INSTALLATION OF ALTERNATIVE GRAVEL BANKS IN CHANNELIZED RIVER

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ABSTRACT

The installation of alternative gravel dikes could represent valuable substitute to classic river restoration projects in channelized rivers, since no widening is necessary. This study assesses the changes in flow heterogeneity, ecological suitability and flood protection caused by this new strategy. The experiments are conducted in rectangular channel with slope 0.01, where gravel dikes are inserted on alternated shores during normal stage. The flow velocity and water surface are measured using electrical-magnetic current meter and point gauge respectively. The installation area is studied under different discharges and further data are collected once at flat gravel bed morphology. With small discharges, the water surface is flat, and the flow meanders and pockets with almost still water are found downstream of each gravel dike. Those characteristics gradually disappear with larger floods, where waves on the water surface and straightening of the flow are observed in the channel's center, coupled with significant speed reduction closing to the lateral walls. Above flat gravel bed, homogeneous normal flow is recorded across the whole section. Further, experiments in prototype yield that the space flows in boulders are successfully used by living fishes to refuge from the flood flows. None of studied discharges reaches the critical Shields stress for erosion, while gravel dikes produce significant habitat improvement for all the studied species, especially where the pockets with almost still water are found. On the other hand, this alternative bed morphology brings unbalance to the hydraulic conditions of the channel and causes the water surface to rise, shrinking the cross-sectional capacity and increasing the flood risk. Future research must be conducted for the installation shapes of gravel dikes to become a valuable restoration strategy.

Keywords: Gravel dikes, Meandering shape, Flow refuge, Habitat suitability modelling, Flood control

1. INTRODUCTION

Restoration projects re-establish the ecological equilibrium of channelized rivers, but often require complex research and widening works. The introduction of gravel dikes on the cemented bed may represent a simpler alternative. Width modifications are not required and the river's ecology should improve thanks to the new flow heterogeneity. This Thesis must quantitatively answer to the following questions:

1. How do the flow conditions change from a flat gravel bed cross section?

Once the generic initial characteristics are assessed, more engineering-oriented questions are addressed. Firstly the focus is given on the riparian ecology and hydraulic:

2. Are aquatic and riparian habitat significantly improved?
3. Can gravel dikes act as flow refugia during floods?

Since the water level is expected to rise due to the gravel dikes, the interactions with already installed engineering infrastructures must also be considered:

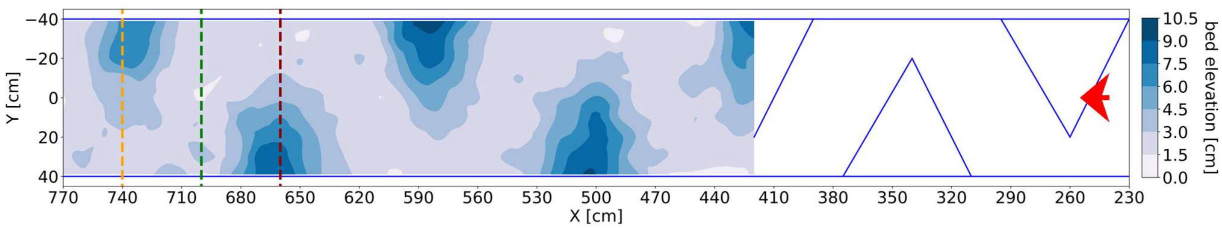
4. Is the studied method useful or bothersome to flood protection engineering?

The actual engineering feasibility of the project should be the closing question:

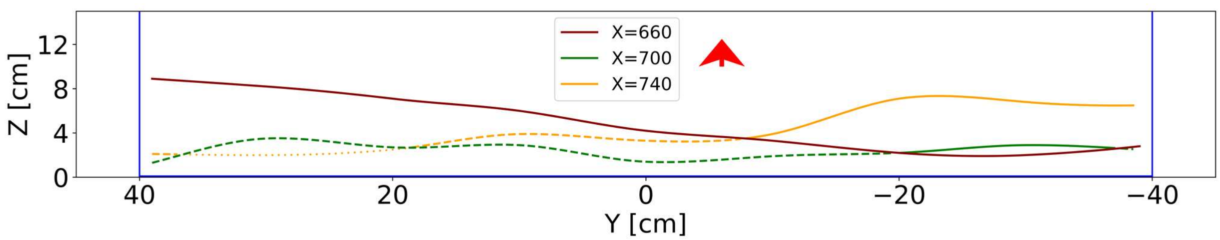
5. Does this new morphology represent a concrete alternative to river restoration?

