A PRACTICAL EXAMPLE OF CHANGE OF RIVER BED ENVIRONMENT DOWNSTREAM FROM DAM RESERVOIR BY SEDIMENT REPLENISHMENT

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ABSTRACT

We reviewed the case of the Nakagawa River, which had one of the largest scales of sediment replenishment. Its monitoring results are composed of river survey, river bed material survey, biological research and so on. The results show the changes of river bed condition such as restoration of river bed materials, the increase in the ratio of fine sediment on the armored river bed and the expansion of riffle. We estimated the amount of transported sediment by one dimensional analysis of river bed variation. We also examined the effects of sediment replenishment on amount of sediment yield by grain size.

1. INTRODUCTION

Implementation of sediment replenishment in the downstream side of dam reservoir has been increased in Japan as a countermeasure for bed degradation and armoring phenomena. Even though, the amount of replenished sediment was small in most of the cases, and the change of river bed environment was found only in few cases. We reviewed the case of the Nakagawa River, which had one of the largest scales of sediment replenishment in order to examine the change of downstream river bed environment of dam reservoir by sediment replenishment.

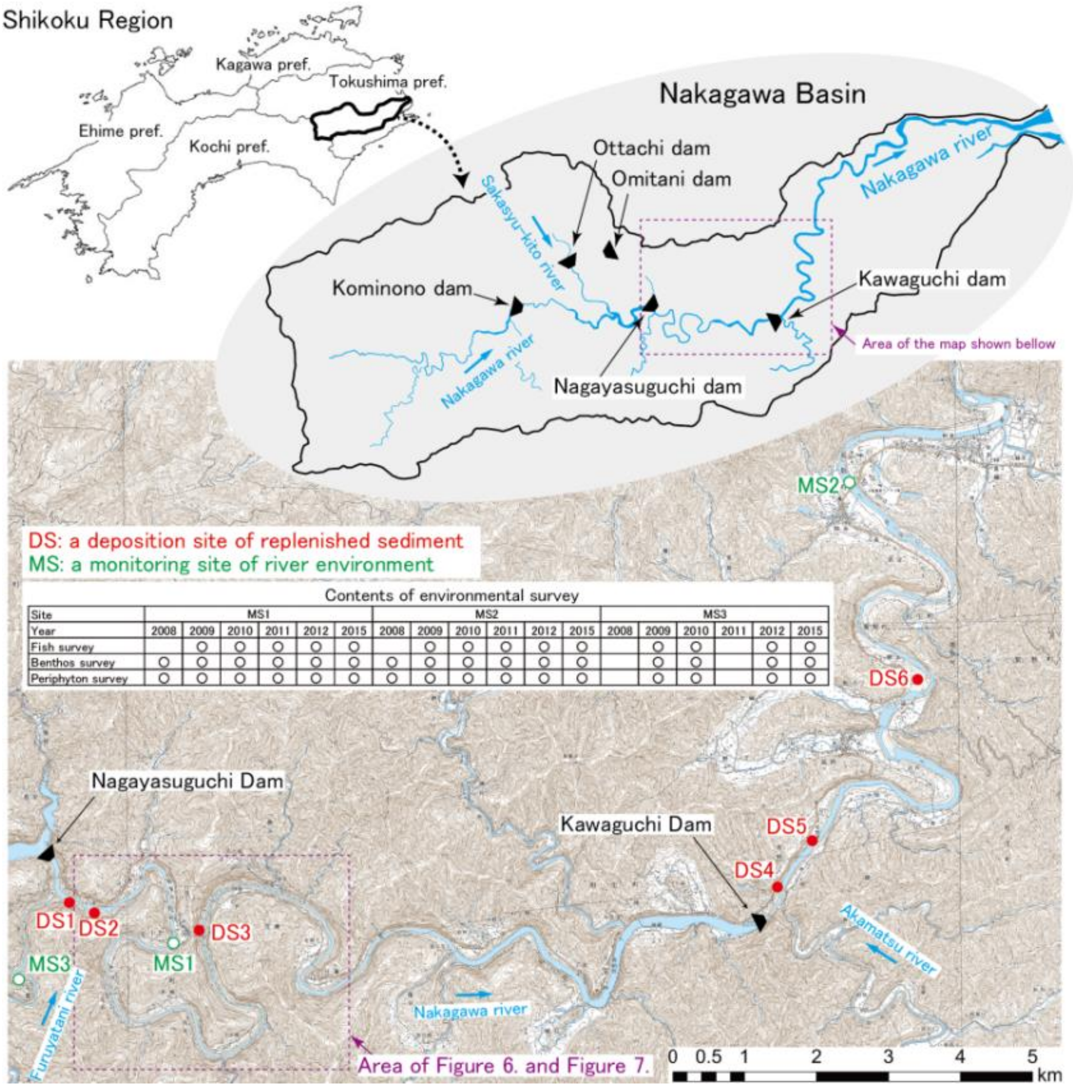
2. SEDIMENT REPLENISHMENT CASE OF THE NAKAGAWA RIVER

The Nakagawa River, located in the south of Tokushima prefecture (Figure 1), is a steep stream river of about 125km in length, 874km^2 catchment area. Large amount of sediments are produced from upper part of the basin, because of the brittle geological structures of the Chichibu Belt and significantly high rainfall of about 3,000mm in annual. The Nagayasuguchi dam was built in 1955 in the Nakagawa River and 59 years have passed from its completion. Total capacity of the reservoir is 54,278,000m^3, but sedimentation in the reservoir reaches 15,977,000m^3 (29% of total capacity). The reduction of supplied sediment to the downstream of the Nagayasuguchi dam resulted in bed degradation, armored river bed and exposure of river bed rock. The Kawaguchi dam is reregulating reservoir with low crest height (EL.81.4m), located downstream of the Nagayasuguchi dam.

