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Assessing Nature-Based and Classical Engineering Solutions for Flood-Risk Reduction in Urban Streams

Olga Ourloglou[1], Konstantinos Stefanidis[2], Elias Dimitriou[2*]

[1] Hellenic Open University, School of Science and Technology, Parodos Aristotelous 18, 26 335, Patra, Greece

[2] Hellenic Centre for Marine Research (HCMR), Institute of Marine Biological Resources and Inland Waters, 46.7 km of Athens, Sounio Ave., 19013 Anavyssos, Attiki, Greece

* Corresponding author's e-mail: elias@hcmr.gr

ABSTRACT

Urbanization of stream ecosystems with the purpose of managing the flash-flood events is nowadays considered responsible for habitat loss and alteration of the natural flow regime with severe implications for the ecosystem functioning. Unsurprisingly, the river scientists have started seeking alternative options inspired from nature for mitigating the flood-risk and maintaining the stream at its natural state. With this article the authors demonstrate the effects of a nature-based solution (NBS) for managing an urban stream based on the use of bioengineering materials (e.g. plants) and the implementation of the actions that restore the stream to its natural form (e.g channel widening). The HEC-RAS software was employed to simulate the flow and hydraulic components of an approximately 800m long reach of an urban stream under three different scenarios of flood risk management with a design flow set to 400 m^3/s. The first scenario was based on the current situation of the stream, the second scenario concerned the stream restoration by following the nature-based solutions, while the third scenario was based on the classical "grey" engineering approach of concrete channelization. Unmanned Aerial Vehicle (UAV) photogrammetry methods and the Pix4Dmapper software were used in order to develop a detailed 3D model of the studied reach that accurately captured the current geomorphology. The obtained results showed that with concrete channelization, the average and maximum flow of the stream increases significantly in relation to the current situation, from 2.48 and 4.88m/s to 9.82 and 11.22 m/s, respectively, while the average Froude number raises from 0.36 to 1.69 implying super-critical flows. In contrast, the NBS scenario retained lower flow velocities and average Froude number similar to those under the current conditions. In addition, a cost estimation analysis for both stream management techniques revealed that the NBS is much cheaper than the traditional channelization (1.1 mil € vs 5.6 mil €). In conclusion, our findings suggest that the future restoration of urban streams should consider the nature-based solutions since i) they can be effective with regard to the reduction of flood-risk, ii) are cheaper than the traditional "grey" techniques and, most importantly, iii) maintain the natural state of the ecosystem which improves not only the ecosystem functioning but also the aesthetic value within the urban context.

Keywords: Urban streams, stream restoration, bioengineering, nature-based solutions, hydraulic modelling, UAVs

INTRODUCTION

Urban streams are prone to the ecological degradation due to the anthropogenic disturbances, namely water pollution and channel morphology deterioration. Particularly for the latter, heavy modifications of the river banks and the channel bed (e.g channelization) are traditionally used as the mitigation measures that prevent bank erosion and/or reduce the impacts of urban floods and flash floods [ECRR 2019, 2018]. These alterations are responsible for the channel simplification which is linked with habitat loss and biodiversity reduction, e.g. decline of macroinvertebrate communities and other aquatic biota [Violin et al. 2011]. Therefore, the stream restoration projects often implement the management interventions that attempt to naturalize the urban reaches hoping to increase the habitat heterogeneity and thus improve the ecosystem functioning [Anim et al. 2018a].

Yet, the climate change will increase the intensity and frequency of extreme weather events in the Mediterranean region [European Commission 2019] and consequently increase the risk of flash floods in urban areas [Konrad 2016]. Until recently, large scale flood defense works (e.g. concrete channelization) were the main option for mitigating the flood risk in urban streams [ECRR 2019]. However, it is now well acknowledged that the urbanization of stream ecosystems with the purpose of managing excessive stormwater runoff may alter the natural flow regime due to increase of impervious surfaces [Anim et al. 2018b]. Burns et al. [2012] reported that impervious surfaces in urban catchments are connected not only to increased volume, magnitude and frequency of storm flow, but also to increased total runoff as a result of reduced evapotranspiration caused by vegetation loss.

Unsurprisingly, the river scientists have placed emphasis on the concept of nature-based solutions (NBS) as an alternative for reducing the flood risk and improving the ecological quality. These solutions practically aim at restoring the natural in-stream processes in order to enhance the ecosystem functions as well as the delivered services and at the same time – to improve the flood management.

According to the definition of the NBS given by the European Commission [EC 2019], NBS are inspired and supported by nature, benefit the environment, society and the economy and simultaneously contribute to balancing the human well-being and nature protection. Such solutions are cost-effective and implemented using the latest technological and engineering achievements [Eklipse 2019].

