IN-SITU ESTIMATION FOR SPATIAL AND TEMPORAL VARIATION OF HYDRAULIC CONDUCTIVITY IN A NEWLY CREATED GRAVEL BAR

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ABSTRACT

Reach scale heterogeneity of riverbed hydraulic conductivity has been investigated previously, while few examined the vicinity riverbed hydraulic conductivity response to dam removal projects. In this study, CHIT(Constant Head Injection Test) method was used for *in-situ* estimation of hydraulic conductivity (K) in a newly created gravel bar after a weir removal project at three depths: top(0-30cm), middle(30-60cm) and deep (over 60cm). Data were used to generate the spatial and temporal variation map of K. Results showed that K has a negative relationship with the measurement depth. Low K areas are mainly distributed in the middle and deep layer at the bar head, especially at the right-bank side. As to the bar tail (line E and F) the K was over 100m/day throughout three layers. After one-month period, the overall K increased due to a small flood, however, specific site with decrease of K were found in all layers which indicates the complexity of K evolution with time. Based on detailed background and local geomorphic settings investigation, we found that the artificial impact to the original riverbed and the strong sediment sorting during bar formation could be the fundamental control of the heterogeneity of K, which implies that during removal work, proper riverbed management strategy is crucially needed for the purposes of hyporheic ecotone restoration.

Keywords: spatial and temporal variation, hydraulic conductivity, gravel bar, weir removal

1. INTRODUCTION

The hyporheic zone (HZ) is an active ecotone between stream flow and groundwater where water flows through the substrate (Boulton et al., 1998). Stream water and groundwater interactions, or hyporheic exchange take place in the hyporheic zone and has a profound impact on the aquatic organism especially the benthos and hyporheos (Stanford et al., 1993). Previous studies have shown that microbes and invertebrates use HZ as permanent habitats (Brunke and Gonser, 1999) and/or as temporal refugee during adverse conditions. (Stubbington et al., 2009; Wood et al., 2010). The hyporheic exchange is largely controlled by the hydraulic conductivity of riverbed and surrounding aquifer (Kollet and Zlotnik 2003; Nowinski et al., 2011). Traditionally, the riverbed was treated as a homogeneous layer for simplification in many previous hydrological studies (Boulton et al., 1998). The natural heterogeneity of riverbed hydraulic conductivity has been increasingly recognized in the recent years by both hydrologists and ecologists (Sophocleous, 2002). The hyporheic exchange is directly affected by the spatial and temporal variation of riverbed hydraulic conductivity (Packman and Salehin, 2003). Researchers implemented various methods in the field to acquire 3-D structure of riverbed hydraulic conductivity. Cardenas and Zlotnik (2003) used Constant Head Injection Test method to invest k in a gravel stream, and k showed great spatial variability ranged from 0.15-74.5m/day. Yamada et al (2003) used Parker test for the high permeable area and Falling Head Method for the low permeable area of a gravel bar in the Kamo river (2003). Nowinski (2011) studied the k changing with time in a point bar of an artificial channel, and he concluded that the decrease of k was due to fine material movement and accumulation. One of the widely acknowledged model for describing k evolution in the riverbed is the clogging-flushing theory. In this theory the k would be continually decreased due to fine sediment accumulation in the top layer of the riverbed until the next flood event flushing out the fine materials and a new layer with the maximum initial K_0 would be formed (Schälchli, 1992; Cheng Cheng et al., 2011; Simpson1 and Meixner, 2012;). However, such model simplified many hydrological and hydraulic factors such as the variation of sediment load, the local geomorphic settings and biological activities on hydraulic conductivities (Springer et al., 1999; Schubert, 2002; Packman and MacKay, 2003; Blaschke et al., 2003; Genereux et al., 2008).

Sediment control works such as weirs and check-dams could result in increasing of vegetated area on gravel bars and in alteration of habitat quality for hyporheos (Takemon, 2003). Removal of such structures can greatly alter the local channel geomorphology, such as formatting new bars at the lower reach. As more and more dams (mostly are small ones) are going to be removed in the near future, it is critical to gain more knowledge for channel response to such kinds of structures' removal. For better guiding river restoration work and improving the overall aquatic ecological conditions, this study provides a unique aspect from the hyporheic zone's response to a weir removal project.

