of the global pattern of the suspended sediment yield ($t \cdot km^{-2} \cdot y^{-1}$).

It is remarkable that they could provide, from a thorough review of the literature, the estimate of the global sediment flux to the ocean as well as the distribution of the production sources considering the lack of data.

Fig. 1 shows the estimate of the global distribution of suspended sediment (Walling and Webb, 1983) from which it is clear that the major sediment yield regions coincide with the orogenically active zones, the Alps-Himalayan Orogenic Zone and the Circum-Pacific Orogenic Zone. Southeast Asian rivers discharge roughly two thirds of the total global sediment discharge. Especially the Loess Plateau produces large amounts of sediment to the Yellow River. According to the Yellow River Conservancy Commission (2004), its "average annual sediment inflow to downstream is 1.6×10^9 $t \cdot y^{-1}$ with sediment content 35 $kg \cdot m^{-3}$. Every year, average 0.4×10^9 $t \cdot y^{-1}$ of sediment deposit on the lower reach of the Yellow River, which results in raising of river bed with a speed of 10cm. The river channel of downstream is 4 m-7 m higher than the ground outside the river on average, the maximum is up to 13 m higher." The statements above imply that the Yellow River produces 8 (or 8-11) % of the total global sediment production, which seems rather small considering the tremendous problems caused in the river. Sediment production is high in the regions indicated dark in Fig. 1 by many reasons, including geological, pedological and climatological phenomena. Steep slopes easily collapse, geologically young and stressed rocks are easily weathered and heavy rainfall promotes landslides as well as sheet erosion.

Current climate change is also contributing to an increase of sediment production. According to IPCC report (Folland *et al.*, 2001), in many places the maximum 5 day total rainfall shows an increasing change in the latter half of the 21st century which would imply an increase in rainfall intensity as well as rainfall volume, which might have been increasing global sediment production. The expected intensification of heavy rainfall by global warming would imply further increase in the future.

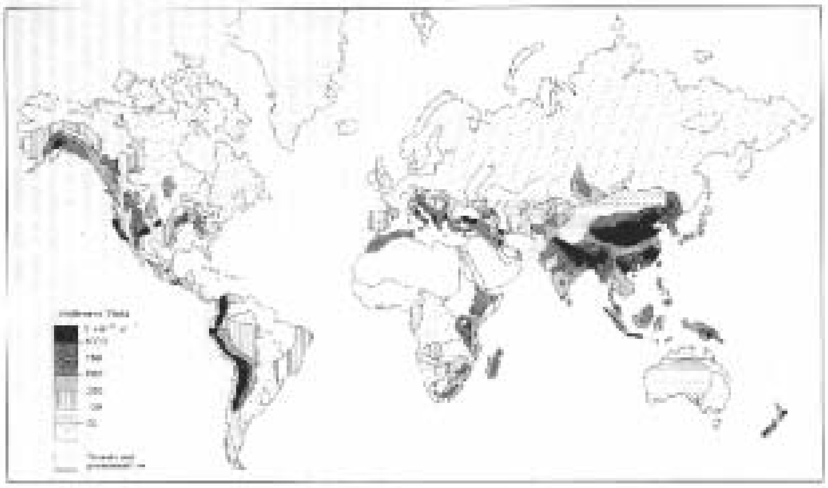

Fig. 1 Global Patters of Suspended Sediment Yield according to Walling & Webb (1983)

Desertification is another source of sediment increase. Since the United Nations Conference on Combating Desertification (UNCCD) was established in 1994, various efforts have been made, but desertification is still expanding. The UNCCD (2004) says that "one fifth of the world's population is threatened by the impacts of global desertification. Its effects can be seen all over the world, be it in Asia, the Sahel, Latin America, throughout North America or along the Mediterranean. Today, a third of the earth's surface is threatened by desertification, which adds up to an area of over 40×10^6 km^2 of the planet." The cause of desertification is human activities such as over-cultivation, deforestation and poor irrigation practices combined with climate change. Fertile soils become barren patches of land. Since 1990, the UNCCD estimate that some 60,000 km^2 of productive lands have been lost every year due to land degradation. There is no mention, however, of the magnitude of increase in sediment production due to desertification.