As a countermeasure for sedimentation of the Nagayasuguchi dam reservoir and sediment reduction in the downstream, sediment replenishment has been conducted in the Nakagawa River since 1991. Annual sediment volume of 3,000m^3 to 24,000m^3 was replenished as the Tokushima prefectural project from 1991 to 2006. From 2007, amount of replenished sediment was increased up to maximum annual volume of 297,000m^3 as the project under ministerial jurisdiction.

Figure 1 shows deposition site of replenished sediment. The replenished sediment is excavated at the upstream end of the Nagayasuguchi dam reservoir and in the sedimentation area of Ottachi check dam which was constructed for erosion control, transported to the downstream by dumper truck, and deposited on the bank or the dry bed of the site. Figure 2 shows the volume of replenished sediment. Main sites are DS1 and DS2 close to the Nagayasuguchi dam. Their total volumes are up to 335,000m^3 and 691,000m^3 respectively, from 2007 to July 2015. The replenished sediment consists of sand and gravel ranging from 0.075 to 100mm with 12mm of d_{60} grain size(Figure 3).

The volume of sediment flowing down from the deposition sites was monitored by cross section survey before and after floods. On August 2009, the sediment flowed down for the first time after the replenished sediment was increased in 2007. Then 869,000m^3 of the sediment flowed down by 2014 and 1,003,000m^3 flowed down by July 2015 as shown in Figure 4.



Site	MS1						MS2						MS3					
Year	2008	2009	2010	2011	2012	2015	2008	2009	2010	2011	2012	2015	2008	2009	2010	2011	2012	2015
Fish survey		○	○	○	○	○		○	○	○	○	○		○	○		○	○
Benthos survey	○	○	○	○	○	○	○	○	○	○	○	○		○	○		○	○
Periphyton survey	○	○	○	○	○	○	○	○	○	○	○	○		○	○		○	○