Using direct measurement methods, we were trying to figure out how K was distributed and evolved during low flow conditions within one-month period. The present study focuses on the following goals, 1) the horizontal and vertical distribution of K in a newly created bar after dam removal and 2) evolution of K with time.

2. STUDY SITE

The study site is in Katsura River which is a typical urbanized river segment in the downtown area of Kyoto City. There were eight weirs constructed in the main channel, and by the end of 2019, two of them has been removed in a government flood control and channel modification project. No.4 weir was completely removed in March 2019, and a mid-channel gravel bar was created nearby after typhoon No.10 in August. After No.4 weir removal the riverbed excavating work has been done in the vicinity, which resulted in a flat and compacted channel.

The triangle-shaped bar has an area of 2193 square meters and located just downstream of a large point bar with a huge channel bend. The main channel was diverted into two subchannels by the gravel bar. The elevation of the left-bank side channel was significantly higher than the right side based on field observation, which, was proved by the water table mapping afterwards, indicating the hyporheic flow direction could be from left-bank side to the right side (blue lines in Figure 1).

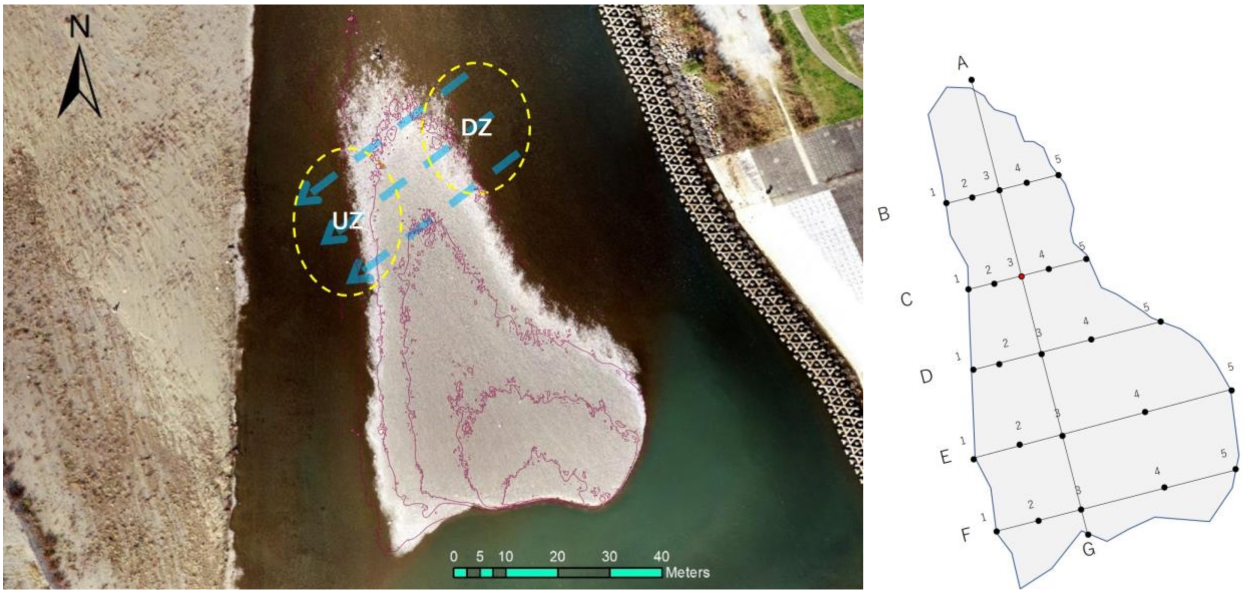

Figure 1. The study site in Katsura River and the corresponding naming system, drone photos were taken by Takemon, 4th December 2019. The bar surface contour line interval is 10cm.

The field surveys were conducted two times during the low flow season, on 4th December and 11th January, respectively (Figure 2). No heavy rainfall happened during this period, and no major anthropogenic interference was noticed. However, several small rainfalls were detected and caused water level fluctuated between the two surveys. During December, the water level fluctuated to a maximum 3cm (1.69m±3cm), while on January 8th, two days before the second survey, a rainfall has resulted in a 10cm water level increase(1.69m+10cm). On January 11th, the water level has returned to the same level of the first survey (1.69m).