2. EXPERIMENTAL SETUP

The experiments are conducted in a hydraulic channel with following characteristics: 15 m long, 0.8 m wide, 0.6 m lateral height and rectangular cross section. Slope is fixed at 0.01 and the installation area is long 5.4 m (channel x-coordinates 230 to 770 cm). Arrow-shaped gravel dikes are built on alternated side with maximal height of 0.08 m (uniformly decreasing from the lateral wall), length of 0.6 m and upstream and downstream width of 0.3 m and 0.35 m, respectively. Electrical-magnetic current meter (KENEK CO.,LTD model VM-806H/VMT2-400-04P) and point gauge record the flow velocity and the water depth, respectively. The data is collected along 3.5 m (channel x-coordinates 420 to 770 cm). An aerial reconstruction of both installation area and interrogation window is exposed in Figure 1a, while the profile of three selected cross sections is reproduced in Figure 1b.



a) Installation area and interrogation window from above.



b) Profile of three cross sections in the interrogation window.

Figure 1: The installation area stretches from x-coordinates 230 to 770 cm, while the interrogation window from x-coordinates 430 to 770 cm (detailed surface plot). Three cross section are highlighted in Figure 1a with dashed line and their profile is exposed in Figure 1b (the scale is not constant between figures). The red arrow represents flow direction.

Gravel with median diameter 1.65 cm is used to build the gravel dikes and to cover the installation area's surface (further grain characteristics are: d_{30}=1.49 cm and d_{90}=2.03 cm), while the rest of the experimental channel is kept empty. The installation area with gravel dikes is tested under two discharges ($Q_{channel}$=8.8 l/s and $Q_{channel}$=58.8 l/s) and a further experiment is conducted with flat gravel bed (i.e. a single layer of gravel is placed uniformly along the installation area) at $Q_{channel}$=58.8 l/s. In this Thesis, the channel scale is used to assess the flow conditions of both gravel dikes' and flat gravel bed's morphology, while the hydraulic research and the habitat suitability are described on prototype scale (15:1). Under this definition, the installation area represents a theoretical channelized river section 12 m wide (15*0.8 m) and 81 m long (15*5.4 m). The gravel dikes becomes 9.75 m wide, 9 m long and 1.2 m high with median gravel diameter d_{50}=0.248 m. The (rectangular) cross section's profile and the slope 0.01 are scale-independent. Prototype scale boulders are used during a separate experiment with living small fishes from Tama River (多摩川, Tokyo Pref.). The boulders are places like fallen dominoes along installation area's bed and are tested under two different flood discharges ($Q_{prototype}$=16.3 m^3/s and $Q_{prototype}$=104.5 m^3/s). The efficiency of the gravel to disrupt the flow profile and to act as flow refuge for aquatic animals during flood stages is tested here. The different studied discharges are exposed in Table 1.

Table 1: Bed morphology and measurement terms for each discharge in experiment (Notations in Table: A=alternative gravel dikes, F=flat gravel bed, L=living fishes).

$Q_{channel}$	[l/s]	8.8	58.8	58.8	18.7	120
$Q_{prototype}$	[m^3/s]	7.7	51.2	51.2	16.3	104.5
Bed morphology		A	A	F	L	L

