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Sustainable Water Management: Virtual Reality Training for Open-Channel Flow Monitoring

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Abstract: The estimated population growth in the next decades will create severe scarcity of water and will have a tremendous impact on the natural environment. Both the developed and developing countries will have to face increasing challenges to match the greater demand of clean and safe water, looking for supplies far from the residential area. This situation will be furtherly exasperated by the effects of climate change which, increasing the frequency and intensity of extreme events, will reduce the availability and the quality of water resources and will subject the population to serious and ongoing hazards. In such context, an accurate and continuous monitoring of surface waters represents a fundamental step to reduce the contamination status and plan actions for a sustainable management of this resource. In the last years, the development of advanced methodologies and high-tech equipment able to lower the times and costs of the field surveys has not been associated with an appropriate training of the technical staff of public and private bodies responsible for the control of the territory. In most cases, unable to outsource highly qualified personnel due to lack of funding, such bodies tend to reduce the monitoring activities, leaving the areas even more subject to the risk of disastrous events. The present paper proposes an innovative educational tool based on the virtual reality in support to technical and non-technical workforces in field activities. The tool represents a Virtual Laboratory able to train on the standard techniques for the accurate monitoring of the water discharge in open-channel flows and was successfully tested on a sample of people from the private and public water sector. According to the results, its use increased the fieldworkers' ability to quickly move within the river as well as to easily and correctly manage the measurement equipment and methodology, so reducing the costs and times of surveys in situ.

Keywords: virtual reality laboratory; sustainable water management; mobile fieldworkers; water discharge monitoring; field survey; professional training

1. Introduction

Only 2.5 percent of all water on earth is fresh water and even less than 0.3% can be used for human consumption [1]. Therefore, more than 700 million citizens are currently suffering from water stress and scarcity, with about 1 billion of people having no access to clean water and over 2.6 million who lack adequate sanitation facilities. Eighty percent of diseases in developing countries are caused by poor water and sanitation facilities: only 10% of the world's cities currently have water treatment systems and 90% of untreated wastewater is discharged into rivers, reducing even more the availability of clean water [2]. This issue will become more serious in the next three decades: the world's population will continue to increase and it is estimated that more than six billion people will be concentrated in cities by 2050 [3]. The increase in urban population will be around 2.3 percent and 1 percent per year in less and more developed countries, respectively, leading to a gradual deterioration in water

quality due to urban pollution and, thus, to an ever growing demand for clean water supplies and safe sanitation [4]. Climate change is an additional factor that limits the availability and quality of water resources, besides heightening the city's susceptibility to the risk of environmental disasters, either more frequent droughts and water shortage or more intense storm events. In detail, in countries where there is low flow and high water temperature, the amount of pollutants is less diluted, the bio-geo-chemical processes are altered, and the dissolved oxygen concentration is reduced; on the other hand, the zones exposed to storm peaks, and subsequent flooding, experience a higher occurrence of runoff with overflow of treated and untreated wastewater systems and increased loads of pollutants, besides greater damage to structures and infrastructures [5]. Therefore, the combination of clear water scarcity, underpowered and sometimes inefficient water treatment systems and distribution networks [6], and the damaging effects of climate change could seriously undermine the reaching of a sustainable development as well as the meeting of socio-economic and environmental goals in various countries [2].

Within this context, a more efficient and accurate monitoring of surface waters represents a crucial point to improve a management policy addressed to the right use of water resources, to the reduction of pollution sources, and to combine prevention and defense actions against environmental degradation. Additionally, the sampled data are an important input for the resolution of analytical and numerical models in order to analyze complex processes within open-channel flows and forecast extreme events such as floods and/or droughts.

In the last decades, the advancement of the research and technology has allowed the adoption of non-invasive, sophisticated sensors [7–9] as well as the implementation of expeditive methodologies [10,11] able to monitor the hydro-infrastructures and their environment at low costs and times, in order to quickly react to potential flood or other water-related issues and, thus, to support decision-making steps. However, the technical staff of private and public bodies responsible for the control of the territory are not always qualified to correctly use either traditional or innovative measurement systems. In addition, the recent global financial and economic crisis has furtherly reduced the investments in on-the-job training addressed to increasing knowledge and improving technical skills. Therefore, such bodies are obliged to spend large amounts of money to recruit external experts and this leads to a reduction of monitoring activities and to a greater exposure of more areas to the risk of catastrophic events over time.