Figure 1. Location of the Nakagawa River and the Nagayasuguchi dam

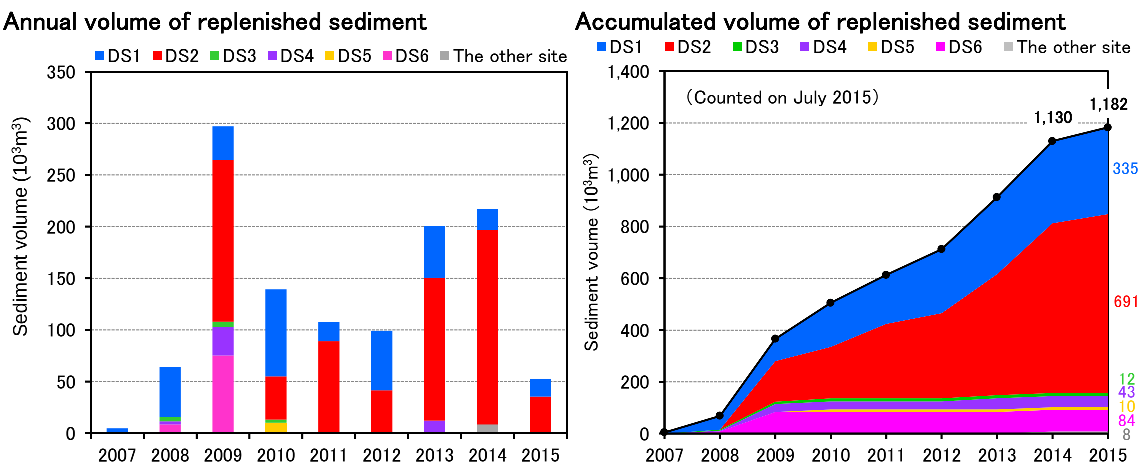


Figure 2. Volume of replenished sediment

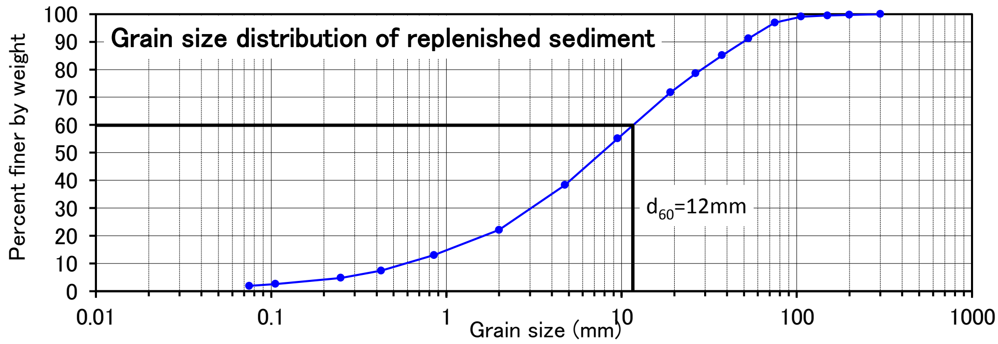


Figure 3. Grain size distribution of replenished sediment

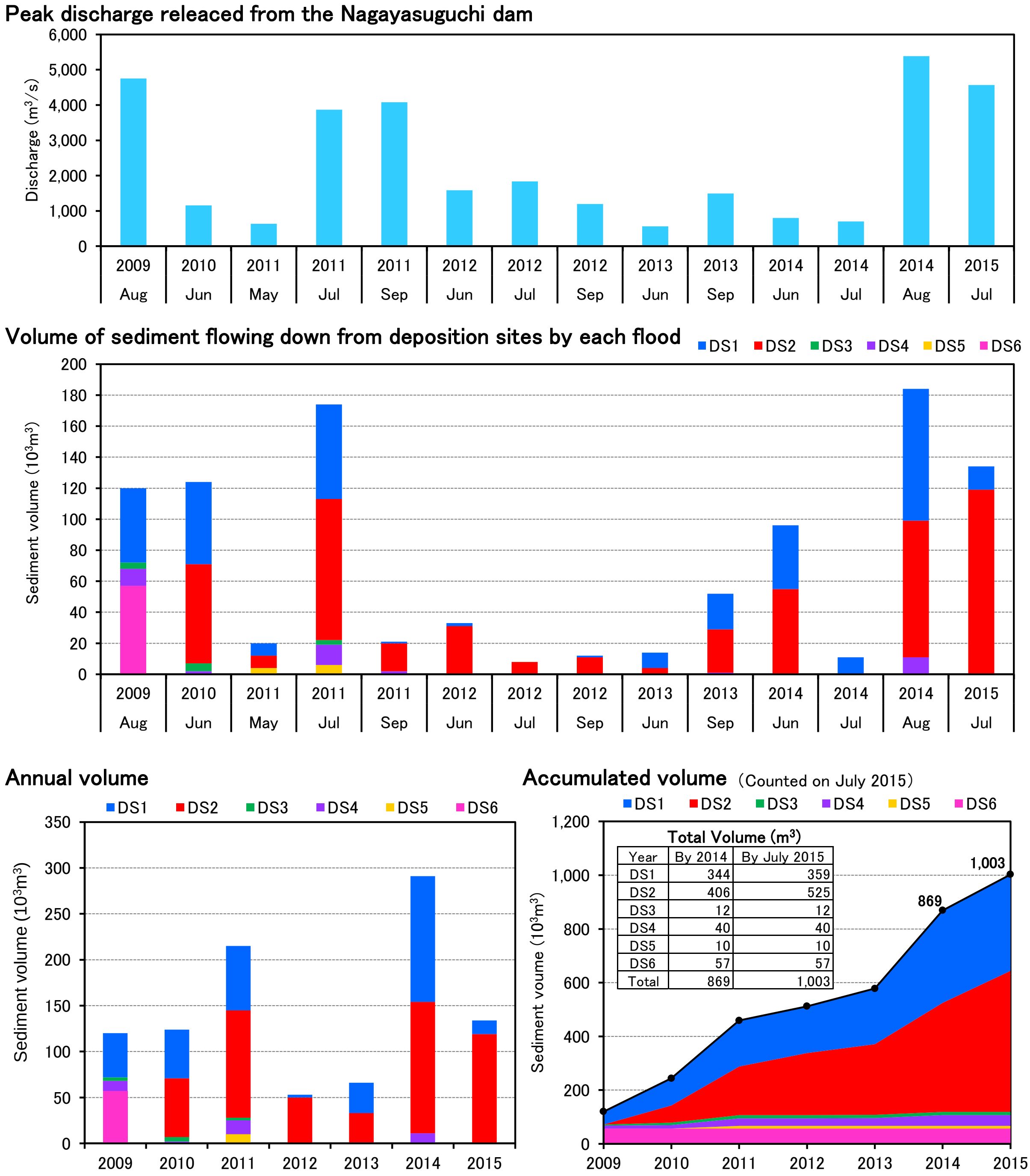


Figure 4. Volume of sediment flowing down from deposition sites

3. MONITORING SURVEY

3.1 River bed variations

River bed variations are observed by longitudinal survey and cross section survey as shown in Figure 5. Rise of river bed bottoms was remarkable about 10km downstream from DS1 and DS2. Mean river bed rose largely between DS1, DS2 and the Kawaguchi dam. Variation of river bed was small in the downstream of the Kawaguchi dam.

Variation of sediment volume was 513,400m^3 in the upstream of Kawaguchi dam reservoir and 252,400m^3 in the Kawaguchi dam reservoir, Volume of sediment flowing down from DS1, DS2 and DS3 was 762,000m^3 which was close to 765,800m^3 of total variation in the upstream of the Kawaguchi dam. It is inferred that most part of sediments flowing down from the main site of DS1 and DS2 was deposited in the upstream of the Kawaguchi dam.

3.2 River bed materials

Original river bed materials, which were not affected by sediment replenishment, were surveyed from 2002 to 2008 and some were surveyed in 2010 at the places, where river bed rise were not found. Materials of new deposition after the flood in August 2009 were surveyed at spots with remarkable sediment deposition in 2009, 2010 and 2012. Sample materials were taken from 50cm depth in the surveys. River bed material gradation was classified into S (under 2mm), M1 (2-20mm), M2 (20-200mm) and M3 (over 200mm) based on longitudinal existence range of original river bed material. River bed materials contained in new depositions were mainly M1 in the upstream of the Kawaguchi dam reservoir. They are smaller than original river bed materials mainly in the range from M2 to M3.

