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Effect of vegetation on suspended sediment transport: Turbidity analysis

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Abstract: The resistance to flow in canals and rivers is strongly influenced by the roughness of the bottom, the presence of obstacles and vegetation. This phenomenon is closely linked to the risk of flooding, since it increases energy dissipation and raises water levels.

In this context, an experimental study was carried out with the aim to process and analyze the effect of vegetation on the transport of suspended particulate matter from sediments injected upstream by monitoring changes in turbidity as a function of time and quantifying the balance of transported sediments. The experimental set-up consists of an open-air rectangular glass channel 10m long, 0.8m high and 0.6m wide. As the slope of the channel is adjustable, two slopes were chosen: 1% and 5%. A (stable) water circulation loop was provided by an electric pump delivering a variable flow rate. The bed was covered with dense artificial vegetation in the longitudinal direction of the flow. Two experimental series were carried out, the first with a fixed quantity of sediment injected and a variable flow rate, the second with a variable quantity and a fixed flow rate. The two series were reproduced at slopes of 1% and 5%.

The results show a decreasing variation in turbidity as a function of time from upstream to downstream in the presence of vegetation. The increase in flow and slope favors the removal of sediments from the vegetation and thus increases turbidity, which reduces the quantities retained by the vegetation, thus favoring sediment erosion and deposition.

1. Introduction

Over the last few decades, the quality of the watercourses in the Medjerda catchment area, like that of most rivers, has deteriorated. This deterioration in water quality is associated in particular with the input of numerous pollutants (Muste *et al.* 2017), and is also largely controlled by the behavior of suspended solids (SS). Once introduced into watercourses, pollutants are distributed between the various compartments of the aquatic system: dissolved, particulate and organic phases. However, it is considered that 99% of pollutants are stored in sediments. Sediment can therefore act as a sink for contaminants, since sediments can be heavily polluted and can retain traces of old pollution, and they can also be a pollution source when they are resuspended (Simpson *et al.*, 2016; Belbachir *et al.*, 2013). Pollutants contained in sediments therefore migrate within the river basin (Zebracki *et al.*, 2008; Brahimi *et al.*, 2015). This possibility makes the management of polluted sediments very tricky.

The transport of many pollutants in rivers is associated with the suspended particles mobilization, which generally occurs during floods (Mingfu *et al.*, 2017). Quantifying the mass of sediment transported is therefore necessary to better understand these transfers (Thollet *et al.*, 2013). The total suspended sediment quantity in rivers can be monitored by measuring turbidity. Turbidity is an optical property caused by the scattering of light rays by suspended matter, which may be composed of sand, silt, clay, particulate organic matter, plankton and other micro-organisms (Merten *et al.*, 2014); it can be used as an indicator of the total concentration of suspended particles in the water (Romdhane *et al.*, 2018).

It has also already been recognized that the vegetation development in river beds and on the banks of natural or artificial watercourses has the capacity to eliminate fine solid pollutants by retention and absorption (Romdhane *et al.*, 2019a; Laita *et al.*, 2024). The reduction in flow velocity by vegetation leads to changes in sediment transport and deposition, thereby modifying river morphology (Vargas-Luna *et al.*, 2015). Solid pollutants are generally deposited in the vegetated bed (Kazem *et al.*, 2021), seep into the far field and accumulate in crops, threatening human health, or are transported again during flood events, causing structural problems (Akhtar et al., 2023; Sui *et al.*, 2023).

In this study we use water turbidity assessment to analyze the solid particle propagation over vegetated open channel beds, the evolution over time and space, and the relationship with the flow and slope variations.

2. Methodology

2.1 Experimental setup

The experiments were carried out in an artificial channel at the Laboratory of water science and technology at the National Institute of Agronomy of Tunisia, which is used to study free-surface and loaded flows in a controlled environment **(Figure 1)**. This is an experimental facility comprising an open- air rectangular channel designed for the study of free-surface and loaded flows, 10m long, with a rectangular cross-section of 0.80x0.60m, with a variable gradient and operating in a closed circuit. This artificial channel can be used to test a variety of different flow conditions and slope scenarios.