The present paper proposes an innovative educational tool based on Virtual Reality (VR) able to train fieldworkers on the job on a correct and fast method for conducting surveys during ordinary and extraordinary field activities. The VR-Laboratory, created to support the traditional field lessons in the Hydraulic Engineering courses and help the academic students to become familiar with sophisticated equipment and advanced methodologies [12], is here introduced for the first time to guide technicians towards more accurate monitoring of the water discharge in open-channel flows. This way, the public and private bodies involved in water management will be able to improve the knowledge and skills of their mobile workforces while reducing time and cost of the professional training, increasing safety in field, enhancing efficacy of survey actions and the quality of service at the same time. In fact, after a short-term guided training, the VRLab can be used autonomously on the job, speeding up and improving the surface water monitoring, the acquisition and retention of information, and the standardization of the methodology, none of which is possible with just the traditional training. Furthermore, the faster and more accurate monitoring of open-channel flows supports the implementation of more and more sustainable water management, strengthening the environmental protection actions and the resilience of the territorial systems. In detail, an improved flow monitoring helps maintaining and restoring ecosystems that rely on a healthy aquatic environment and obtaining reliable data able to reduce inaccurate forecasts on the future water demand and supply. In fact, better operational control allows improving decision-making for water investments and strategies by prioritizing choices and, at the same time, acquiring tools useful to cope with the pressures of an increasing urbanization and the effects of climate change. Additionally, after the initial investment

on the technological infrastructure, the resulting long-term savings might be reallocated to refresher courses and new VR training modules for more qualified and specialized employees. In addition, the familiarization with the innovative immersive technologies makes the work environment more stimulating and better performing. This Virtual Laboratory was developed through the Unity 3D game engine and tested using a head-mounted display (HMD), called Oculus Rift, and HTC controllers whose application was previously investigated by the same Authors [13,14]. It was designed as simple to use as possible, without adding many functions but implementing only the flow measurement techniques. However, the tool is easily extensible and scalable to include further modules on the survey of other hydraulic parameters in the future. Although tracking devices such as HDM or HTC controllers used in this research are gaining popularity in conjunction with virtual reality environments, the proposed virtual lab provides a novel contribution compared to other VR tools developed in Hydraulics so far. In fact, few are those implemented in this sector and most of them refer to laboratory experiments with static plants with no or little interaction with the real environment. In addition, they are mainly used in both schools and universities to help students refine their techniques and abilities and to advance faster in their studies. These educational tools can generally be divided into two main categories: 2D virtual hydraulic circuits and 3D virtual hydraulic equipment.

2D animations, widely used in courseware, are developed with solver tools such as the one in Microsoft Excel and a variety of software or programming technologies, going from general programming languages, such as Visual Basic and Matlab, to more professional software including Macromedia Flash and the Metaio framework. In particular, addressing Engineering students, Rivas et al. [15] applied the Microsoft Excel spreadsheet built-in solver to evaluate the performances and the optimum design of piping networks. Wong et al. [16] designed a software application using Visual Basic to help students to visualize and understand the dynamic behavior of fluid phenomena. In 2009, within a hydraulic transmission and control course at Harbin Engineering University in China, Gao and Wang developed the process of constructing virtual hydraulic circuits using Macromedia Flash software. Such software allows students to perform some actions similar to those on real hydraulic circuits, such as starting or stopping the electromotor, changing the position of the directional valve, tuning the pressure relief valve to modify its cracking pressure, or changing the area of the throttle valve orifice and the flux rating of the hydraulic pump [17]. More recently, for students of control engineering courses at Slovak University of Technology in Bratislava, Cápková et al. [18] designed an interactive simulation tool able to control a nonlinear hydraulic plant in different configurations using a graphical user interface developed in Matlab/Simulink. In the water monitoring sector, Mirauda et al. [19,20] implemented an Augmented Reality mobile platform, based on the Metaio framework and multimedia smartphone technology, in order to improve the technical skills of workforces for managing of flood events.