3.3 Change of river bed condition

Planar distribution of pool, run and riffle shown in Figure 6 were drawn by visually reading based on the aerial photographs recorded in 2010 and 2014. The target area is from downstream of DS2 to upstream of the Kawaguchi dam reservoir where the rise in a river bed was remarkable (the area of Figure 6 is indicated in Figure 1). Classification is based on definition shown below.

- Pool: area of deep water, slow moving, no ripples.
- Run: area of shallow water, fast flow with ripples over cobbles partially submerged finer sediment.
- Riffle: area of shallow water, fast flow with breakers over cobbles.
- Puddle: area of water divided from stream by dry river bed.

Longitudinal unit of river was divided by riffle's positions which were not moved from 1947 to 2014, in comparison to the condition before the Nagayasuguchi dam construction using the aerial photographs recorded in 1947. Seventeen units were defined in the upstream of the Kawaguchi dam reservoir. Figure 8 shows the area ratio of pool, run and riffle in each unit. Area of pool occupied more than 70% in most of the unit in 2010. It is inferred that run and riffle were not formed because of sediment shortage on the river bed. The area ratios of run and riffle were obviously increased in 2014. Increase of run and riffle was most likely caused by recovery of river bed materials supplied from replenished sediment.

The distribution map of river bed materials shown in Figure 7 were also drawn by field surveys in 2010 and 2014. River bed sediments were visually read on site and classified into S, M1, M2, M3 and 'exposed bed rock'. Main materials and sub materials are expressed by assignment to background colour and dot pattern collectively. Figure 9 shows the area ratio of river bed materials by grain size based on the classification. Area of exposed rock was decreased from 2010 to 2014. Area ratio of S was extremely small in both 2010 and 2014. Therefore, it is obvious that the sediments finer than 2mm were easily transported and reach to the Kawaguchi dam reservoir immediately. The area ratio of M1 was larger than 20% in most units of upstream of Unit-11 and smaller than 20% in the downstream of Unit-12. Moreover, the area ratio of M1 in the downstream of Unit-14 was increased in 2015. It indicates that sediments of 2-20mm were transported about 6km in 2 years (2009-2010) and about 11km in 6years (2009-2014). The area ratio of M2 in the upstream of Unit-3 was larger than the one in the downstream of Unit-4 in 2010. In 2014, the area ratio of M2 clearly increased in the upstream of Unit-14. It indicates that sediments of 20-200mm were transported about 2km in 2 years and about 9km in 6years. Increase of area ratio of M3 was remarkable only in Unit-1 from 2010 to 2014.

Therefore, it was inferred that sediments coarser than 200mm were transported about 1.5km in 6 years.