The construction of wetlands and two-stage channels that incorporate floodplains is considered as a viable nature-based solution for both flood regulation and retention of nutrients [Kabisch et al. 2017, Kalantari et al. 2018]. Other measures are based on the use of bioengineering techniques that employ natural materials (e.g. plants) to mimic the natural characteristics and features of rivers. Bioengineering has several practical advantages over the traditional engineering techniques because it can improve not only the structural component of the restored ecosystem, but also the aesthetic value within the urban context. In addition, it can be cheaper than the use of hard materials (e.g. concrete) and it can be combined with the use of other restoration techniques (e.g. daylighting).

In this study, the authors assessed the effects of two intervention scenarios and the current situation on the flood risk in an urban stream of Attica (Greece) by applying hydraulic modelling to simulate the restored hydromorphological features. The first scenario involves the implementation of traditional channelization techniques (use of concrete) while the second scenario employs bioengineering techniques as a nature-based solution. Low-cost topography mapping with the use of Unmanned Aerial Vehicles (UAVs) was implemented to obtain a detailed 3D model of the studied stream and to demonstrate the effectiveness of drone photogrammetry in the stream restoration studies. Finally, a cost effectiveness analysis was conducted to compare the implementation costs for the two scenarios.

METHODS

Description of the study area

Athens is characterized by high urban density, lack of green areas and running waters. The Podoniftis stream is one of last remaining natural streams of Athens. The stream originates from the Penteli mountain and it joins the main channel of Kifissos River. It has a total length of 16 km and a basin area of approximately 80km^2. Hence, it is a significant stream for the region of Attica, as it drains a large area of the urban fabric. The surrounding area is characterized by a high urban density with buildings, roads and parks distributed along the stream. The main environmental issues include pollution, solid waste disposal, flash floods during rainstorms and morphological alterations (e.g. channel narrowing, man-made buildings within the channel bed, etc).

In this work, the authors studied a 771.55m long reach of the Podoniftis stream characterized with rich riparian vegetation and significant biodiversity (plants, birds, small animals). The flow is permanent throughout the year and the riverbed is natural with hard substrate. For the purposes of this work, the hydraulic functioning of the studied reach was compared under three different scenarios. A) current conditions, B) stream restoration implementing a nature-based solution with the use of natural materials and bioengineering techniques, and C) concrete channelization as proposed in a recent study for the flood protection of the reach [Region of Attica 2017].

Prior to hydraulic modelling, the topographic and hydrologic data were collected from previous studies and from field measurements (e.g. flow measurements with a flowmeter). In addition, a detailed 3D model of the reach was obtained with UAV photogrammetry. Then, the hydraulic simulations for each scenario were conducted with the use of HEC-RAS software ver. 5.0.5 of U.S. Corps of Engineers, (Hydrologic Engineering).

UAV photogrammetry and 3D mapping

The technological advances in unmanned aerial vehicles and systems have offered new possibilities in monitoring stream morphology at high level of accuracy [Langhammer 2019]. In this study, the authors used the photogrammetric techniques implemented with UAV systems in order to produce a 3D model that captures the geometry of the studied reach.

The flight campaign was conducted with a DJI Phantom 3 Professional UAV equipped with a 12 Mega pixels camera. The Pix4Dcapture software was used for flight planning using the single grid mission. Specifically, 770m of the natural part of Podoniftis stream and 130m of the artificial part were captured (approximately 900 m) with a width of 70m to ensure that both the channel and the whole extent of the riparian zone was recorded. The flight altitude was 50m according to the legislation regulations. Due to dense vegetation and man-made constructions, an 80% overlap rate of the images was selected.

The collected imagery was then processed with the Pix4Dmapper software and the final product, a 3D model of the studied reach, was imported to ArcMap 10.2 and AutoCAD Civil 3D 2019 software for further analysis. The Pix4D analysis process includes the extraction of common image points (tie points) between the overlapping images captured, image calibration by using the camera parameters and the development of a Digital Surface Model. The cell size of the 3D model is approximately 3 cm, while the relative accuracy of the produced Digital Elevation Model (DEM) is in the magnitude of 1 – 3 cells (approx. 1 – 9 cm) [Kung et al. 2011].

Hydraulic modeling

Hydraulic modeling was carried out with the HEC-RAS software ver. 5.0.5 of U.S. Corps of Engineers in one dimensional analysis under steady flow conditions. In this case, HEC-RAS calculates the free water surface from one cross section to the other by solving the energy equation.