3 LARGE DAMS OF THE WORLD

According to the World Register of Dams 1998 edition of ICOLD (International Congress of Large Dams) (1998), "the member countries reported 41,413 operational dams in 1996." Among which there are 25,410 records in the Register. A large dam is defined in ICOLD as a dam higher than 15 m. The Register indicates that the chronological distribution of dam construction shows that in 1950s, 60s, 70s and 80s, there were 2,733, 4,788, 5,415 and 4,427 new dams constructed, respectively. The number slightly decreased in the 80s as compared with the peak period 60s and 70s, yet the construction rate is still high. The recent slowdown may be due to the exhaustion of economically justifiable sites in developed countries as well as the increased concern on environmental and societal impacts.

Approximately 45,000 large dams and their 7,000 km^3 total storage capacity (Varma, 2002) are the major source of river flow retardation and sediment trap on the global land surface. Vorosmarty *et al.* (1997) estimated by analyzing 633 large reservoirs with over 0.5 km^3 storage that more than 40 % of the global river discharge goes through large reservoirs and is retarded longer than 0.21 y. They postulate that "the actual global sediment retention by reservoirs may exceed 25% of the global flux" which obviously greatly impacts the global mass balance, landscape as well as water and nutrient circulation.

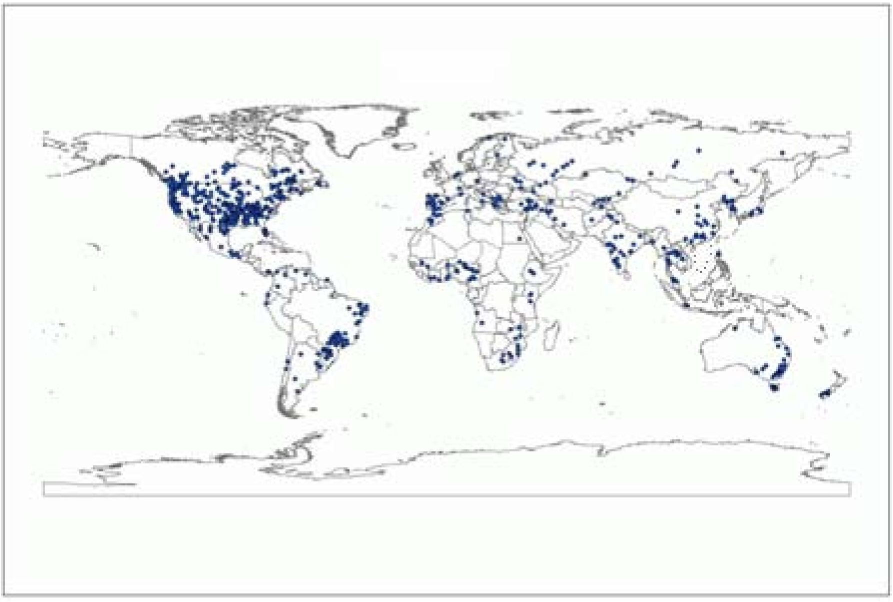

Fig. 2 Global Distribution of Dam Reservoirs Greater than 500 MCM (Magome, 2004)

Fig. 2 depicts the global distribution of 738 dams out of the total 1,251 large dams with storage capacity more than 500 MCM (Magome, 2004). As the coordinates of any particular reservoir are not given in the ICOLD Register of Dams, various other information sources such as Operational Navigation Chart (Defense Mapping Agency Aerospace Center, 1973), Bertelsmann World Atlas (Mairs Geographicher Verlag Ostfildern, 1999) were used to identify them. The figure lacks many reservoirs such as those in China where the data accessibility is limited. The reservoirs greater than 500 MCM can trap a large amount of sediments. The construction of giant dams, such as Three Gorges and Xiaowan in China and Ataturk in Anatoria, Turkey, is continuing around the world. Many giant dams were built in the 1960s and 1970s typically for hydropower generation and nowadays its rationale seems regained as the environmental concern on the nuclear power increases. Thus the global capacity of sediment trapping by reservoirs would continue to increase.