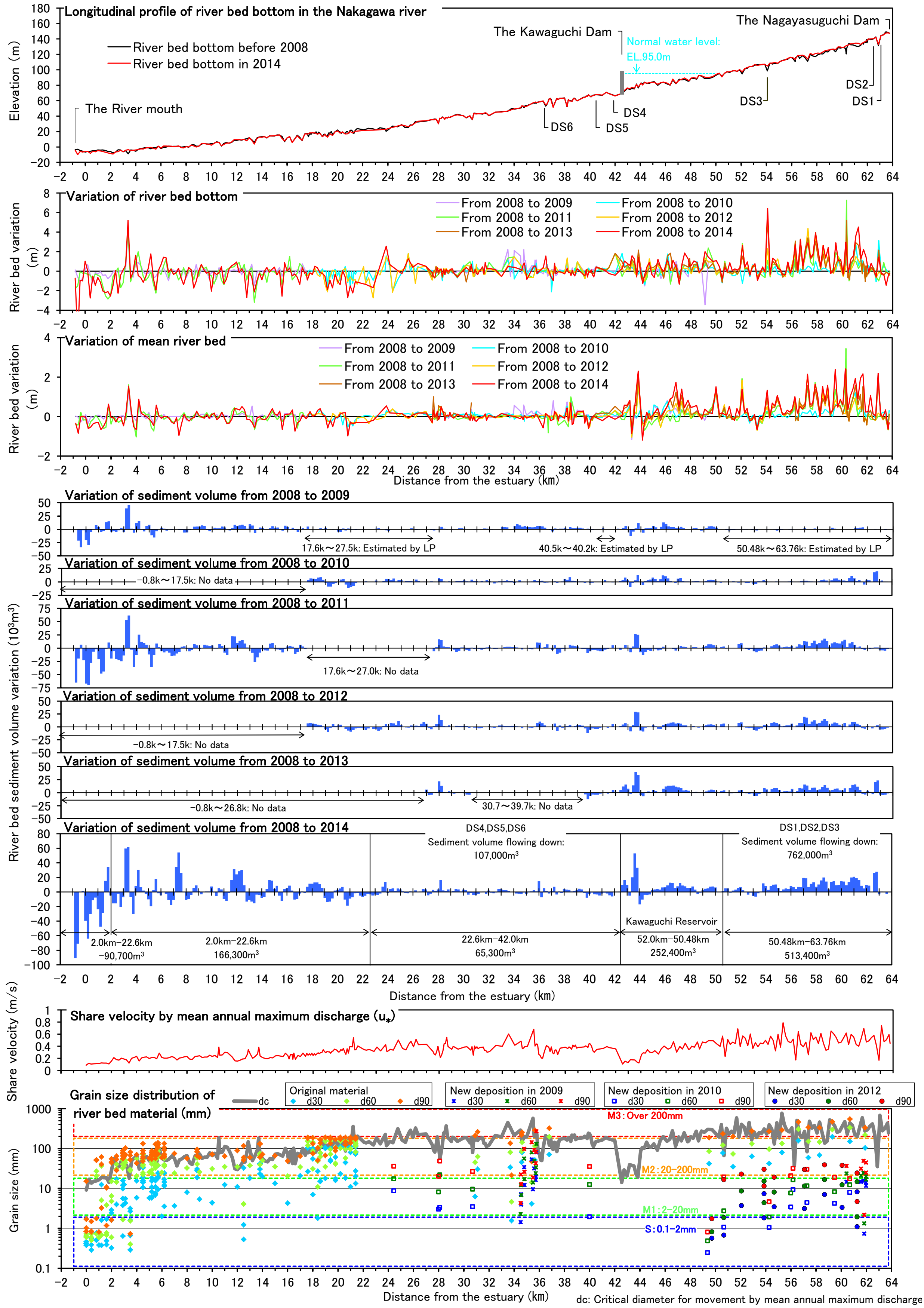


Figure 5. River bed variations and grain size distribution

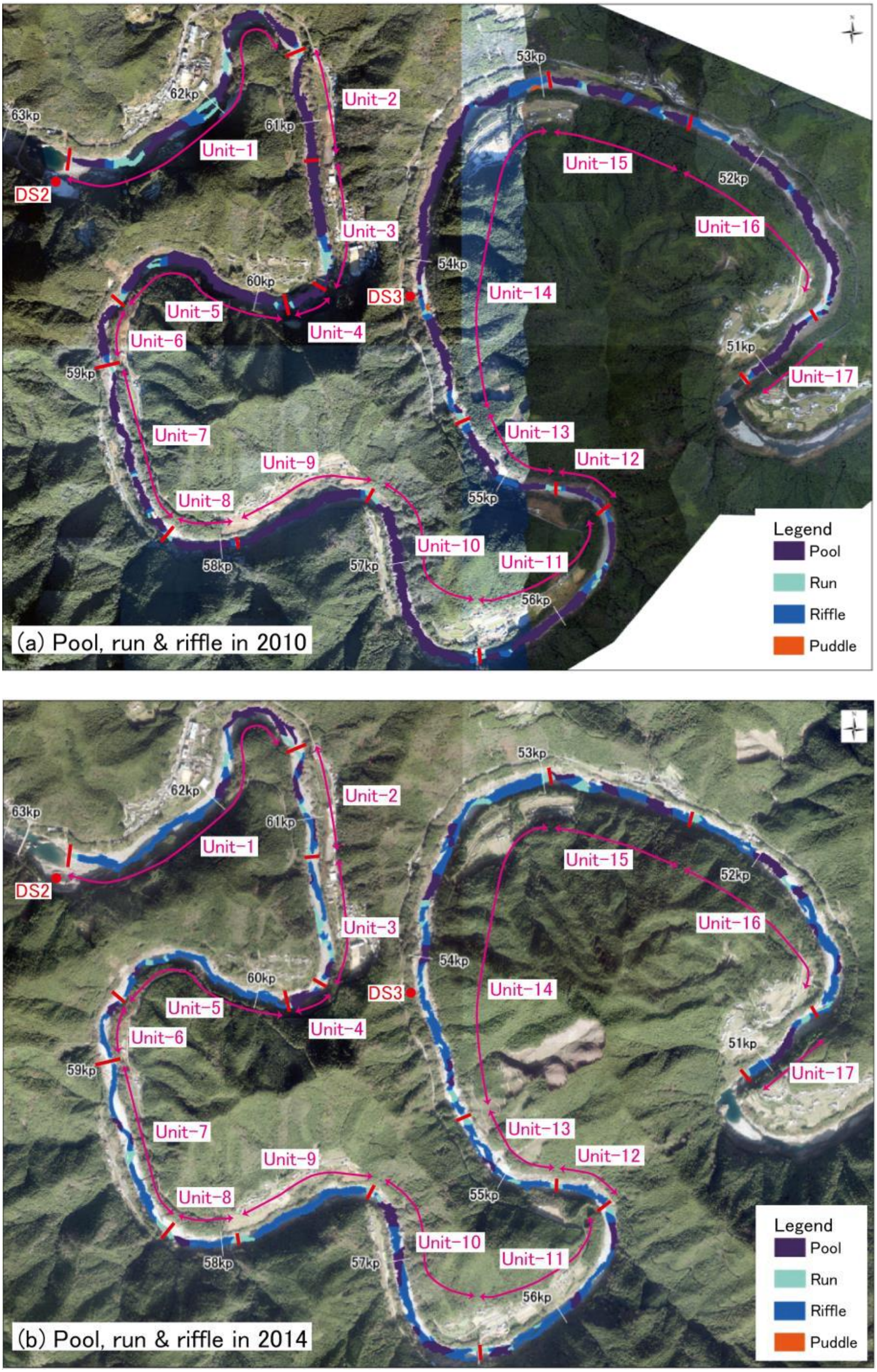


Figure 6. Planar distribution of pool, run and riffle

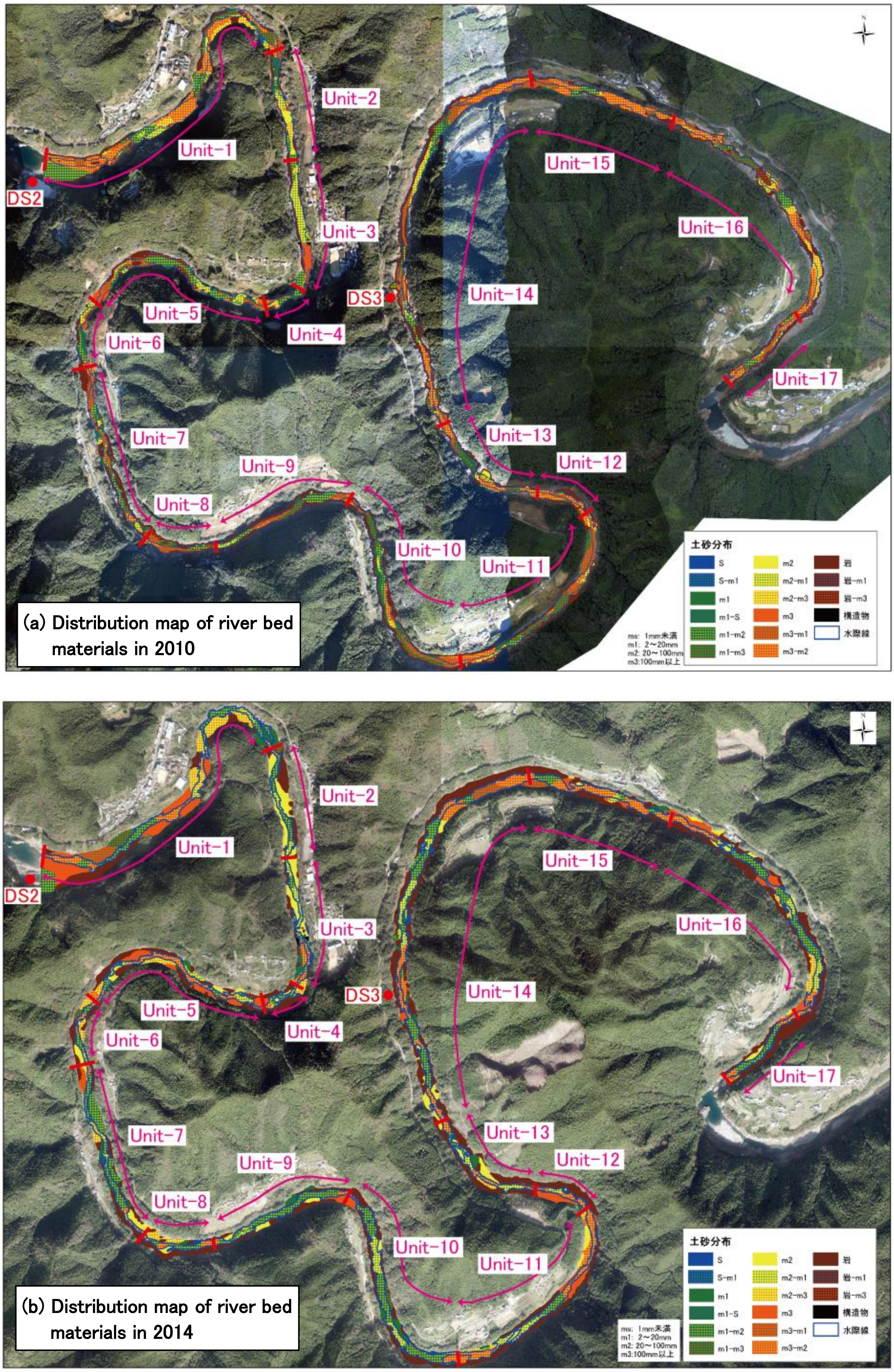


Figure 7. Distribution map of river bed materials

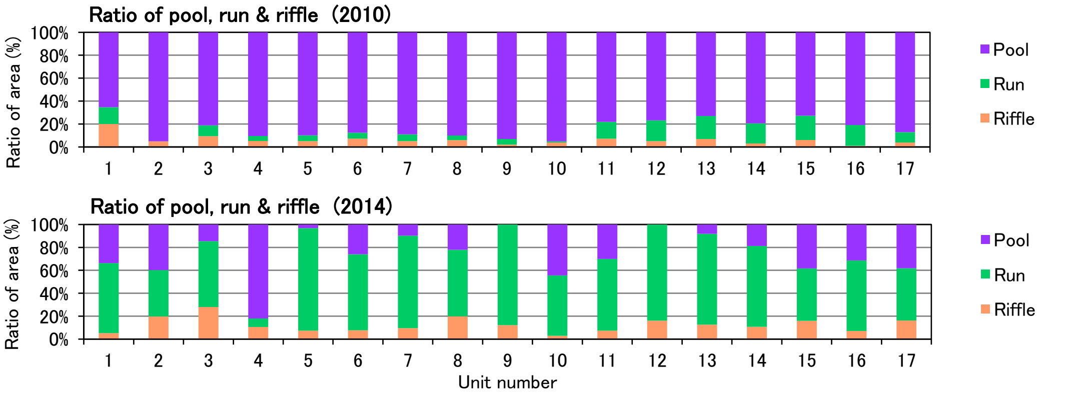


Figure 8. Area ratio of pool, run and riffle

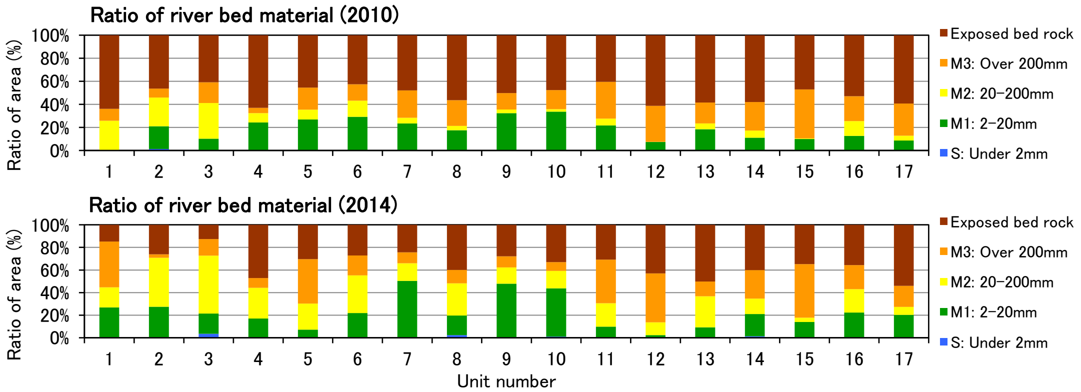


Figure 9. Area ratio of river bed material by grain size

4. ESTIMATION OF THE AMOUNT OF TRANSPORTED SEDIMENT BY ONE DIMENSIONAL ANALYSIS OF RIVER BED VARIATION

Even though the monitoring results show the transported distance for each grain size in 6years (2009-2014), transported volume of sediments were not clear. Therefore, we estimated the amount of transported sediment by one dimensional analysis of river bed variation.

4.1 One dimensional analysis of river bed variation model