For the simulation of the current conditions, cross sections were set along the reach according to the stream geometry obtained from the 3D model. The position of the cross sections was selected based on such criteria as change

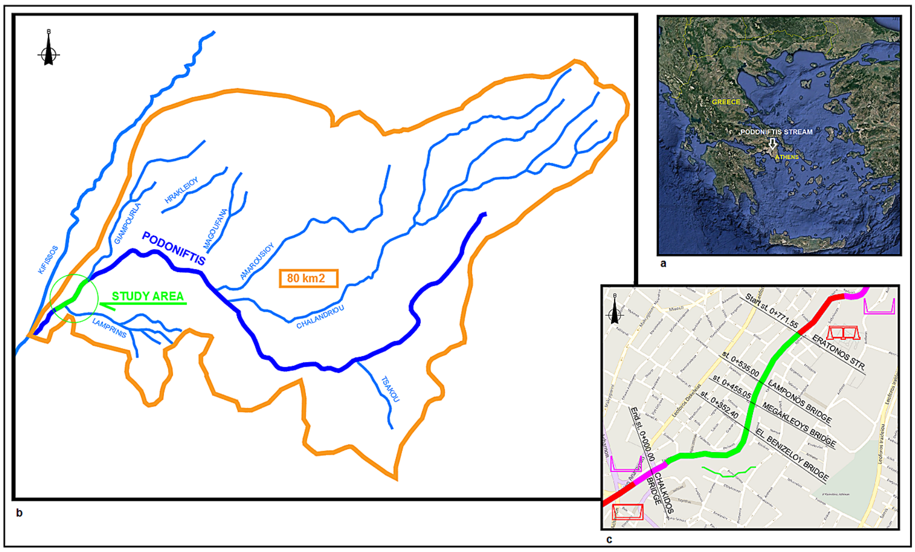

Figure 1. a. Location of the studied stream (Google Earth 2019). b. The basin area of the stream delimited by the orange line. The studied stream segment is colored green. c. The study area (in green line the natural section, in red the concrete channel section and in pink the open concrete section).

of direction, location of bridges, stenosis and/or widening of the channel etc. and ensuring that the minimum distance between the cross sections was 10 m. The presence of levees, 3 bridges and the limits of banks were included in the model set up. The geometry numbering starts from cross section 900.00 and ends at 128.45 at scenario A, B and from 771.55 cross section until 0.00 at scenario C.

The Manning's roughness coefficient for the channel and the floodplains was calculated according to the Cowan method [Ven Te Chow 1956] as follows:

$$n = (n0 + n1 + n2 + n3 + n4) * m5 = \\ = (0.025 + 0.003 + 0.010 + 0.020 + 0.025) * 1{,}000) \quad (1)$$

where n_0 is base value for the riverbed and main channel material (ranging from 0.020 to 0.028),
n_1 is additive value that accounts for the degree of abnormalities of the bed (0.000–0.020),
n_2 accounts for changes in cross-section geometry (0.000–0.015), n_3 accounts for barrier effects (0.000–0.060), n_4 accounts for the type and density of vegetation (0.005–0.100) and m_5 is and adjusting factor that accounts for the degree of channel meandering (1.000–1.300).

For the floodplain areas, the Manning roughness coefficient was selected from Ven Te Chow, (1956) reference tables. The selected values are characteristic of natural streams and floodplains similar to those of the study area.

The calculation of the flood water lines was based on a return period of 100 years. The design flow was set to Q = 400 m^3/sec according to a recent study for the flood risk reduction of the river (Region of Attica, 2017). The boundary condition used was the Normal Depth, where the energy line slope was selected to calculate the uniform depth for each profile. Because the energy line slope is unknown, the slope of the river bed [Brunner 2008] was used, which is equal to 0.01.

The manning coefficients which were used for the 3 different scenarios tested with HEC-RAS can be found in Table 1.

For Scenario A, in the channel the Manning coefficient was calculated by using the following values:

$$n = (n0 + n1 + n2 + n3 + n4) \cdot m5 = \\ = (0.025 + 0.003 + 0.010 + 0.020 + 0.025) \cdot 1{,}000)$$

For the floodplain area, a n value of 0.1 was selected that accounts for dense vegetation with trees and shrubs. The Manning's coefficient for Scenario B (NBS) was selected respectively to the above methodology and is presented below.

The coefficients in the Scenario C (Concrete channelization) were selected by the Region of Attica for the official study for the flood risk reduction measures conducted in 2017, according to the Greek legislation for concrete stream bed and concrete the stream banks.