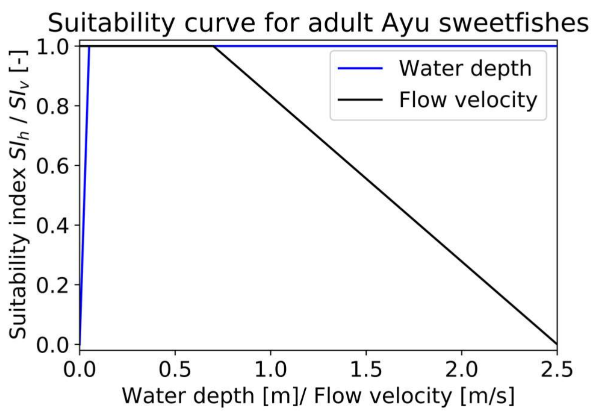
3. ANALYTICAL APPROACH

3.1 Biological approach

The habitat suitability is researched for two hydraulic parameters water depth *h* [m] and flow velocity *v* [m/s] using the cell suitability index method (*CSI* [-]). This index expresses how a specific cell *i* in the measurement grid is expected to meet the habitat requirements of the studied species with a value between 0 (not suitable) and 1 (perfectly suitable). In this Thesis, the *CSI* is defined by the minimum between the suitability indexes *SI* of the two hydraulic parameters in the cell *i*:

$$CSI_i = \min\,(SI_{\{h,i\}}; SI_{\{v,i\}}) \tag{1}$$

The *SI* value is extracted from the *suitability curve,* a species-specific plot that exposes the habitat suitability as a function of the researched hydraulic parameter (here water depth and velocity). In this Thesis Ayu Sweetfish is taken as reference species (*Plecoglossus altivelis*, Figure 2b). The used *suitability curve* is exposed in Figure 2a and is selected from field-observation based curves found in the literature research [Onitsuka 2005; Onitsuka 2009; Nakamura 1995; Japan Times article 2005/09/21; www.fishbase.org and www.fao.org].



a) The suitability curve.

b) Two adult Ayu Sweetfishes.

Figure 2: Left: the index scale of the suitability curves is the same as the *CSI*. Right: the Ayu Sweetfish is the most common fish in the Japanese rivers. Adults (length>7 cm) are plankton-eaters and grow up to 20-30 cm (Picture's source: www.bassresource.com/bass-fishing-forums/topic/16148-blue-ayu/).

The suitability of the whole flowing area is quantified with the hydraulic suitability index (*HSI*). The number of cells in the measurement grid is expressed with *n*, while A_i and A_{tot} are the flow area of the cell *i* and the total flowing area, respectively. The index scale is the same as the *CSI*.

$$HSI = \frac{1}{A_{tot}} * \sum_{i=1}^{n} A_i * CSI_i \tag{2}$$

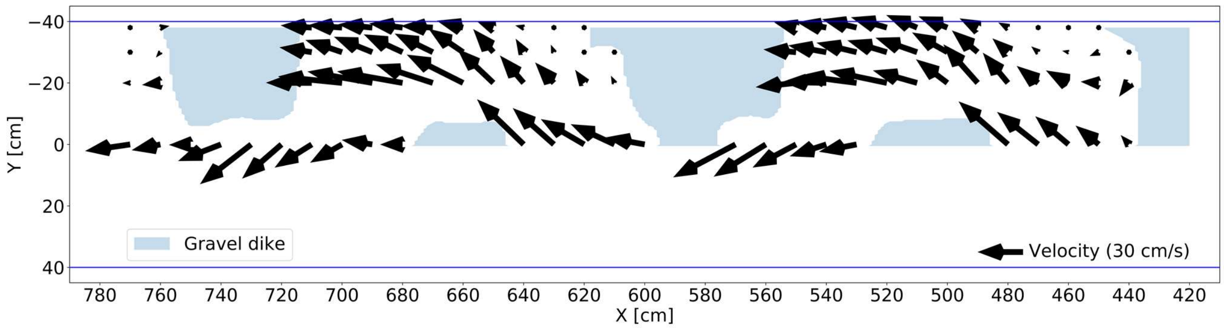
Beside water depth and flow velocity, the efficiency of gravel dikes to protect the aquatic animal during flood stages is characterized by important factors such as temporal stability of the flow field and the turbulence, with a low degree of both preferred by the most of aquatic animals. Furthermore, the holes between the boulders are expected to host smaller riverine inhabitants such as Ayu Sweetfishes.