Dam construction drastically changes the flow regime downstream, especially large reservoirs having inter-annual carryover storage capacity. In Bhumibol Reservoir in the Chao Phraya River, Thailand, the annual flood and lowflow cycle in Asian Monsoon regime is totally flattered out (Takeuchi, 1993). There has been virtually no sediment discharge from the Nile River below Aswan High Dam since its construction (completed in 1970), which resulted in a significant retreat of estuary. There have been virtually no water flows out from the mouth of the Colorado River in a number of years since 1960 to date (Gleick, 2003)The sediment trapped in reservoirs limit the life of reservoirs but the estimates indicate the Aswan and Hover Dams have over three hundred years of life (Takeuchi, 1998).

Reductions in sediment discharge to the ocean also occur as a result of reductions in river discharge due to water use upstream. The flow reduction contributes, by accelerated sediment deposition, to the raising of riverbed elevations to the eventual formation of ‘sky rivers’ and the increase in flood risk as typically experienced in the lower reaches of the Yellow River. On the other hand, in countries which applied extensive sediment control works such as Japan, the riverbed is lowering in the middle to downstream reaches of rivers by Sabo works causing serious scoring of bridge piers and disconnection between water use or intake facilities and the lowered river water table. The assessment of sediment balance is therefore essential for local river basin management as well as the global land and water system study.

4 SEDIMENT PRODUCTION FORMULAE

For river basin sediment management, the most important information is the sediment production function. In contrast to well advanced river sediment transport study, sediment production study is not well developed. The only formula available for general use is the USLE (universal soil erosion equation) developed by USDA ARS in 1960s for sheet and rill erosion of agricultural land (USDA-ARS, 1961). It is so successful to be used all over the world including, unfortunately, in the area where sediments are mainly produces by the land slides and debris flow events.

USLE (Universal Soil Loss Equation)

In the USLE (Wischmeierand Smith, 1978), the sediment production rate is expressed as the multiplicative equation of five factors,

$$A = RKLsCP$$

where A is the soil erosion mass $t \cdot ha^{-1} \cdot y^{-1}$, R is rainfall-runoff erosivity, K is soil erodibility $t \cdot ha^{-1} \cdot y^{-1}$, Ls is a slope parameter, C is a factor relating to land cover and management, and P is a conservation practices factor.

The rainfall-runoff erosivity R is calculated using the maximum 30 min rainfall intensity and the volume of rainfall (i.e., the total kinetic energy of the storm). Soil erosivity K is tabulated for different combinations of clay, loam, silt and sand. Land slope parameter Ls is for 0% to 10 % and crop type parameter C is for corn, bean, cereal, horticulture, fruit trees, hays and pasture, etc. It is therefore meant strictly for agricultural land, but can be extended to any land by simple parameter modification, which obviously leads to a false image (Bastari, 2001).

Soil Rainfall Index and Snake Curve Methods

In Southeast and East Asian orogenically active regions, the sediment production is dominated by landslides and slope collapses that occur not as a continuous process proportional to rainfall intensity and/or accumulation but as a probabilistic process with some threshold. The threshold is highly nonlinear with rainfall patterns. In Japanese rivers, two methods are widely used for predicting land slides and debris flow prediction, i.e., the Soil Rain Index and the Snake Curve, the former used by Prefectures suggested by Ministry of Infrastructure, Land and Transport (MILT) and the latter by Japan Meteorological Agency (JMA) which now also belongs to MILT. Based on these indices, the official warning is issued to the public.