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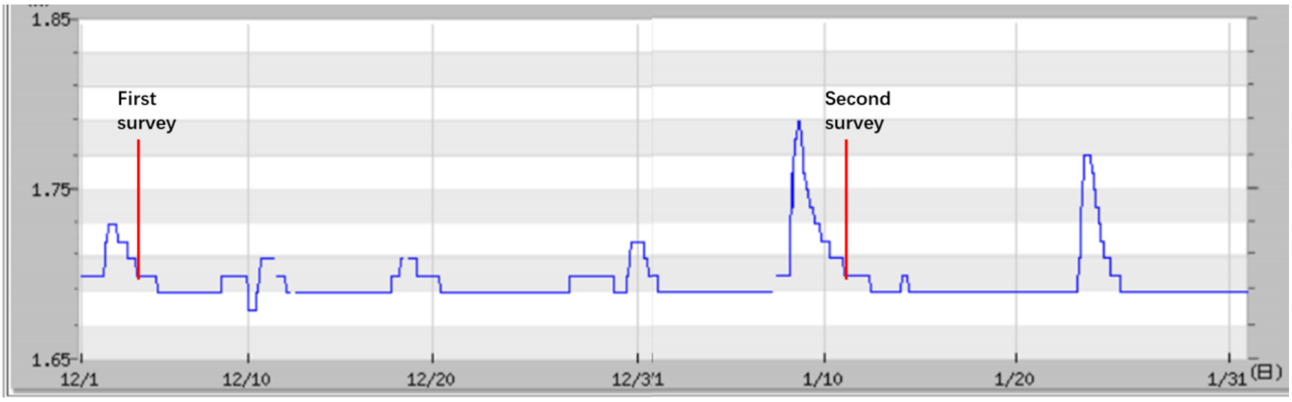

Figure 2. The water level(m) fluctuation from 1st December to 31st January.

3. METHODS AND MATERIALS

In the first survey we measured the bathymetry of the gravel bar and made a coordinate system shown in figure 1(transects were named by A to G). longitudinally, from A to G the bar showed a significant sediment sorting, in the bar head the sediment is mainly consist of gravel and cobbles, while in the bar tail a thick layer of clean and loose sand was deposited with a higher elevation than the bar head. Cross-sectionally, the bar middle is higher than the side area. Fine materials were detected on the bar surface, however near the waterfront they were flushed and a "cleaned" bar edge area can be detected from the aerial.

3.1 Water table mapping

Water table was measured in the main channel and in the gravel bar by a level station with the accuracy of 1mm. In the gravel bar wells were dug at every survey point in figure 1 by a shovel and measured after the water table was steady.

3.2 Hydraulic conductivity estimation and grain size analysis

The riverbed hydraulic conductivity (K) was estimated using Constant Head Injection Test (CHIT) following Cardenas' method (2003). A set of equipment including a permeameter made of steel which has a length of 110cm, 2cm for the inner diameter and 2.5cm for the outer diameter, and a solid metal cone was welded on the tip for penetrating the hard gravel bed. The screened area is 10 cm long and has a 2mm diameter for the slot size. A micro water pump was used for injecting water with a manually tuned, maximum discharge ability of 6000ml/min.

While during the preliminary test for determination of precision and repeatability, our equipment was not able to estimate K for the line E, F, and point G, for the sediment is consist of a layer of clean sand on top and very loose, the hydraulic conductivity was too high for our equipment design, we also dug holes in this area and try to estimate K in the deeper layer, however the value was still over the upper limits of our equipment. thus, for this part (bar tail) we generally assume the K is high. For better understanding and interpolation, during the preliminary survey we assigned "100m/day" for the points that the K value was over the upper limit measurement ability of our apparatus, and "0" for the extremely low K situation. In the rest part of this paper, 100m/day means the K value is generally high, however, the actual value could be more than 100m/day as we estimated in the field (100-300m/day).