3D animations, developed through the technologies OpenGL, Virtual Reality Modeling Language (VRML), and some other popular 3D modeling software (LabVIEW, 3DMax, SolidWorks, etc.), create more immersive virtual environments so to retain more involvement of the users. For example, Pieritz et al. [21] designed an interactive, Web-based virtual laboratory with OpenGL technology to simulate and study fluid flow problems addressed to students and professionals in the field. Pauniaho et al. [22] introduced a three-dimensional model in a Hydraulics course at Tampere University of Technology (TUT), in Finland, using the Virtual Reality Modeling Language (VRML) to teach the structures and functions of fluid power systems and hydraulic components. Gao et al. [23] found a relationship between 2D and 3D animations, supporting the already mentioned schematic diagram-based 2D virtual hydraulic circuits, through VRML-based 3D virtual hydraulic equipment in order to help students exercising experiment operations in a hydraulic transmission and control course. Recently, at the University of Belgrade Faculty of Mechanical Engineering Hydraulic Machinery and Energy Systems Department, Nedeljkovic et al. [24,25] performed virtual experiments in the LabVIEW application for testing hydraulic pumps operating in parallel and series modes. Sivapragasam et al. [26] involved undergraduate students of Engineering in the development of virtual labs in Fluid Mechanics

using the LabVIEW platform in order to track the profile of the jet trajectory from an orifice fitted in a tank and to draw the flownet for a given velocity potential stream function.

The aim of this paper is to propose a virtual laboratory training approach, which represents a first experience of the sort in the professional hydraulic field and is presented in the work environment here for the first time. The VRLab was tested on about 60 users of different backgrounds and IT knowledge levels, among self-employed professionals and technical and non-technical employees, working for both private and public companies in the water field. The results of the first part of the validation procedure underlined a high-quality system and the effectiveness of the virtual lab, despite the difficulty encountered by few workers during the simulation when using some sensors, mainly due to their little familiarity with interactive applications in general. The users considered the experience with the VR-Laboratory very interesting and useful. In addition, the mobile workforces during field activities, carried out after a constant autonomous employment of the educational tool, showed an increase of their knowledge and technical skills. The second part of the testing procedure involved two groups of technicians, assessed both with and without virtual training. The analysis was carried out considering three quantitative indicators of performance regarding the completion time of the different measurement phases, the number of mistakes made while applying the techniques and handling the equipment in field, and the number of correct sequences of the monitoring steps. The results obtained from both groups confirmed the importance of the virtual training tool, highlighting improvements in the quality and speed of some tasks.

The paper is organized as follows: the architecture and the use of the proposed virtual laboratory are described in Section 2; the testing results on the use of the VR-Laboratory are shown and discussed in Section 3; the main findings of the present work are summarized in Section 4.

2. Virtual Reality Laboratory

2.1. Hardware and Software

The Virtual Reality Laboratory (VRLab), here proposed to train the fieldworkers on the techniques and methodologies for an accurate and expeditive measurement of the water discharge in open-channel cross-sections, was developed through the Unity 3D game engine using a head-mounted display (HMD) called Oculus Rift. The Graph scene is based on a GameObjects hierarchy which, in addition to having a spatial position and orientation, can be connected to one or more scripts, sound, textures, animations, and 3D models. The programming language is C# and the virtual reality visualization and interaction were developed through the SteamVR SDK version 2.0, whose configuration is browser-based, and all changes are stored in several JSON files. The HMD allows the user to visualize 3D VR scenes through its OLED panel, one for each eye with 1080 × 1200 pixel resolution. The main features of the Oculus Rift HMD, such as 110 degree field of view and 90 Hz refresh rate, are well adapted to the user's human features. The VR scene interaction was allowed through devices called Oculus Touch motion controllers, which are individually associated to a specific user's hand and follow it to simulate the motion in the VR scene. The controllers allow moving across the scene also for a long distance; in addition, they manage the user's fingers gesture to activate other features. All sensors and the equipment within the simulation were modeled with accuracy and precision through Autodesk 3D Studio Max 2019 and Adobe Photoshop CC 2018.