3.2 Hydraulic approach

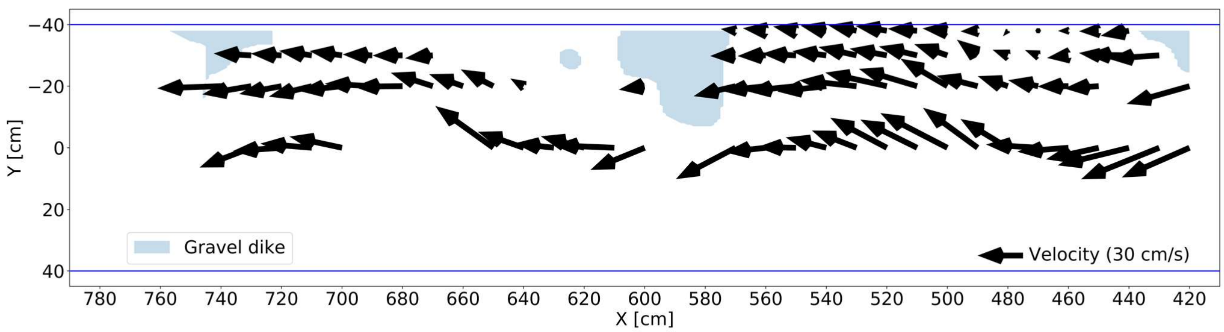
The electrical-magnetic current meter measures u_t [m/s], the longitudinal (x-direction), and v_t [m/s], the lateral velocity components (y-direction) at time *t* [s]. The turbulence intensity is assessed conduction a simple Fourier transformation on both velocity components. The resulting frequencies and absolute values allow to assess the wave character of the data set. In this Thesis, only the turbulence of the measurements within 80 cm from the upstream gravel dike is studied (i.e. x-coordinates: 420≤x≤500 cm and 580≤x≤660 cm).

The gravel's start of motion is calculated using the Shields stress θ [-]. For θ<0.03 no grain motion is expected; partial grain motion happens for 0.03≤θ<0.05, while the erosion is considered for θ≥0.05. The sediment transport is measured using the Meyer-Peter and Müller equation.