Figure 1. The INAT experimental channel (Length: 10m; width: 0.8m; height: 0.6m)

2.2 Sediments proprieties

The relationship between suspended particulate matter and sediment diameter is complex and depends on a number of factors (Xiaonan *et al.*, 2021), including the particle composition, density, slope, and flow velocity. However, in general, smaller particles are more likely to be suspended in water than larger particles (Fan *et al.*, 2023). This is because smaller particles have a lower settling velocity and they are more easily carried by the flow.

The following equations **(Eqn. 1, Eqn. 2)** can be used to calculate the settling velocity of a particle in water:

Laminar regime $R_e < 1$

$$V_c = \frac{(\rho_s - \rho) g d^2}{18\mu} \qquad \textbf{Eqn. 1}$$

Turbulent regime $R_e > 1$

$$V_c = \sqrt{\frac{4}{3} g d\,(s-1)\frac{1}{C_d}} \qquad \textbf{Eqn. 2}$$

where:

- V_c is the settling velocity of the particle
- $\rho_s$density of particle
- ρdensity of the water + particle mixture in suspension
- g is the gravity acceleration
- d is the particle diameter
- μ is the water dynamic viscosity
- $s = \frac{\rho_s - \rho}{\rho}$sediment density
- R_e Reynolds number
- $C_d$drag coefficient

This equation shows that the particle settling velocity increases with the particle diameter and density. It also shows that the settling velocity decreases with water viscosity. The flow velocity is also an important factor that affects the suspended matter transport. In fact, higher flow velocities can keep larger particles suspended in the water column (Box *et al.*, 2019).

The condition for setting a solid particle on the bottom in motion is assessed on the basis of equilibrium between the forces applied to it (Tsuda *et al.*, 2013), but too often the values of the parameters defining this threshold are very widely dispersed. By increasing the water velocity over a bed with aggregates, until a certain critical value, we can see that the grains making up the bottom start to move, giving rise to a solid flow. Solid transport is therefore a threshold phenomenon.

This is why we chose natural siliceous quartz to ensure that the sediments were transported in the form of individual particles that did not exhibit cohesive behavior. The quartz material chosen for the experiment was distributed after sieving into classes of precise particle size.

Particle size distribution (PSD) is a measurement of the relative abundance of different particle sizes in a sediment mixture. It is typically expressed as a cumulative frequency distribution, which shows the particles percentage that are smaller than a given size. PSD is an important property of sediment mixtures because it influences their behavior in transport, deposition, and erosion (Lepesqueur *et al.*, 2019). The weight of each grain class is determined from the results of sieving the following figure **(Figure 2)** shows the narrow particle size distribution and complex geometry of the chosen sand. The particles are flat to angular in shape and have a solid density (ρ_s) of 2.65 g/cm3 and a median diameter (d_{50}) of 118 µm. Consequently, the trend in the particle size distribution of our sample is relatively acceptable in proportion to the gentle slope of our channel with the vegetation presence.