One dimensional analysis method of river bed variation based on non-uniform water flow calculation was applied in order to simulate long term phenomena (Musashi et al. 2011). Equilibrium sediment transportation model of Ashida and Michiue(1972) was applied for estimation of bed load, and non-equilibrium sediment transportation model was applied for estimation of suspended load with Lane & Kalinske formula.

4.2 Verification Calculation

The target period of verification calculation was from the occurrence of flood in August 2009 to December 2014. Analytical condition of sediment supplied from deposit sites of replenished sediment was input at the cross sections immediately downside of the deposit sites. Sediment supply from river branches were also input at confluences. Hourly discharge data was used for flood and daily discharge was used for ordinary times. Boundary water height data were input at the river mouth and the Kawaguchi dam. Figure 10 shows the result of verification calculation. Variation of river bed height was well reproduced. Therefore, we considered that the model was applicable.

Calculation case of 'No sediment replenishment' has been also conducted. As shown in Figure 10, increased volume of sediment transported by sediment replenishment was estimated by the difference of verification and no sediment replenishment case. Further, increased volume of river bed variation by sediment replenishment was also estimated. Focusing on sediment from DS1 and DS2, Figure 10 shows the sediments finer than 2mm flew down through the Kawaguchi dam reservoir. The sediments of 2-20mm reaches to the Kawaguchi dam reservoir. 20-50mm reaches about 10km, 50-100mm reaches 4km, 100-200mm reaches 2km downstream of DS1 and DS2. The transported length estimated by analysis was generally corresponding to the estimated from the distribution map of river bed materials (Figure 7).