Thus, vertical hydraulic conductivity of saturated aquifer was estimated from A to D5. For each point measurement was made at three different depths: the top (0-30cm), middle (30-60cm) and deep (over 60cm) to detect the vertical heterogenous of K.

Aerial photos taken by DJI Phantom 4 drone were analyzed using Agisoft Metashape Pro of Agisoft LLC, to create an Orthomosaic. Grain size analysis of bed surface was done by ImageJ bundled with 64-bit Java 1.8.0_112. The historical river longitudinal profile was collected from Yodo river bureau and processed by Microsoft Excel software.

All the data acquired was processed and visualized in the ESRI's ArcGIS software. The spatial distribution of K was interpolated by IDW method.

4. RESULTS

4.1 Water table of gravel bar

The water table generated in ArcGIS showed a good coincidence with the field observation(Figure 2 left), which indicates that the stream water was directed from the left-bank side and penetrate inside the gravel bar to the right side due to the elevation differential. This is particularly notable at the bar head area. The possible hyporheic flow line was also drew in the figure 1. The inundated map during the 10cm water level rise was also generated (Figure 3 right), yellow line indicates the boundary of dry and wet area. Fine materials were detected along the yellow line especially at the middle part.

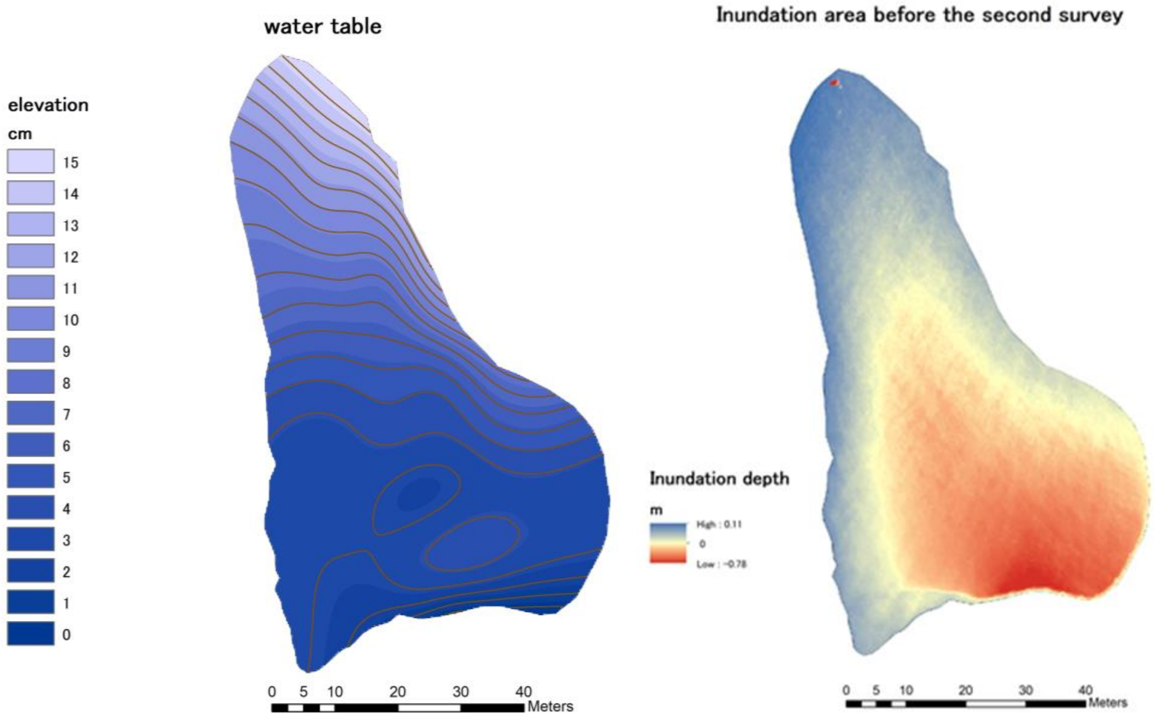

Figure 3 Measured water table elevation, the contour line interval is 1cm (left). The inundated area of the gravel bar during the water level increase before the second survey, blue color indicates the inundated part (right).