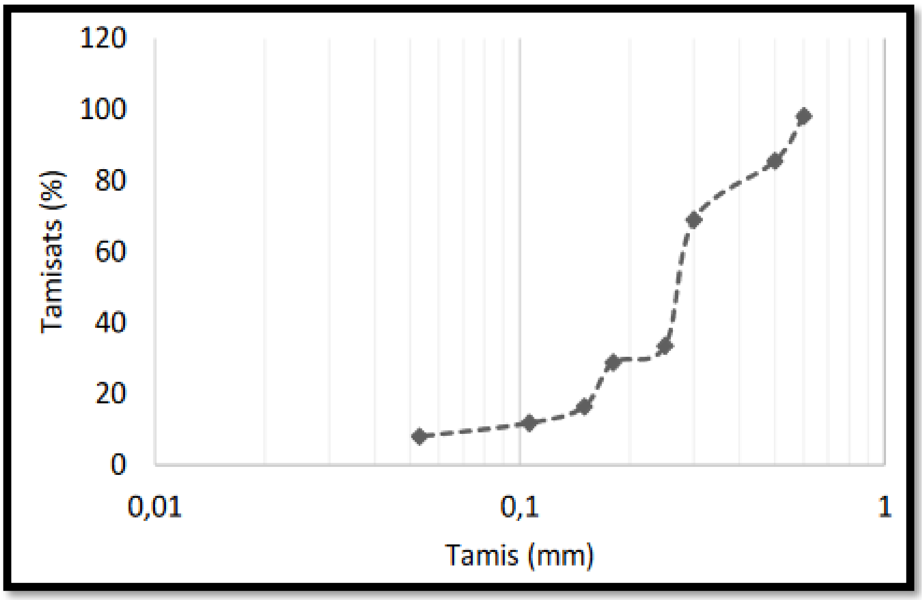

Figure 2. Particle size distribution of injected sand

2.3 Vegetation

Artificial vegetation is used in an experimental open channel flow to study the vegetation effects on the flow characteristics, such as velocity, turbulence, and sediment transport. It can be used to simulate a variety of natural vegetation types, such as emergent vegetation, submerged one, and riparian one.

One of the main advantages of using artificial vegetation in experimental open channel flow studies is that it allows greater control over the vegetation parameters, however, we can control the vegetation height, density, and flexibility. This allows them to isolate the effects of individual vegetation parameters on flow characteristics.

To this end, the bed was covered with dense artificial vegetation 0.8m wide in the longitudinal direction of the flow. It was installed 2m downstream of the outlet and spread over 4min the central part of the channel. The stems are 4cm high **(Figure 3)**. This artificial cover was chosen to represent flexibility and reconfiguration behavior similar to that of the natural grasses found on the middle bed and floodplain. This vegetation will reveal a lower velocity in the zone close to the bed than in the vertically distant zone, which favors the sedimentation phenomenon.

2.4 Experimental Procedure

Since turbidity measurement is often used to assess the quantity of suspended solids in water, it can be used as an approximation for a number of specific pollutants. To this end, an environment similar to a natural watercourse, with vegetation and sediment at the bottom, was created in a rectangular canal in the laboratory. The aim is to process and analyze the vegetation effect on the suspended particulate transport of sediments injected upstream, and to monitor their evolution using turbidity measurements.

So, the higher the turbidities, the less light can penetrate the water column, and this can have a negative impact on aquatic life and human use of the water body (Jarrod *et al.*, 2020)). Turbidity can also reduce the water bodies usability for recreation and safety purposes (Davies-Colley *et al.*, 2001), it can also give water a foul odor and make it unpleasant to drink. Currently, there are various pieces of equipment and instruments (Garcia-Renteria *et al.*, 2001), such as turbidity tubes, Secchi disks, spectrophotometers, turbidimeters which are used to measure the water turbidity (Marimon *et al.*, 2021); Turbidity measurement results are generally expressed in turbidity units (e.g. Nephelometric Turbidity Units - NTU).