In order to resolve the Scenario B of the Nature-based Solution by using natural materials and bioengineering techniques, the preservation and enhancement of the natural bed in relation to the current situation was selected.

More specifically, the following changes were made to the geometry and roughness at the existent hydraulic model:

- increase the channel width where stream stenosis is large due to anthropogenic interventions.
- change the river banks slope where bioengineering methods will be applied
- raise the river banks in cross-sections where required
- increase the Manning's coefficient

The Manning's roughness coefficient for the NBS restoration scenario was increased in relation to the current situation, since the highest density and vegetation of a stream, results in higher coefficient values, lower velocities, higher elevations of the flow area, and greater mean shear stress [AloTerra Restoration Services et al. 2016].

Therefore, the authors expected the use of bioengineering materials to increase the channel roughness coefficient as follows:

Table 1. Manning's coefficient for the 3 Scenarios

Criteria	Scenario A: Current conditions	Scenario B: NBS with the use of natural materials and bioengineering techniques (stream restoration)	Scenario C: Concrete Channelization
Design flow Q (m^3/sec)	400.00	400.00	400.00
Manning's coefficient (channel)	0.083	0.115	0.018
Manning's coefficient (floodplains)	0.100	0.120	0.014

$n = (n0 + n1 + n2 + n3 + n4) \cdot m5 = (0.025 + 0.010 + 0.010 + 0.020 + 0.050) \cdot 1{,}000) = 0.115.$

For the floodplain areas in Scenario B, the Manning's roughness coefficient was calculated according to Ven Te Chow [1956] and was 0.12.

Table 2 lists a series of specific actions that have been incorporated in the hydraulic model set up in order to describe the NBS of the studied reach and table 3 presents the differentiations between the three scenarios (current conditions, NBS and channelization) with regard to the adopted modelling considerations.

The bioengineering techniques which are proposed for the Nature-based Solution (Scenario B) and were incorporated into the HEC-RAS software with the Manning's coefficient value incensement include, among others:

- techniques such as fascines, wattle fences, bush-mattress constructions, live slope gratings, bush wattles, cordons etc [Donat 1995] by using natural dead and live material materials [Maris 2017] (trees, bushes, riparian vegetation, wood, gravel etc.), in order to achieve the increment of Manning factor, stream stabilization and enhance biodiversity [Shrestha et al. 2012].
- plantings where needed
- change of bank slopes

Cost estimation

The examples of natural stream restoration in Greece are scarce, which means that the cost effectiveness analyses are also missing from the local literature. Thus, in this study, the authors

Table 2. List of actions that have been incorporated in the hydraulic model (geometry) set up in the NBS Scenario

Station	Method
st. 900.00–st.120.00	Demolish of concrete or other illegal constructions within the river bed of the stream.
st.900–st.870 right	Remove gabions from the right overbank and uplift 4 m
st.850–st.760 left	Uplift left overbank 2 m
st.720–st.680 left	Channel enlargement and expropriation of legal constructions that exist at these locations
st.680–st.620 left	Uplift left overbank 3 m
st. 671.75	Remove and reconstruction of Lamponos bridge at a higher height.
st 590.5	Remove and reconstruction of Megakleous bridge at a higher height.
st.550–st.500 right	Uplift right overbank 4 m
st.488.25	Remove and reconstruction of El. Venizelou bridge at a higher height.
st.480–st.400 left	Uplift left overbank 3 m
st.370–st.310 right	Uplift right overbank 5 m.
st.240–st.120 right	Uplift right overbank 1 m.
st.180–st.120 left	Uplift left overbank 3 m

Table 3. Differentiations between the three scenarios

Criteria	Scenario A: Current conditions	Scenario B: NBS with the use of natural materials and bioengineering techniques (stream restoration)	Scenario C: Concrete Channelization
Geometry/River bed	Natural cross section / natural	Natural cross section with some interventions/ natural.	Rectangular concrete channel cross section / concrete.
Stream Bank slope	Steep slopes in places	Smoother slopes who lead to mechanical reinforcement, stability and protection from erosion caused by rain splash.	Width: height = 1: 6
Vegetation	Dense	Increased vegetation in order to strengthen the soil with the plant roots and stems [Shrestha et al. 2012].	Eradication and destruction of vegetation.
Cross section absorption	Relatively good	Increased due to roots that absorb surface and underground water, reducing the saturation level of soil and the concomitant risk of slope failure [Shrestha et al. 2012].	Non-absorbent surface.
Flash Flood Risk & Surface runoff	Very high due to anthropogenic interventions	Reduction due to the stems and roots who reduce the velocity of surface runoff by increasing surface roughness, increased infiltration, stream stabilization [Li and Clarke 2007].	Very high due to the smooth and non-absorbent surface of the concrete cross section.

followed a step by step approach for calculating the implementation costs for both management scenarios by estimating the cost of the materials and labor required at each construction phase. In addition, a bibliographic research was conducted in order to compare the cost estimations per meter of the stream's length with those from similar studies conducted worldwide.