2.2. Indoor Use of the VRLab

VRLab aims at reproducing the measurement procedure for determining the water discharge flowing in open channels [27–29], based on the international standard methods [30,31], which includes a set of actions to follow in situ: (1) choice and demarcation of site; (2) measurement of cross-sectional area; (3) acquisition of velocities in several points of the section distributed from the bottom up to the free surface flow. To make the users better understand the different measurement steps, the wading methodology was applied in the virtual laboratory.

According to the ISO rules, the selected area should satisfy different requirements, such as: (a) the channel should be straight and its bed and margins should be stable and well defined at all stages of the flow; (b) the flow directions for all points on any vertical across the width should be orthogonal to the measurement section; (c) the site should be easily accessible at all times and the section unobstructed by trees, aquatic growth or other obstacles, away from pumps, sluices, and outfalls and without vortices, reserve flow, or dead water in the lateral areas; d) the water depth should be always sufficient to provide for the effective immersion of the sensors.

The Unity 3D terrain editor, used in the virtual tool, ensures that the stability conditions of the banks and the uniformity of the whole cross-sectional profile are observed (Figure 1), while the Unity 3D asset called AQUAS, modifying the flow velocity value and direction, allows the water movement to be orthogonal to the cross-section and the velocity distribution to be regular (Figure 2). Moreover, managing the water color, bank fade, and bank and depth transparency, AQUAS controls the depth for the immersion of the instruments. The Unity 3D asset named Vegetation Studio, instead, creating vegetation along the banks and within the river, shows when the conditions of the cross-section are ideal to measure the water discharge, that is unobstructed by trees and aquatic growth (Figure 2).

Figure 1. 3D virtual scene developed through the Unity 3D terrain editor.

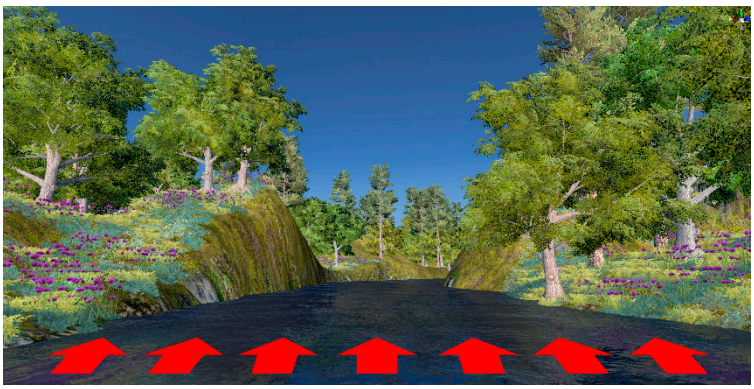


Figure 2. Reproduction of a real open-channel cross-section with the water direction orthogonal and unobstructed by trees and aquatic growth.

The demarcation of the site is simulated through the installation of posts on the two banks, used as clearly visible and readily identifiable markers. In this scenario, the user/operator learns to grab a post with one hand and the hammer with the other, hitting its top and so simulating hammering in the post. Such part of the post is represented by a white/grey cylinder which, as all the other tools, is colored in yellow when touched by the user (Figure 3a). When the hammer collides with the top of the post, a trigger is activated, turning the post red if it is misplaced (Figure 3b) and green when it is positioned correctly (Figure 3c).