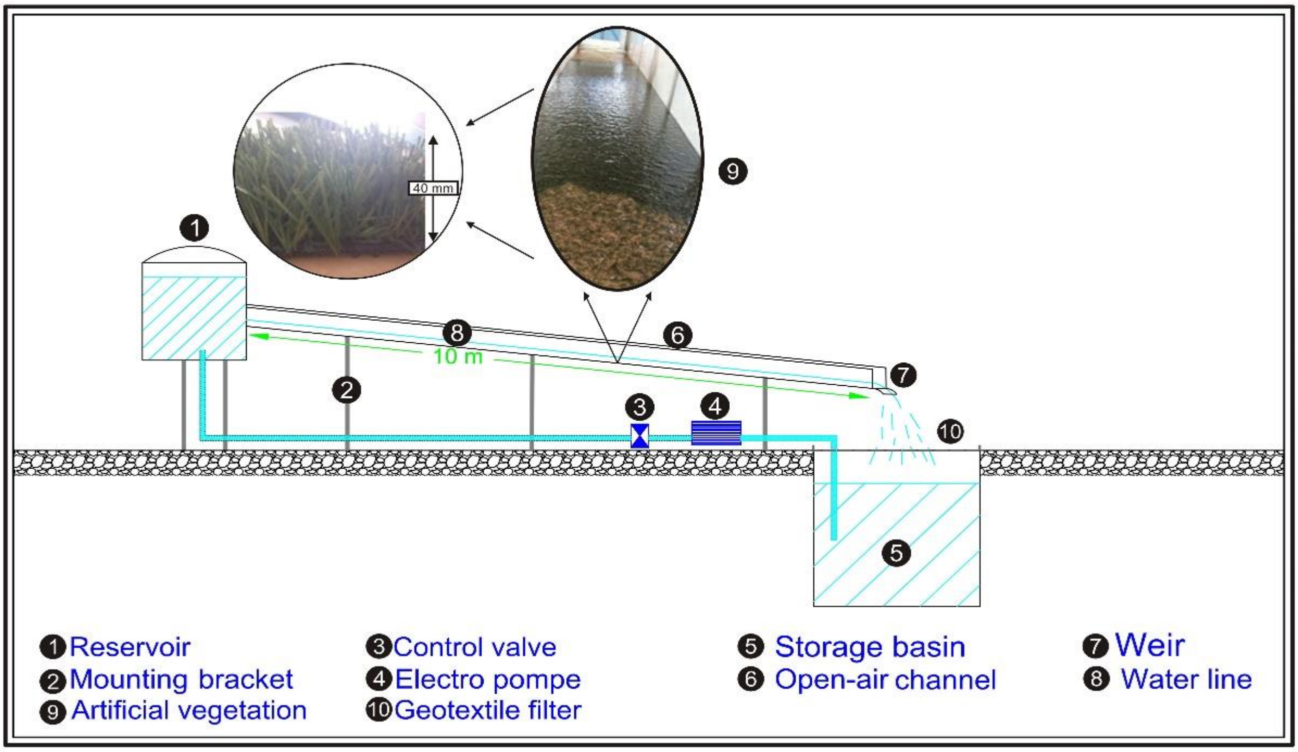

Figure 3. Experimental equipment's and artificial vegetation used

In our experiments, turbidimeters are used to monitor and control water quality **(Figure 4)**. Generally, they use a light source, such as a laser or LED, to emit a beam of light through the water sample. It is a device that measures the cloudiness or haziness of a liquid. It is based on the principle of light scattering. When light passes through a liquid with suspended particles, some of the light is scattered by the particles. The scattered light quantity depends on the concentration and size of the suspended particles.