4.2 Spatial distribution of K

In the first survey (Figure 4), the K value of top layer was high (100m/day), only at point B1, B3 and C1 showed significant lower K ranged from 19.5m/day to 21.0m/day. The middle layer revealed a similar pattern but generally lower than the top layer. At B1 the K was 0.95m/day, 21 times lower than in the top layer, and K at C1 was 4.6m/day, 3 times lower that in the top layer. K in the rest part was still high. As to the deep layer, low K area covered the majority part of the bar head, only at A showed a different higher value of 18.3m/day. In the bar middle (C3, C5 and D line), K ranged from 16.6-39.1m/day, with an average value of 26.2m/day.

In the second survey, the area with a high K value increased compare to the first time. Particularly in the bar head, B1 and C1 along the water edge increased from 19.5 m/day and 21.0 m/day to “100 m/day” (estimated). Only B2 and B3 showed low K value of 8.4m/day and 1.3m/day. Fine materials were detected during the second survey at B2 and B3, the different color from the first survey indicated that they might deposited during the water level increase on 8th January. The distribution pattern of K in the middle layer is similar to the top layer of the first survey. The low K value area was still concentrated at the right-bank side of the bar head (potential upwelling zone), with an average value of 1.2m/day. For the deep layer, the edge of the bar head area showed an increase of K (at A, B5 and C5) and because in the second survey we added two additional survey points in line B and C, we were able to generate a more detailed K distribution map of the bar head. The low K area seemed “eroded” in the middle and spread to both the bar head and bar tail direction. From C5 to D5 (bar middle) the K ranged from 47.6 to 75.9 with an average of 64.6m/day. As to the bar tail (line E and F), K was still high even in the deep layer.

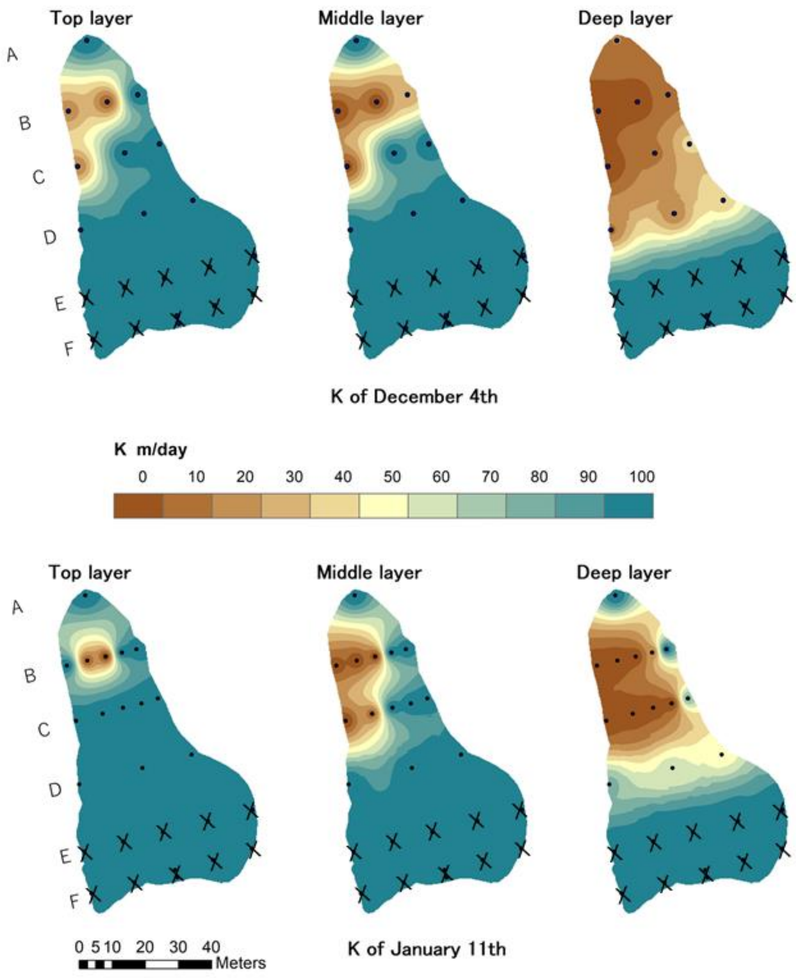

Figure 4 Spatial distribution of K in December and January. Solid points indicated measured value in the field. Cross marks indicate that the k was beyond measurement ability and were assigned 100m/day during the interpolation process.