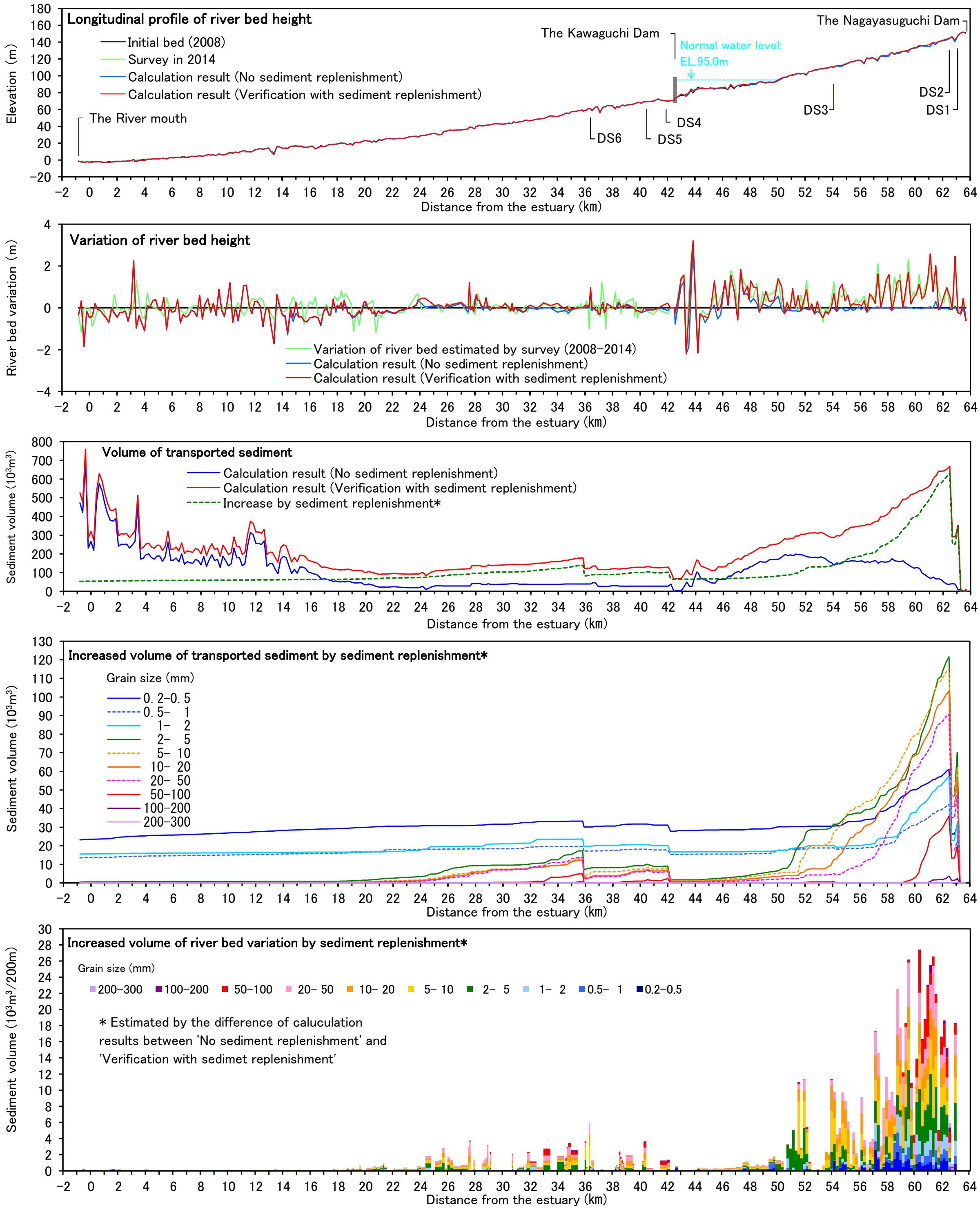


Figure 10. One dimensional analysis result of sediment transportation from 2008 to 2014

5. THE EFFECTS OF SEDIMENT REPLENISHMENT ON AMOUNT OF SEDIMENT YIELD BY GRAIN SIZE

Figure 11 shows the volume of sediment reached to every unit based on one dimensional analysis of river bed variation and the ratio change of pool, run and riffle from 2010 to 2014. Focusing on increase of area of run, high increased rate of near 90% are shown from Unit-5 to Unit-9 which was end of range M2 mainly reached. Increased rate of run near 80% are shown in the upstream of Unit 14 where sediment of M1 was mainly reached. Thus, recovery of run was probably caused by increase of M1 and M2. However the coarser material of M2 was smaller in volume, its contribution seems to become larger as volume of supply increased.

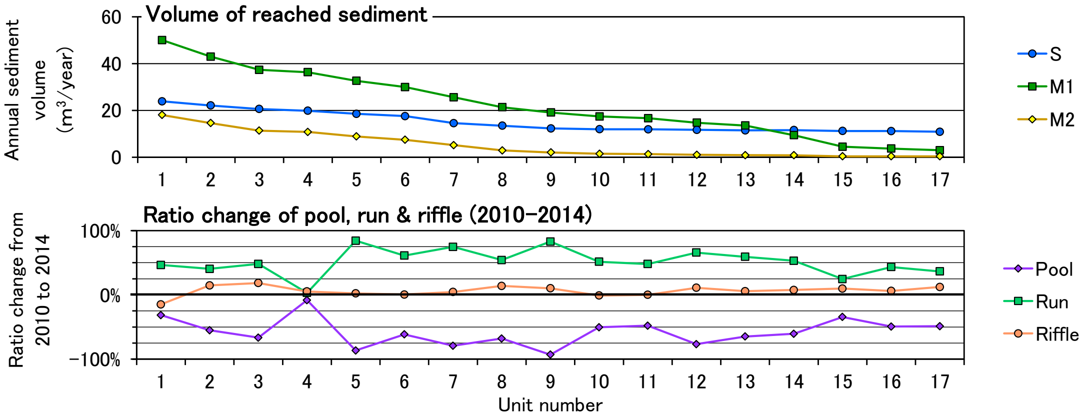


Figure 11 Volume of reached sediment and ratio of pool, run & riffle

In the case of Nakagawa River, grain sizes of M1 (2-20mm) and M2 (20-200mm) contribute to river bed rise, recovery of river bed materials and recovery of run and riffle. Critical diameter for movement by mean annual maximum discharge shown in Figure 5 indicates 200-400mm. Therefore, continuation of sediment replenishment is needed to keep the dynamic equilibrium effect under the current condition of replenishment. Larger sediment of M3 (coarser than 200mm) seems to be needed in order to keep the effect statically without replacement of the pebbles. In addition, the sediments coarser than 20mm (M2 and M3) moved slowly. They need long time in units of several decades to spread downstream enough. Therefore, more consideration is needed to supply sediment coarser than 200mm by sediment replenishment. For example, immediate deposition to the required point can be a possible method.

6. CONCLUSION

We reviewed the sediment replenishment case of the Nakagawa River in this study. The effects such as restoration of river bed materials, the increase in the ratio of fine sediment on the armored river bed and the expansion of run and riffle are observed. Sediment of over 2mm (gravel) contributed to these effects. Transported distances of sediments were 11km for M1(2-20mm), 9km for M2(20-200mm), 1.5km for sediments M3(coarser than 200mm) in 6years observation.

7. ACKNOWLEDGEMENT

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8. REFERENCES

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