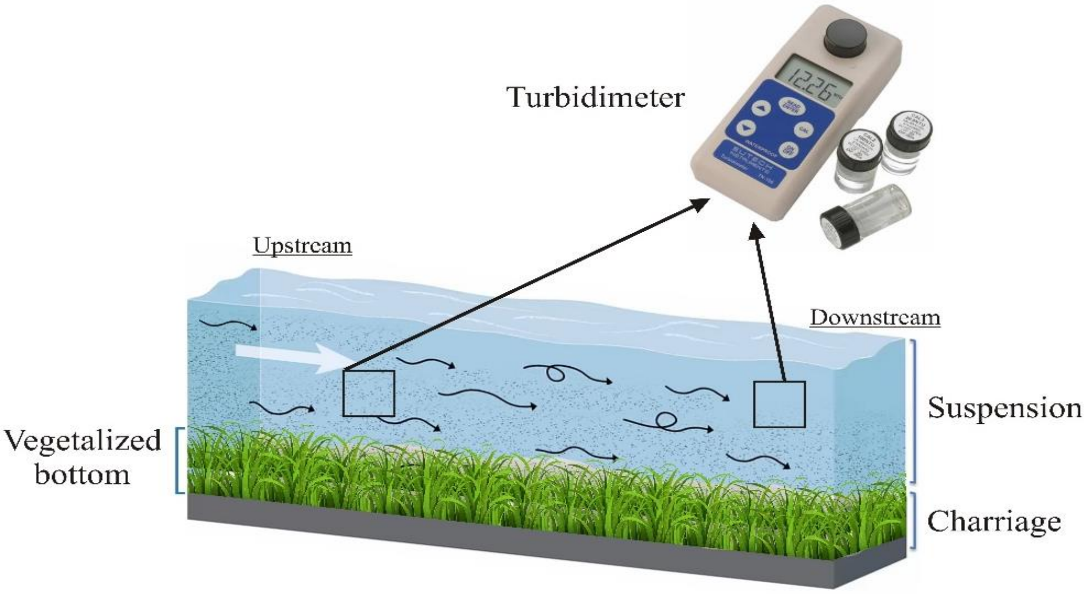

Figure 4. Turbidity measurement procedure

Experiments were carried out on a slope set at 1%, where different quantities of sand were injected upstream at different flow rates, and then the corresponding upstream and downstream turbidities and quantities of sand retained by the vegetation were determined.

Two sets of experiments were carried out:

- For the same flow rate, we varied the quantity of sediment injected upstream **(Table 2)**
- To inject the same quantity of sand upstream, the flow rate was varied **(Table 1)**

Table 1. Variation in flow rate for the same quantity of sand injected upstream

Flow rate (l/s)	10	15	20	25	30
Quantity of sand injected upstream (kg)	2	2	2	2	2

Table 2. Variation in the quantity of sand injected upstream for the same flow rate

Quantity of sand injected upstream (kg)	0.3	0.5	0.7	1	2
Flow rate (l/s)	15	15	15	15	15

A geotextile will be placed downstream on the basin in order to recover the quantity of sand leaving the channel, and by measuring the difference between the initial weigh to the geotextile and the final weight, we can determine the quantity of sand trapped in the vegetation. Geotextile filtration is used with the aim of ensuring clear water in our closed system, it prevents the solids from re-entering tanks before it is discharged into vegetalised channel.

3. Results and Discussion

3.1 Series 1: different flow rates and a fixed injected sand quantity

The following table **(Table 3)** summarizes the details relating to the experiments carried out with an upstream injected sediment quantity and with different flow rates. In **Figure 5**, we have reproduced the turbidity profiles as a function of time for the upstream and downstream turbidities for different flow rates and for a quantity of sand injected of 2 kg.

Table 3. Experiments carried out with a given quantity of sediment injected upstream and with different flow rates

Flow Q (l/s)	Poured sand quantity (kg)	Initial geotextile mass (g)	Final geotextile mass (g)	Released sand quantity (g)	Retained sand quantity (g)
10	2	490	510	20	1980
15	2	490	520	30	1970
20	2	490	540	50	1950
25	2	490	535	45	1955
30	2	625	660	35	1965