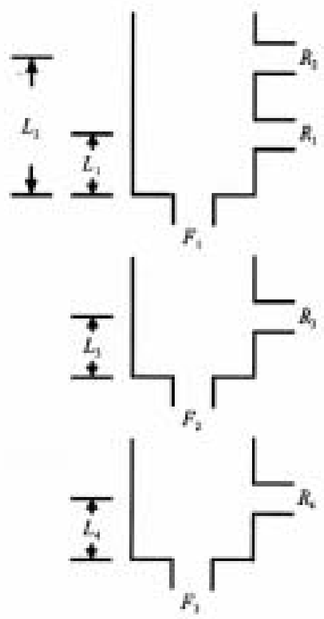

Fig. 3 Tank Model to Estimate the Landslides And Debris Flows (Okada, 2002)

The Soil-Rainfall Index is calculated by using a Tank model developed by Sugawara (1961) as depicted in Fig. 3. The Index is the total sum of storage heights in the three tanks. The tank parameters were identified on an hourly basis in the Kizu River in Nara Prefecture by Ishihara and Kobatake (1979). Japan Meteorological Agency uses, according to Okada (2002), the same tank with the same set of parameters all over Japan regardless of the climate, topography or geology. The local index is calculated by local rain. If the index (i.e., sum of storage heights) exceeds the third largest in the local 10 years of historical records, the warning is issued to the local public. This method has been officially exercised by Japan Meteorological Agency since 2001 but has been experimentally used more than a decade. Its prediction accuracy is measured by the 'prediction hit', or a percentage of land slides or debris flow occurred within 5 km grid cell or the city where rainfall station is when the warning is issued. Okada (2004) says that the accuracy is different for land slides, slope collapse and debris flows. The best is for debris flow. Based on 10 years of simulation he found that 75 % of debris flows occurred when the warning was issued. It was only 40 % in case of land slides. The accuracy indicates the degree of randomness attaching to those phenomena.

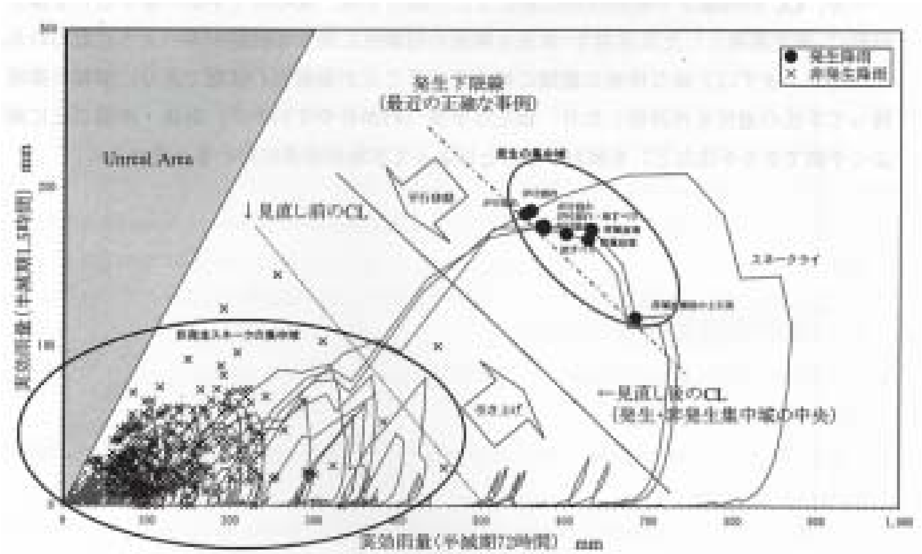

Fig. 4 Snake Curves to Predict the Occurrence of Land Slides, Slope Collapses and Debris Flows by Terada and Nakaya (2001)

The Snake Curve is drawn in *x-y* plane as shown in Fig. 4 where the horizontal abscissa is the accumulated hourly effective rainfall (mm·h^{-1}) $R_w = \left[\sum_{t=1}^{n} \alpha_t P_t\right]$ of a storm where P_t is rainfall at time t (hour intervals) starting from the beginning of a storm, n is the current time step, $\alpha_t = 0.5^{t/T}$ the impact decay factor and $T = 72$ hours, the half life, and the vertical abscissa, the same with the different half life $T = 1.5$ hours. The horizontal coordinate indicates the impact of the accumulated rainfall volume and the vertical, the impact of short term rainfall intensity.