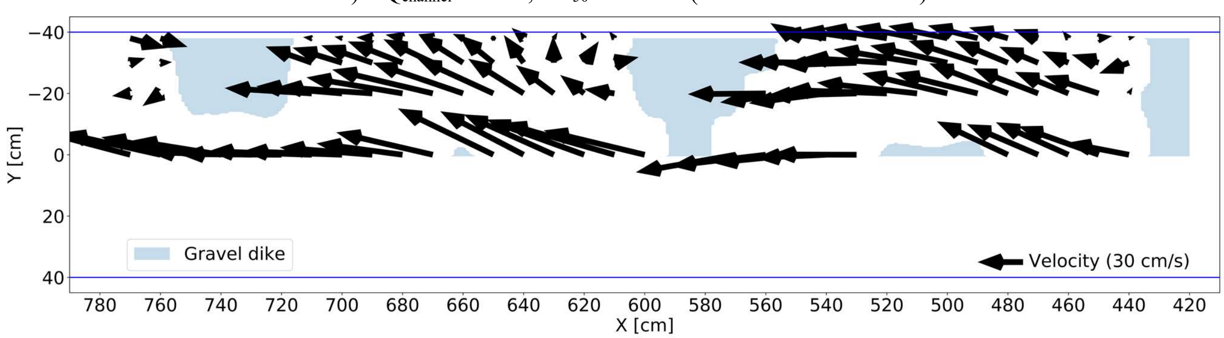
4. EXPERIMENTAL RESULTS



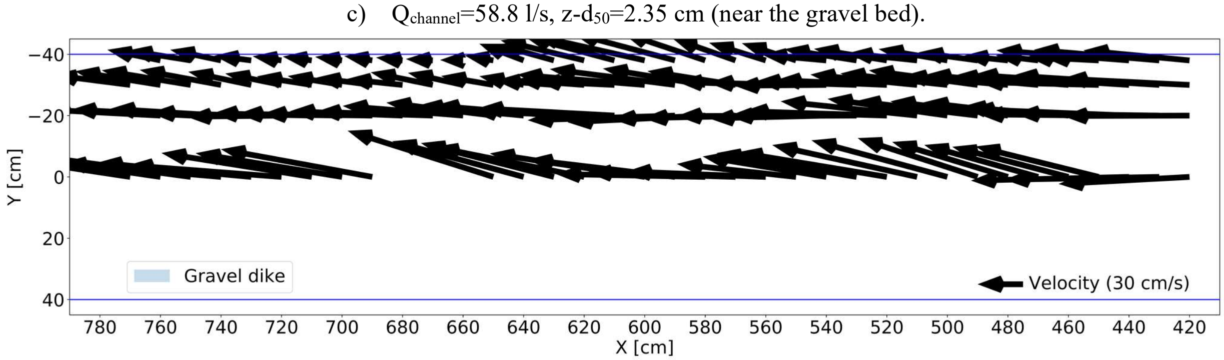
a) $Q_{channel}$=8.8 l/s, z-d_{50}=2.05 cm (near the gravel bed).



b) $Q_{channel}$=8.8 l/s, z-d_{50}=6.05 cm (near the water surface).



c) $Q_{channel}$=58.8 l/s, z-d_{50}=2.35 cm (near the gravel bed).



d) $Q_{channel}$=58.8 l/s, z-d_{50}=8.35 cm (near the water surface).

Figure 3: Plane velocity vectors at different discharge and z-d_{50} (i.e. measurement elevation - median grain diameter). The arrow in legend references longitudinal velocity u=30 cm/s in flow direction (velocities are scaled 2:1 to the channel's (x,y)-coordinates.

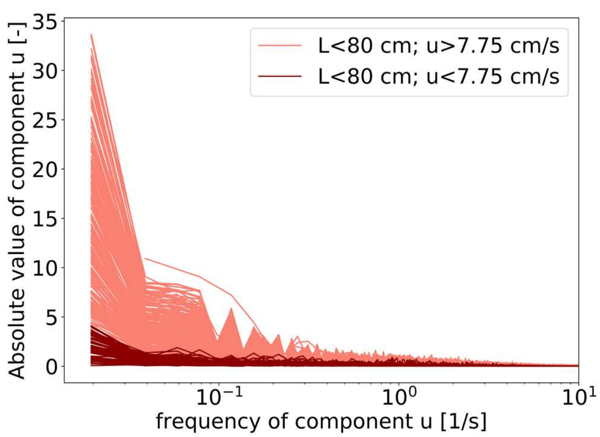
4.1 Flow characteristics around gravel dikes

The gravel dikes force the flow to meander, in particular near the bed, where the highest deviation from the straight longitudinal flow are observed. The meandering behavior appears to become less evident near the water surface and with increasing discharge. At $Q_{channel}$=8.8 l/s some gravels emerge from the flow and the water surface is flat along the interrogation window, with very small increase right upstream of a gravel dike. At $Q_{channel}$=58.8 l/s, two important changes are observed: firstly on channel's sides (y-coordinates ±38 cm) the water surface profile is flat and the backwater effect disappears; secondly large waves are found in the center of the channel (y-coordinate 0 cm). The water depth rises because of the increased discharge and the gravel dikes are now fully submerged.

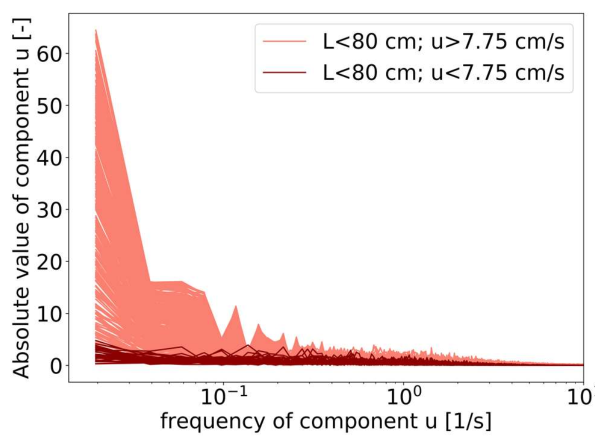
Very similar observations are assessed from the plane velocity vectors reported Figure 3. The meandering behavior of the flow around the gravel dikes is confirmed and recorded in all the studied discharges. Furthermore, downstream to each gravel dike a pocket of almost still water is generated, generally between x-coordinates 440 and 480 cm and again from 600 to 640 cm. There, the flow is much smaller and in some cases even moves backwards (cf. Figure 3a and Figure 3c). Those areas are greatly reduced near the water surface at $Q_{channel}$=8.8 l/s (Figure 3b) and have completely disappeared at $Q_{channel}$=58.8 l/s (Figure 3d), where the flow is significantly faster and straighter.