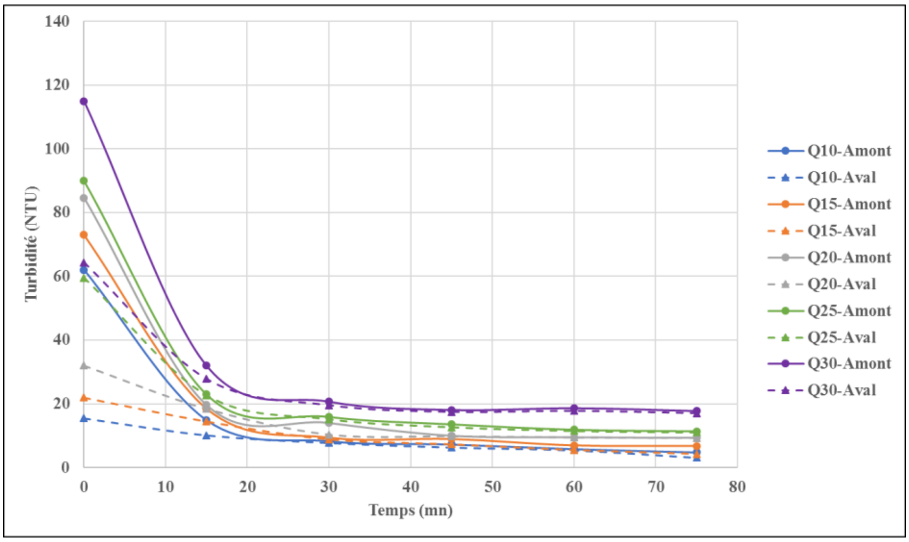

Figure 5. Comparison of upstream and downstream turbidities for different flow rates and for a quantity of sand injected of 2 kg.

In these experiments, it was found that the upstream and downstream turbidities of the vegetated system decreased over time. It was also shown that the downstream turbidity is lower than the upstream turbidity at the first moment of the experiments, but after a certain time, which is the steady state, the concentration tends towards a constant value. This is due to the fact that as soon as the sediment is injected, a quantity of sand will first come out, then the rest will be trapped in the center of the vegetation, and will gradually come out, until stability is reached. It should also be noted that as the flow rate increases, so does the velocity of the flow, and therefore the sediments retained in the vegetation leave the environment, thus increasing turbidity, because the distribution of the suspended sediments deposited is the result of the spatial variation in the concentration of sediments in the flow and the interaction between the transported materials and the bed (Sharpe *et al.*, 2007).

3.2 Series 2: Different sand injected quantities and a fixed flow

The following table **(Table 4)** summarizes the details relating to the experiments carried out with a constant flow and with different upstream injected sediment quantities. In **Figure 6**, we have reproduced the turbidity profiles as a function of time for the upstream and downstream turbidities for the different quantities of sand injected and for a flow rate of 15 l/s.

Table 4. Experiments carried out at constant flow for different quantities of sediment injected upstream

Flow Q = 15 l/s				
Poured sand quantity (g)	Initial geotextile mass (g)	Final geotextile mass (g)	Released sand quantity (g)	Retained sand quantity (g)
300	530	533	3	297
500	520	525	5	495
700	515	525	10	690
1000	505	520	15	985
2000	490	520	30	1970