According to the Greek legislation and the Ministry of Infrastructure and Transport, General Secretariat of Infrastructure, the costs for specific stream restoration actions have been estimated and are listed in Table 4.

RESULTS

UAV originated DEM

The UAV flight mission covered an area of 0.175 km^2 above the Podoniftis stream and the surrounding urban area with an average ground sampling distance of approx. 3 cm (Table 5). According to the quality report of the Pix4D software the mean reprojection error was 0.264 pixels (less than 1 cm) while the number of 3D points that were created by the photogrammetric algorithm was more than 13 million. The estimated elevation in the study area fluctuated from approx. 87 to 116 meters above mean sea level and the DEM of the area was produced after the removal of the vegetation, which was achieved through an image classification process, the built-in the software and the interpolation of the resulting gaps with the Inverse Distance Weighting (IDW) method. The resulting DEM was examined for discrepancies and anomalous topographic patterns; after a few manual corrections in the elevation around bridges crossing the river, the DEM was imported to the hydraulic model for simulating the flood scenarios.

Hydraulic model outputs

The results of the hydraulic simulation output include the water level, critical depths, energy line and hydraulic variables (flow rates, Froude number etc) for each cross section.

The results for the Scenario A (Current conditions) show that the stream flood capacity is not sufficient for the discharge value of 400m^3/s (100 years return period) (Figures 3 and 4). The width of the reach in the upstream part is 30–40m, while downstream the width is only up to 16m. In addition, the bank height is greatly reduced in many cross sections downstream, with the largest decrease observed in the right bank at cross section 190.00 as shown in Figure 4A2 (scenario A). According the model output, both banks were flooded in all sections and the water level reached the decks of the 3 bridges of the stream. The average flow velocity for Scenario A is about 2.48m/sec and the maximum is 4.88m/sec which occurs after the Megakleous Bridge.

For Scenario B (NBS), the flood resilience of the reach is increased since no overflowing

Table 5. Characteristics of the flight mission and the image analysis

Flight mission and image analysis parameters	Values
Area covered (km^2)	0.175
Average ground sampling distance (cm)	3.04
Mean reprojection error [pixels]	0.264
Median no of keypoints per calibrated image	44321
Number of 3D densified points	13480916
Average Density (per m^3)	77.97
Number of calibrated images	166

Table 4. Costs for specific restoration actions according to the Greek Ministry of Infrastructure and Transport

Task	Cost (€)
Remove illegal pipeline connections and outbreaks of water pollution sources	82.00/m^3
Removal of solid waste and debris from the steam bed and banks	11.3/m^3
Demolition of gabions	82.20/m^3
Demolition of concrete or other illegal constructions within the river bed of the stream.	41.20/m^3
Channel Enlargement and excavations with mechanical means	0.72/m^3
Embankments with natural materials (gravel, etc.) produced on site	0.62/m^3
Embankments in stream banks with natural materials from quarry	11.30/ m^3
Planting: Tree 18–35lt – Height 1.75–3.00 m – bole perimeter 10–25 cm Tree 24–35lt – Height 1.75–3.00 m – bole perimeter 12–25 cm Bush 18–20lt – Height 0.80–1.20 m – perimeter >1.50 Bush 30lt – Height 1.25–1.50 m – perimeter >2.50	 45.00/unit 80.00/unit 30.00/unit 45.00/unit