At smaller discharge, no particular changes are observed between the vertical velocity profiles along the interrogation window. The velocities are rather constant at different depths, decreasing from 60 cm/s in the channel's center to 20 cm/s near the side walls. This reduction highlights the interference of the gravel dikes. At larger discharge the differences become even stronger: from the center to the side of the channel, the maximal velocity values on the water surface shift from 100 cm/s to 20 cm/s just downstream of a gravel dike, while the profile evolve from logarithmic (similar to what is expected inside prismatic cross-sections) to two-layer flow.

Figure 4 exposes the wavy behavior of the longitudinal velocity component *u* per studied discharge (the semi-logarithmic display is used to highlight the smallest frequency values on the horizontal axis). Simple Fourier transformation is applied on the measurements as far as 80 cm downstream of a gravel dike. Further distinction is done to the data with mean longitudinal velocity $\bar{u}$≤7.75 cm/s (i.e. $\bar{u}$≤0.3 m/s in prototype scale).



a) $Q_{channel}$=8.8 l/s



b) $Q_{channel}$=58.8 l/s

Figure 4: Turbulence intensity per discharge and mean longitudinal velocity component *u*.

The flow in both discharges can be described as low frequency wave and the absolute value's maximum span appears directly correlated to the discharge size. The threshold velocity $\bar{u}$≤7.75 cm/s is chosen as the general preference for Ayu Sweetfishes (cf. Figure 2a and Sub-chapter 4.3). The measurements under this threshold appear to possess a very stable flow field with constant long term mean velocities.

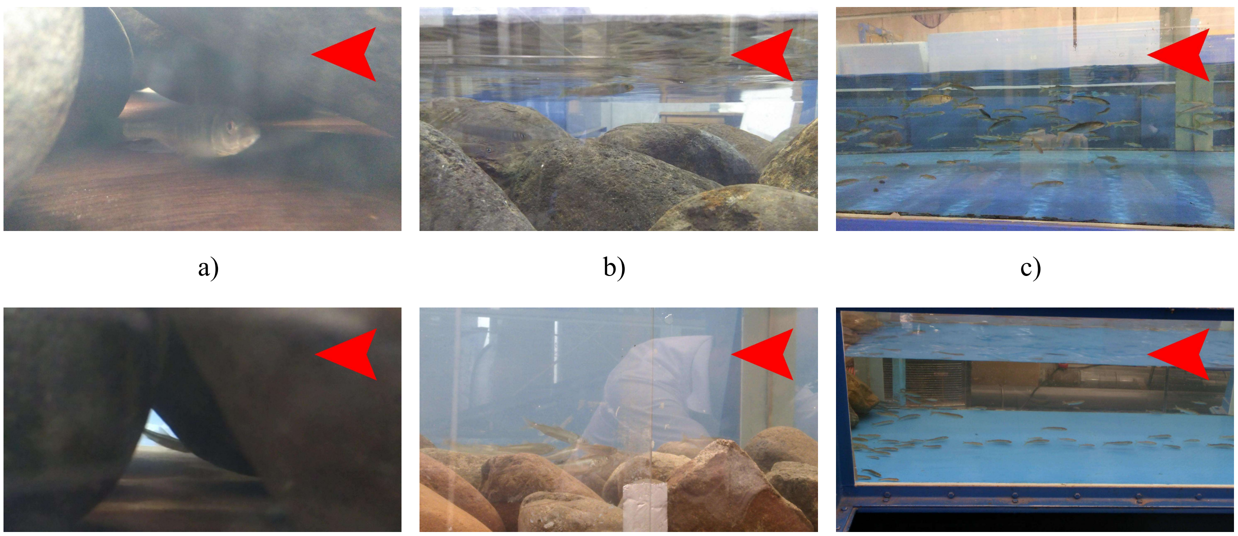
The shear stress appears to increase with discharge in both mean value and standard deviation. The strongest stresses are generally found near the water surface, although in none of the studied discharges, the erosion of the gravel dikes is observed: at $Q_{channel}$=8.8 l/s no notable movement is reported, while at $Q_{channel}$=58.8 l/s some grain is seen shaking in the channel's center.