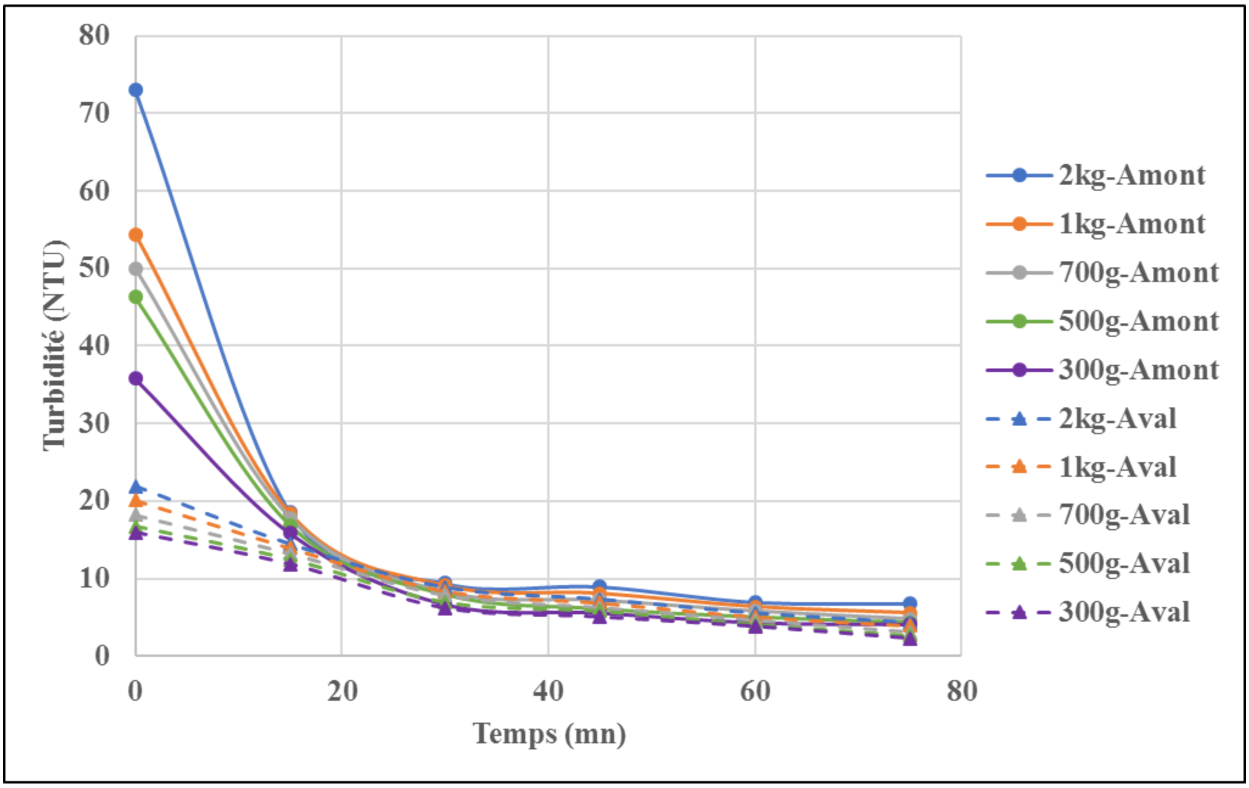

Figure 6. Comparison of upstream and downstream turbidities for the different quantities of sand injected and for a flow rate of 15 l/s

We found that the greater the quantity of sand injected upstream, the greater the quantity retained in the vegetation for the same flow rate of 15 l/s, and the greater the quantity of sediment trapped in the downstream geotextile. In addition, for a quantity of sand injected of 300g, only 3g of this quantity left the vegetation, whereas for 2kg injected only 30g left; this

may explain the change in turbidity in figure 4: the more the quantity injected increases, the more the turbidity increases.

3.3 Slope effect (comparison between S= 1% and S=5%)

The aim was to highlight sediment transport capacity in the presence of vegetation but with different slopes. This work was compared to a previous study with the same flow conditions except for the longitudinal slope of the bottom of the channel, which was different. The slope was greater, at 5%. (Romdhane *et al.*, 2019b). In **Figure 7**, we have reproduced the turbidity profiles as a function of time for the two slopes and with the same flow conditions. We can see that as the gradient increases, turbidity in the watercourse decreases for increasing flow rates. This is because higher flow rates keep particles suspended instead of letting them settle to the bottom. At lower flow rates, particles have more time to settle out of the water, which reduces turbidity. It is clear that an increase in slope automatically leads to an increase in flow velocity. On the other hand, we know that when the velocity increases, convective transport also becomes important, and as are sult the quantity of sediment injected upstream quickly exits the medium, unlike flow with a lower slope, a decrease in velocity and therefore convective transport, which leads to a decrease in water turbidity. This is illustrated in our experiments by as low propagation of turbidity and a slow exit of green sediment downstream, in the case of a low slope, i.e. the water remains more turbid in this case.