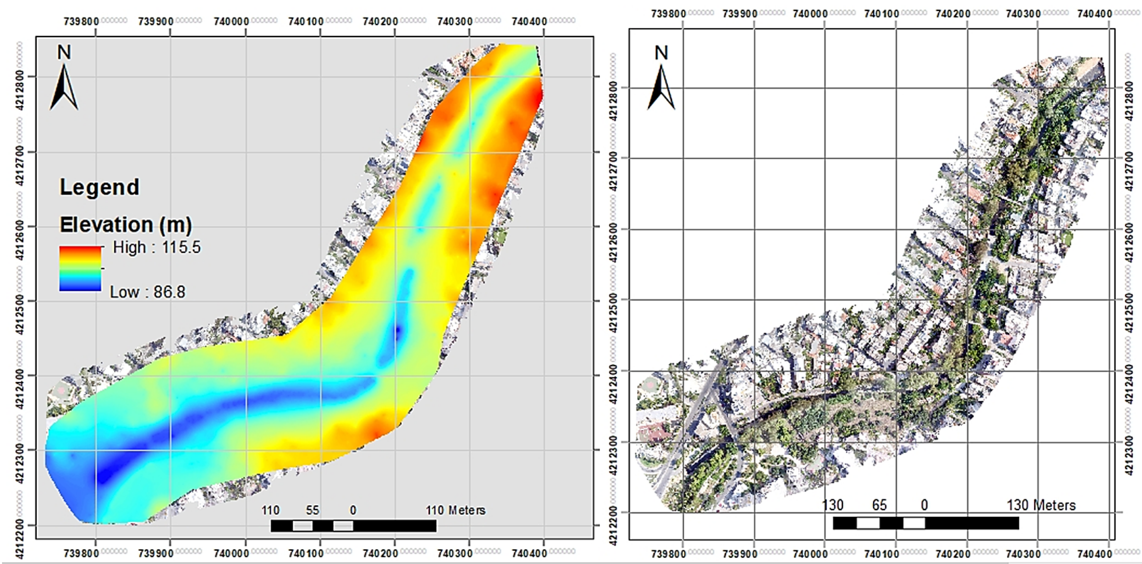

Figure 2. Study area elevation produced by the UAV image analysis

occurred along observed along river banks and close to bridges (Figure 3) while the average and maximum flow velocities are 1.94 m/s and 3.38 m/s, respectively.

Figure 3a shows that the stream banks are submerged for the design flow (Q = 400 m3/sec) at the entire length of the stream. On the contrary, in Figure 3b it is shown that the stream banks are not submerged and the stream is sufficient for the same flood event.

Table 6 lists the key findings regarding the hydraulic and hydrologic features of the studied reach among the three scenario runs. The flow was subcritical for NBS and Current conditions Scenarios with Froude number <1 in contrast to the concrete channelization Scenario (C) in which flow type was supercritical with a Froude number of 1.69. The average and the maximum flow velocity were significantly lower in the NBS scenario than in the concrete channelization scenario (1.94 and 3.38 vs 9.82 and 11.22 m/s respectively). The energy line slope is much lower in the NBS and current situation scenarios in relation to the concrete channelization scenario as a result of the great differences in the flow velocities and manning coefficients between the scenarios.

The simulation results demonstrated that by applying the natural methods of restoration and the natural form of the channel, the cross sections were sufficient for a design flow of Q = 400 m^3/s and the flood problem of the study area was solved because the stream banks are not flooded.

Cost estimation of NBS vs concrete channelization

In order to estimate the Scenario B cost, the examples of river restoration projects using bioengineering techniques were examined. The River Restoration Center [2018] presents a Manual of River Restoration Techniques in the United Kingdom from which the examples

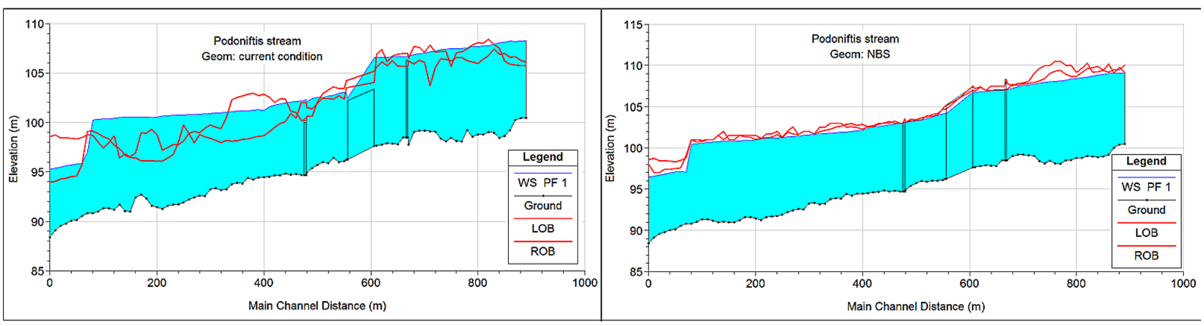

Figure 3. Stream profile created by the HEC-RAS simulation for Scenario A (a) and B (b). Red line indicates the stream banks