4.2 Comparison between flat bed and gravel bed with alternative gravel dikes

The strongly undulating water surface that is generated by the alternative gravel dikes is completely lost above flat gravel bed morphology. The flow characteristics are constant at all measured channel's coordinates: the planar flow heterogeneity disappears, while neither the meandering behavior nor the pockets with almost still water on the downstream side of the gravel dikes are observed when the latter are removed. The water depth sinks and on the surface the water moves straight and constant around 100 cm/s. The vertical velocity profiles are logarithmic similar to normal flow. The smallest velocities are measured near the gravel around 60 cm/s. The calculated shear stresses are around half of the values observed around the gravel dikes as result to the more homogeneous uniform flow. The introduction of gravel dikes in the gavel bed appear to not necessarily improve its stability.

4.3 Fish activities in stacked boulders

About an hundred of small size fishes of different species (the majority of which are Ayu Sweetfishes) are released into the experimental channel filled with prototype size boulders. The holes generated between the rocks have pyramidal shape and general volume of (15...25)x10x10 cm^3 (Width:Depth:Height). The behavior of the fishes under two flood discharges is exposed in Figure 5.



a) b) c)

d) e) f)

Figure 5: Living fishes' behavior at $Q_{prototype}$=16.3 m^3/s (Figure 5a, Figure 5b and Figure 5c) and $Q_{prototype}$=104.5 m^3/s (Figure 5d, Figure 5e and Figure 5f). Left column: in the holes between the grains; center column: above the gravel; right column: upstream of the installation area. The red arrow gives the flow direction.

The holes between boulders are big enough to host the aquatic animals, as shown in Figure 5a and Figure 5d. Fishes are also observed above (Figure 5b and Figure 5e), upstream (Figure 5c and Figure 5f) and downstream from the gravel. The majority of the school swims outside the installation area, in different ways depending of the discharge: at $Q_{prototype}$=16.3 m^3/s the fishes move in all directions in a chaotic manner (Figure 5c); at $Q_{prototype}$=104.5 m^3/s, they relocate themselves closer to the channel's bottom (or the gravel surface) forming single lines (Figure 5f).

At this latter discharge, very similar velocity of 0.3 m/s are measured at the same time right above the boulders and near the channel's bottom, upstream of gravel. Since most of the fishes are observed in those two areas, this specific value appears to be the favored velocity (cf. Sub-chapter 4.1). The flow speed reduces from 0.6 m/s near the surface to 0.07 m/s inside the boulders (i.e. 90% smaller), thus confirming the hypothesis of gravel's efficiency to disrupt the flow field. Because most of the fishes swim outside the installation area, its performance as flow refuge during flood stages is harder to assess. Future research should further force the fishes into hiding inside the boulder's holes, for example by increasing the flood discharge.

5. DISCUSSION

5.1 Stability of river bed converted in prototype during flood stages

Scaling up the prototype, the experimental channel can be compared to a 12 m wide, 1% steep river section, while the median gravel diameter is d_{50}=0.248 m. The studied discharges are converted to $Q_{prototype}$=7.7 m^3/s and $Q_{prototype}$=51.2 m^3/s. As described in Sub-chapter 4.1, for none of the studied floods the Shield stress threshold for erosion θ=0.05 is reached around the gravel dikes. At $Q_{prototype}$=51.2 m^3/s the calculated value of θ =0.044 is classified as *partial motion*, but no sediment transport is found applying the Meyer-Peter and Müller equation. At same discharge and flat gravel bed the Shield stress is θ =0.029, safely in the definition of *no motion*. For both gravel bed morphologies, The results suggest that the erosion flood would start around $Q_{prototype}$=155 m^3/s, well above the hydraulic capacity of the experimental channel of $Q_{prototype}$=105 m^3/s. The lack of erosion data limits the assessment of resilience and lifespan of the gravel dikes. Future research must expand the data collection, comprehending more than one discharge per bed morphology and effective gravel erosion.