4.3 Patterns of K change

We compared the K change between the two surveys (Figure 5). For the top layer, K increased significantly at up welling zone of the bar head area (B1 and C1) by 395%. While at B3, K decreased by 86.7%, the rest part remained high K value. In the middle layer k at B1 and B5 increased by 185.6% and 248.5% respectively, however at B3 K decreased by 77.5%. C1 also showed a different pattern compare to the top layer, decreased by 75.1%. Other area remained similar compare to the first survey. In the deep layer, K generally increased a t the bar head and middle. Specifically, K increased at the tip of the bar head (A), the left-bank side of the bar head (C5, D5) and at the middle of the bar. Only C3 showed a decrease of K. The rest part revealed minor change.

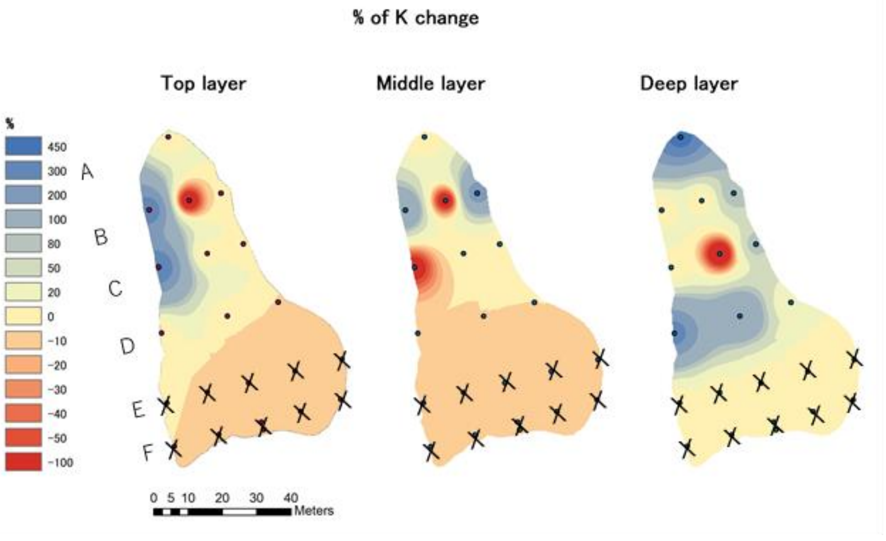

Figure 5. Percentage change of hydraulic conductivity during a month-period

5. DISCUSSION AND CONCLUSIONS

5.1 K distribution and bar formation

After the NO.4 weir removal in order to maximize the discharge ability when flooding, a flat and compacted riverbed was made artificially at the vicinity of the weir site. During the typhoon NO.10, sediment was deposited on the original hard riverbed and formed the gravel bar which showed different physical characteristics. The original riverbed has a relative low K value and the newly deposited bar has high K. Due to a strong sorting, the elevation of the bar tail is higher than the bar head which means that the bar head area is closer to the original compacted riverbed. For the bar tail area, a thick layer of clean sand (2mm) was deposited and explained the general high K value at the area. Figure 6 showed the riverbed longitudinal profile after the weir removal. The gradient of the original riverbed was 2.5% (13.4-13.6K). Such geomorphic settings may explain the spatial distribution pattern of K in the gravel bar: 1) K value has a negative relationship with the measurement depth; 2) the low K area increased from top to deep layer where the permeameter might penetrate into the original riverbed, and revealed K distribution of it; and 3) the apparatus could not penetrate(110cm) the thick sand layer at the bar tail, which explained the high K value through out three layers at this part.