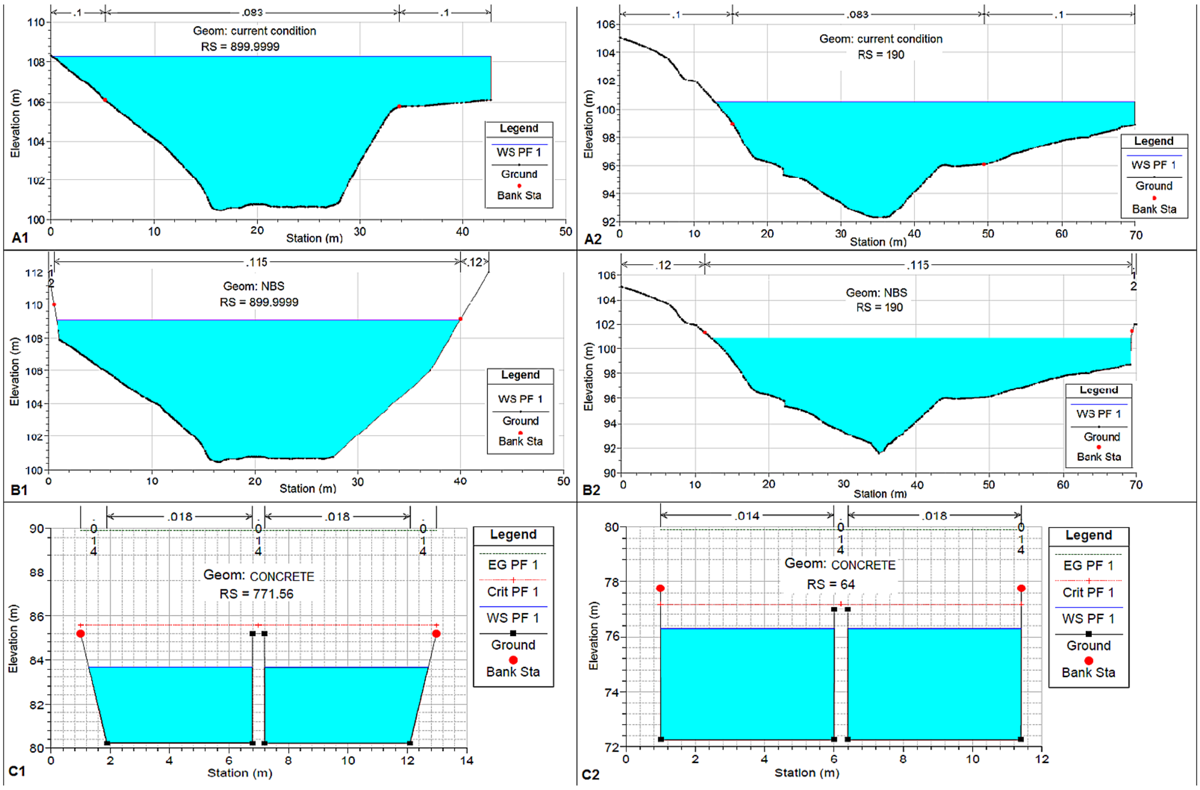

Figure 4. HEC-RAS simulation outputs for two cross sections (900 and 190). Scenario A (A1, A2), Scenario B (B1, B2) and Scenario C (C1, C2)

Table 6. Comparative table. Characteristics hydraulic criteria of the three cases.

Criteria	Scenario A: Current conditions	Scenario B: NBS with the use of natural materials and bioengineering techniques (stream restoration)	Scenario C: Concrete Channelization
Design flow Q (m^3/sec)	400.00	400.00	400.00
Average flow velocity (m/s)	2.48	1.94	9.82
Max velocity (m/s)	4.88	3.38	11.22
Average Froude number	0.36	0.30	1.69
Energy line slope upstream cross section	0.003884	0.005065	0.01737

of cost-restorations with natural materials are presented below (Table 7).

Moreover, according to the United States Department of Agriculture [Bair 2018], the average cost of restoration with natural methods is $129,135.00/mile or 1,416.21 €/m (July 2018). The price includes the plant materials, equipment and labor. On the basis of the above-mentioned values and the official values of the Greek legislation that were presented at the methodology paragraph, the cost of the Podoniftis stream restoration by means of natural methods (Scenario B) was estimated to 1.400 €/m or 1,100,000.00 € for the771m reach. The official study for the flood risk reduction measures conducted in 2017 by the Region of Attica (Scenario C) estimates the total cost for the concrete channelization of a 771m reach at 5.6 mil € (7,265.00 €/m), 5 times higher than the cost for the implementation of Scenario B, (excluding VAT) and not including the costs for reforming the riparian and adjacent areas to the stream.