The critical line (CL) in Fig. 4 is a line separating the areas where land slides, slope collapses and debris flows occurred (black ball points) and not occurred (*x* points). Once the snake line reaches to the CL, that is, the accumulated rainfall is large and the current intensity is also large, the land slides and/or debris flow occur.

It should be admitted that those indices do not necessarily very accurately predict land slides and debris flow since these phenomena are probabilistic in nature. But the indices precisely represent the nature of land slides, slope collapse and debris flows. The sediment production formula should be correlated to such threshold indices in Asian and other orogenically active regions.

Both indices were designed for the same purpose and suggested by the same ministry, MILT. There is an effort of combining the two. It was pointed out that the Soil-Rainfall Index predicts better for deep slides and the Snake Curve for superficial slides that would imply the suitability of the physical mechanism of the phenomena modeled by the two indices.

5 CONCLUDING REMARKS

Both sediment yields and reservoir trapping of sediments seem to be increasing due to climatic change, agricultural development and continuing reservoir construction, but their global state is not well observed or analyzed. Their global impact is significant on land and seashore geomorphology. Quantifying these processes is important for disaster prevention, land conservation and ecological protection. Their monitoring and control are essential for river basin management in heavy sediment producing basins such as the Yellow River and the Mekong. The current global observation efforts such as Global Earth Observation System of Systems (GEOSS) (EO Summit, 2004) and the Global Water System Project (Framing Committee of GWSP, 2004) should incorporate this very important aspect of the earth science in their plans. The IAHS (International Association of Hydrological Sciences) PUB (Prediction in Ungaged Basins) initiative considers this issue one of its most important subjects (Sivapalan *et al*., 2003).

The GEOSS plan is under preparation by the Earth Observation Summits (EO Summit, 2004) initiated by the G8 2003 in Evian, France. This is a follow-up of the Implementation Plan of the World Summit on Sustainable Development (WSSD) (UN, 2002) held in Johannesburg in August-September 2002 as well as the 3rd World Water Forum in Kyoto, Shiga and Osaka in March 2003. The salient feature of the GEOSS is that it covers not only the satellite remote sensing information but also the *in situ* observations on the land including human dimension data such as land and water use. Sediment yields and reservoir trapping are surely very important part of it.

GWSP is also under preparation by the four basic research projects of the International Council of Sciences (ICSU): International Geosphere Biosphere Program (IGBP), World Climate Research program (WCRP), International Human Dimension program (IHDP) and DIVERSITAS for bio-diversity program. The current Framing Committee of the GWSP (2004) outlines the project as follows: “Human-induced changes to the global water system are now globally significant and are being modified without adequate understanding of how the system works.” It addresses the following as an overarching scientific question: “How are human actions changing the global water system and what are the environmental and socio-economic feedbacks arising from the anthropogenic changes in the global water system?” Sediment production and reservoir retention of sediments is necessarily a focus subject in these projects.

The other very important research program relating to this field is IAHS PUB. PUB is the IAHS decadal project launched in 2002 to improve the predictive capacity of hydrology to meet the basic hydrological needs of society. Sediment yield and trapping is one of the major “ungaged” hydrological components. The PUB science plan was published in Hydrological Sciences Journal (Sivapalan *et al*., 2003). It tries to replace the calibration needs of models with the understanding of process hydrology. The strategy is to improve existing models through the better use of existing data and uncertainty analyses and to develop new innovative models incorporating new data, theories and distributed models. The PUB implementation strategy is pluralism and is a grass roots strategy that welcomes working groups using any approaches. There are already many working groups formed all over the world such as in Japan, UK, US, China etc. Eagerly awaited are the proposals from developing countries.

The Millennium Development Goals (MDGs) for poverty alleviation and resources management (UN, 2000) were declared at the United Nations 55th General Assembly in September 2000. In order to achieve the goals, there are at least four major components are prerequisite. They are governmental commitment, secured funding, data to make use of scientific knowledge, and the professional personnel to implement the plans. Among them hydrology is responsible to the latter two, data collection and capacity building. Sediment study is in the midst of such needs. International collaboration on sediment measurements, research and training should further be promoted.

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