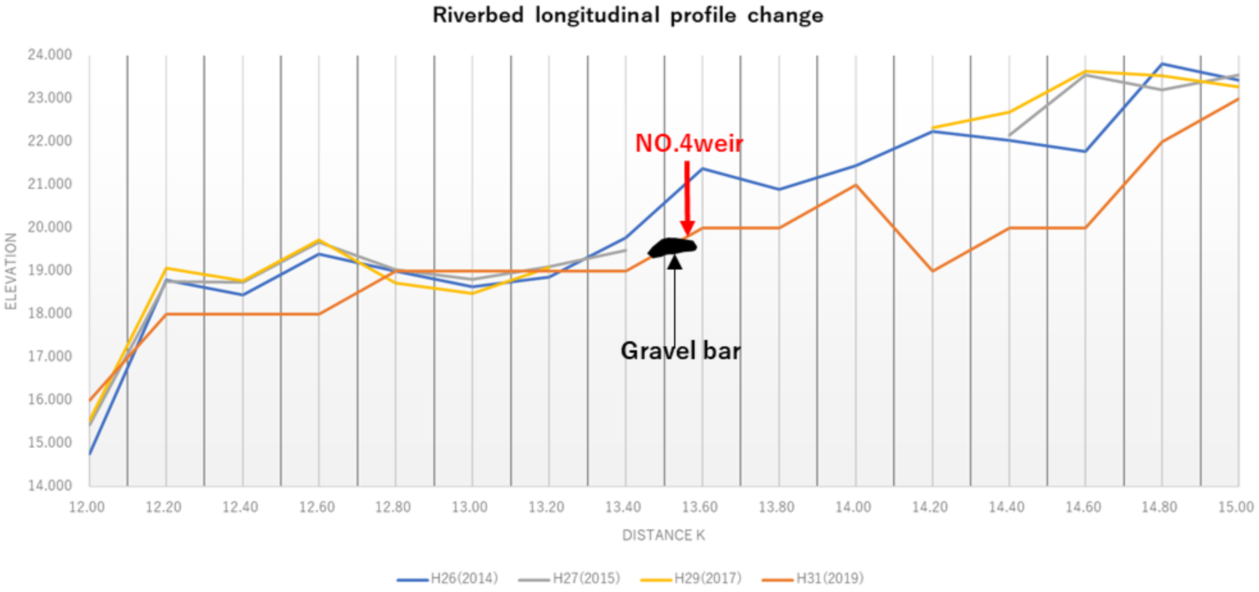

Figure 6. The riverbed longitudinal profile change before and after NO.4 weir removal, the blue, grey and yellow line are before the removal while the orange line is the riverbed profile after the removal.

5.2 Water level fluctuation and flushing-clogging theory

Throughout November and December of 2019, water level fluctuated no more than 3cm, fine material may continually accumulate especially at the right-bank side of the bar. The 10cm water level rise before the second survey could flush out the deposited fine materials which caused the K increase. The possible explanations of some areas where K were decreased in the second survey may related to fine material movement inside the bar (Nowinski, 2011), which needs further investigation of sediment characteristics and modeling efforts to confirm. At the reach scale, the study area serves as a potential downwelling zone, stream water penetrates into the riverbed and come out at the downstream reach. Hyporheic upwelling at the downstream were detected by Takemon during ecological surveys. The increased water level before second survey might be a driving force to facilitate hyporheic flow at the reach scale, which could possibly explain the increase of K in the deep layer, fine materials were transported to the deeper aquifer by the enhanced hyporheic flow.

5.3 Conclusion

Few previous studies examined hyporheic zone response to dam/weir removal, however, more and more dams especially small ones (weirs/run-of-river dams) would be decommissioned or completely removed in the near future. Thus, it is important to concern the dam removal’s impact on the vicinity hyporheic zone. The present study reported how the hydraulic conductivity spatially distributed in a newly created gravel bar after weir removal project and how K evolved at the monthly time scale. Grain size analysis using high resolution aerial image showed that the sediment sorting was significant, with an average grainsize of 12 mm at the bar head area, 4mm at the bar middle and 2mm at the bar tail. The original artificial riverbed management strategy and the strong sediment sorting during the bar formation could be the fundamental control of the heterogeneity of hydraulic conductivity, which implies that during removal work, proper sediment management work is crucially needed for the purposes of hyporheic ecotone restoration.

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