DISCUSSION

The impacts of a nature-based solution vs classical concrete channelization on the hydraulic features of an urban stream within the context of urban flood management were analyzed in this study. The results showed that the maintenance and restoration of the studied reach with the use

Table 7. List of river restoration projects with natural methods in the United Kingdom

River name	Method	Length (m)	Cost (£)	Cost (€/m)
River Alt	Radical redesign from uniform, straight channel to a sinuous, multi channel river	140	40,000.00	251.42
River Avon (Stratford-Sub-Castle	Narrowing of an over widened channel using low cost groynes	125	2,000.00	14.08
River Avon (Amesbury)	Narrowing of an over widened channel using low cost groynes	850	34,000.00	35.2
Braid Burn	New meanders replacing a lined urban channel	310	110,000.00	312.25
Babingley River	Restoring an on line lake to a chalk stream	500	600.00	1
River Bure	Felling and placing trees for habitat and flow diversity	300	5,000.00	14.66
River Cole	New meandering channel through open fields	500	9,000.00	15.84
River Cole (Coleshill)	New channel meandering either side of existing channel	700	25,000.00	31.42
River Cole	Hurdle and coir matting revetments)	40£/m		35.2
River Dulais	Bank protection using root wads	80	18,000.00	225.00
Long Eau	Removing and setting back floodbanks	16ha	60,000.00	3.300,00ha
Burn of Mosset	Breaching a food bank to reconnect active floodplain processes	500	100,000.00	176.00
River Rother	Brushwood mattress bank stabilization on a tidal river	200	170,000,00	748.00
River Thames (Clifton Lock Cut)	Bank revetment using low steel sheet piling and coir rolls	140	45,000.,00	282.82
River Skerne	Plant role revetment	119	130.00**£**/m	114.40
Average value				**161€/m**

of bioengineering techniques and natural materials can protect the urban fabric from the flood events while maintaining the natural character of the stream contributing to its ecological integrity at the same time. The flow velocity and Froude number for the NBS scenario remained significantly lower than the concrete channelization, which is in line with other similar studies outputs. Lumbroso et al. [2012] mentions that super-critical flows (Froude number>1) do not occur in most natural high-gradient reaches even under the conditions of extreme flood waves [Trieste 1992, Yochum et al. 2008]. This implies that the naturally restored streams will dissipate the energy during flash floods keeping the flow sub-critical, in contrast to the typical channelized streams with super-critical flow. This can be also seen in this study by comparing the average and maximum flow velocities between the two restoration scenarios, which indicates that in the traditional channelization approach, the average flow velocity is much higher than in the NBS. In practice, this confirms that the classical simplification of the channel morphology will result in a substantially altered hydrologic regime that will have negative long-term impacts. Several studies have recently reported similar findings highlighting the substantial role of hydraulic diversity on maintaining a natural flow regime [Anim et al. 2018a, 2019]. The scenarios modelled with highly variable stream geometry showed that the channel was less susceptible to the changes in the flow regime. Hence, ensuring natural or near-natural hydraulic features during stream restoration is vital for a healthy ecosystem that in turn will minimize the flood risk.

Concerning the cost effectiveness, although the estimated cost (1,400.00 €/m) was quite high and comparable with the average cost of 1,416.21€/m estimated for the US by the Department of Agriculture [Bair 2018], our analysis showed that the natural restoration of the stream costs much less than the classical method of the concrete channelization. In addition, a reduction of the flood risk is expected to provide socioeconomic benefits such as the reduction of compensations for property damage and improvement of the social well-being. On top of that the aesthetic value of the area will increase with additional benefits for the residents and local economy.

CONCLUSIONS

This study demonstrated that the restoration of urban streams using natural methods and materials is financially feasible and advantageous over the traditional “grey” methods. In particular, the obtained results showed that:

- Nature-based solutions, such as the use of natural materials and methods that restore a stream to its near natural state, can reduce the flood risk
- Nature-based solutions cost, in many cases, less than the classical methods of concrete channelization and can benefit also the delivered ecosystem services and the society
- From a methodological perspective, UAV photogrammetry for detailed 3D mapping is a valuable tool in hydraulic simulation as it produces fast and precise results in a cost-effective manner.

Overall, this study highlights the need for changing the still dominant perception of “grey” flood defense projects to a more environmentally friendly and efficient approach that is based on natural processes and functioning. The restoration of urban streams in particular, should include the techniques that not only prevent floods but also improve the functions and the aesthetics of the ecosystems. Future research could assess the effect of additional natural-based practices in renovation and cultural heritage actions as well as daylighting projects [Wild et al 2010].

Moreover, the implementation of natural solutions is not just a matter of legislation and political decisions, but it also requires societal changes concerning the understanding of the ecosystem mechanics and their importance within an urban context.

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