5.2 Possibility of refuge for fishes behind gravel dikes during flood stages

The habitat suitability index HSI for adult Ayu Sweetfishes are exposed in Figure 6 in relationship with discharge and elevation z-d_{50}. The biological research shows very satisfying results; the introduction of gravel dikes in the bed significantly improves the habitat quality when compared to flat gravel bed morphology. Up to 60-80% of the flow area is assessed suitable at $Q_{prototype}$=7.7 m^3/s around gravel dikes, well above the 30% expected near the flat gavel bed at $Q_{prototype}$=51.2 m^3/s.

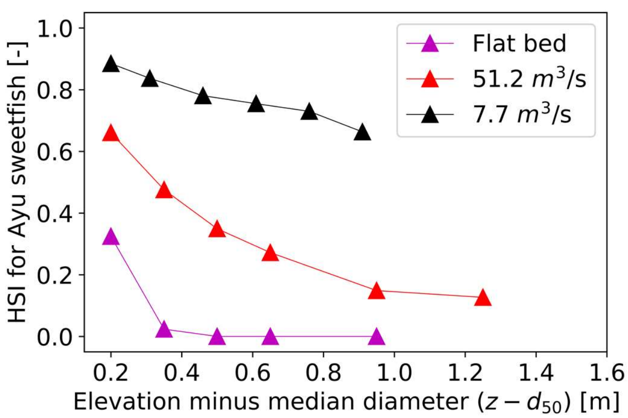


Figure 6: Habitat suitability for adult Ayu Sweetfishes by changing elevation z-d_{50} and discharge. By flat gravel bed (magenta) the discharge is $Q_{prototype}$=51.2 m^3/s.

Several remarks have to be addressed at this point. Firstly, this Thesis focuses only on hydraulic conditions, without considering other important factors for the species survival such as water temperature, turbidity, oxygen or nutrient availability. The accuracy may be improved by considering more parameters and suitability curves, although the habitat suitability method itself is not free of uncertainties. By neglecting the seasonal variations or the single individual preferences (e.g. related to size and age), the problem may become oversimplified. Taking into account the many critics, the *HSI*'s method remains a quick and straight-forward instrument to estimate the ecological state of a river. Considering the complexity of the natural processes, some simplification is necessary. At the current stage, the gravel dikes' design is rough with large room for improvement, therefore, definitive accurate assessments are not a priority and the *HSI*'s method meets the required level of detail.

5.3 Flood control due to the installation of alternative gravel dikes during flood stages

At same discharge $Q_{prototype}$=51.2 m^3/s, the introduction of gravel dikes causes the mean water surface to rise (in prototype scale) 0.32 m when compared with flat gravel bed. Taking into consideration the fixed banks' height of rivers, this difference would implicate a reduction of the channel’s capacity, ultimately resulting in higher overflowing risk. Those results represent a major obstacle to this Thesis' project, especially when considering that the gravel dikes aim to improve the river ecology in urban areas. Future research must focus on reducing the hydraulic impact of the gravel dikes to the natural cross section equilibrium. Proposed alternatives could be to reduce the gravel size to lower the erosion resistance, to redesign the dikes' shape or to increase the distance between dikes.

6. CONCLUSIONS

The introduction of gravel dikes in channelized river cross sections results in remarkable changes in the flow characteristics. The flow heterogeneity is increased and pockets with almost still water are generated on the downstream side of each gravel dike. Those factors lead to a significant boost the riparian ecological value. On the other hand, the original riverine hydraulic is seriously modified, causing undesirable side effects. The decreased velocity causes the water surface to rise and the consequent higher risk of flooding seriously jeopardizes this project's applicability in urban river cross sections. Future research is warmly suggested, with particular focus on reducing the hydraulic frictions.

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