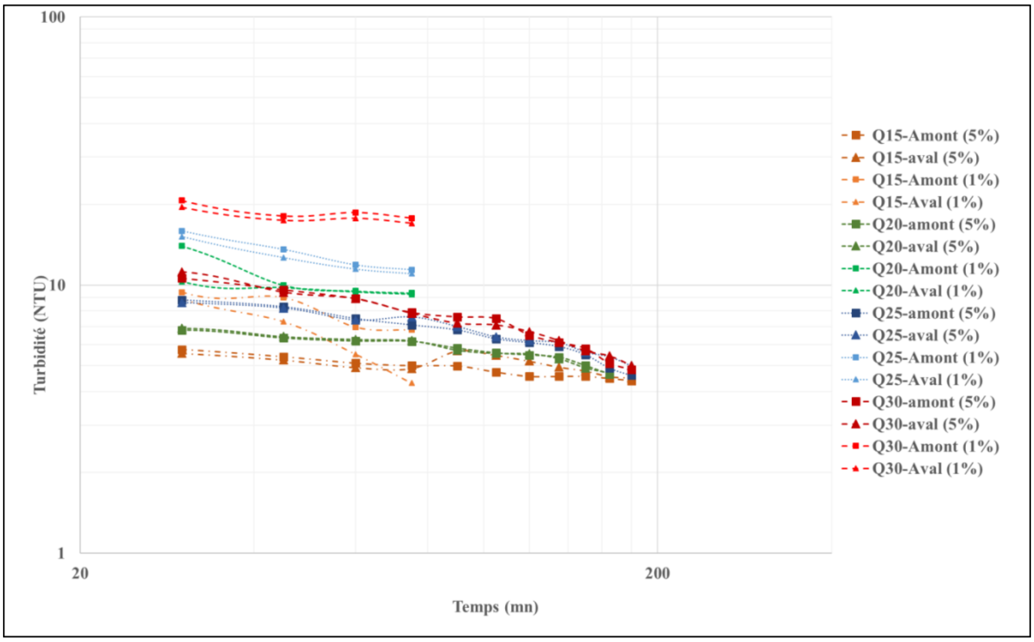

Figure 7. Comparison of turbidities upstream and downstream for the two slopes 1% and 5% (different flow rates and for a quantity of sand injected of 2 kg).

Also, it is logical to note that the sediment quantity trapped in the vegetation is greater for the low slope of 1%, whereas the sediment quantity leaving the vegetation is greater for the high slope of 5%. This is because vegetation is more effective at trapping sediment on gentler slopes. On a steeper slope, the water flows more quickly and has more energy. This energy can resuspend sediment that has been trapped by vegetation, causing it to leave the vegetation and continue downstream. On a gentler slope, the water flows more slowly and has less energy. This makes it more difficult for the water to resuspend sediment that has been trapped by vegetation. This clearly shows the evolution of turbidity on the two slopes, that is a reflection of the different sediment trapping and transport rates. On the low slope, the sediment trapping rate is high and the sediment transport rate is low, this results in low turbidity levels. On the high slope, the sediment trapping rate is low and the sediment transport rate is high, this results in high turbidity levels.

Conclusion

The results of the first series of experiments showed a decreasing variation in turbidity as a function of time from upstream to downstream in the presence of vegetation. The downstream turbidity is lower than the upstream turbidity at the start of the experiments, but after a while it tends to stabilize. This is due to the fact that when the sediment is injected, a certain amount of sand will first pass through, then the rest will be trapped in the center of the vegetation, and will gradually emerge, until it stabilizes.

The results of the second series of experiments also showed that the increase in flow favored the removal of sediments from the vegetation and thus increased turbidity, which reduced the quantities retained by the vegetation. This is logical because velocities are higher, and for low flows the quantities deposited are greater. It can therefore be concluded that vegetation has a strong influence on flow structure, increasing resistance to flow and reducing velocities, which favors sediment erosion and deposition. This explains the changes in river morphology and the reduction in bed cross-sections at low flows. This narrowing reduces the sediment transport capacity in the event of flooding.

The slope also plays a major role in sediment transport: the lower the slope, the more sediment is trapped and deposited in the vegetation. We also note that when the slope decreases, turbidity in the water increases for the different flow rates.

It has been found that dense vegetation strongly favors the deposition of sediments, especially from reliable slopes. This sediment acts as a sink for other types of contaminants and pollutants, constituting a source of pollution when it is resuspended. As a result, these polluted sediments subsequently influence the quality of crops, groundwater and water tables, as well as the quality of drinking water, and therefore threaten human health. They can also cause ecological disruption to the ecosystem, as well as damage to infrastructure during flood events.
This is because the transport and deposition of fine sediments have important consequences for determining water and environmental quality and, consequently, for assessing the possible actions needed to reduce pollution (Walter *et al.*, 2018).

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