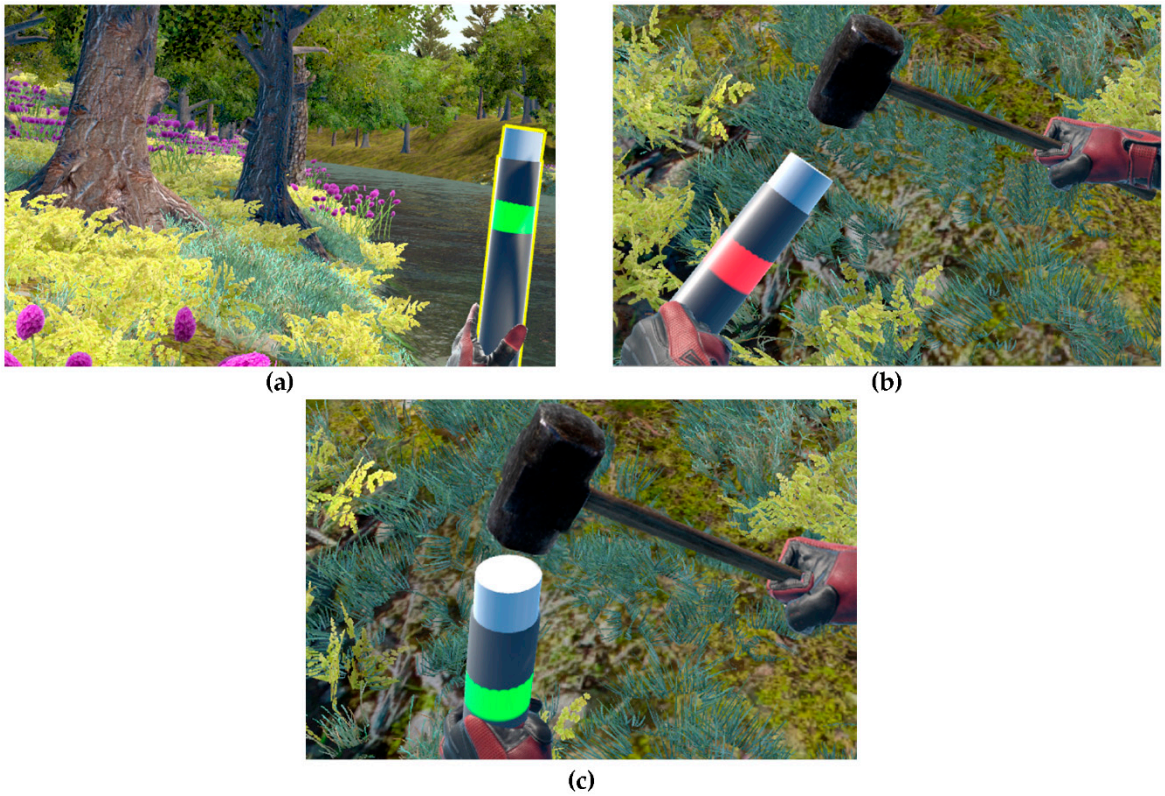


Figure 3. The different colors of the post triggered by the worker's actions: (**a**) yellow at the user's touch; (**b**) red when it is misplaced; and (**c**) green when it is positioned correctly.

The measurement of the width is simulated by the user who divides the section areas into several verticals and acquires, through a graduated tape, their horizontal distance from or to the reference post on one bank of the channel (Figure 4). The choice of intervals between the segments is suggested during this step: the accuracy of the water discharge measurement is increased by narrowing the space between verticals. The tape was implemented through the 'simple cable' Unity 3D asset, which allowed reading the centimeters and meters clearly in real-world scale. A dynamic texture mapping is used in order to visualize the unit of measurement displayed on the tape as the cable extends.

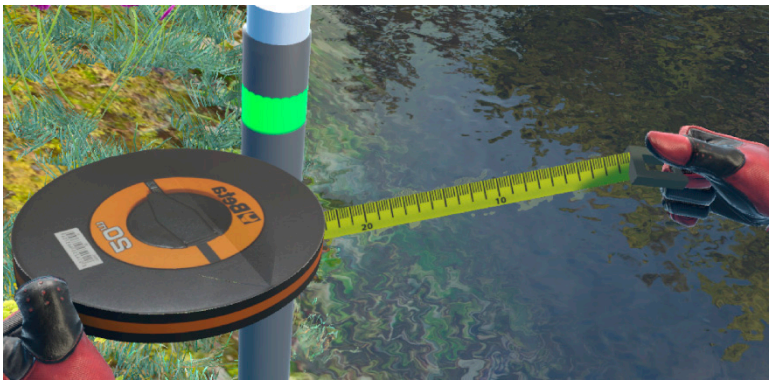
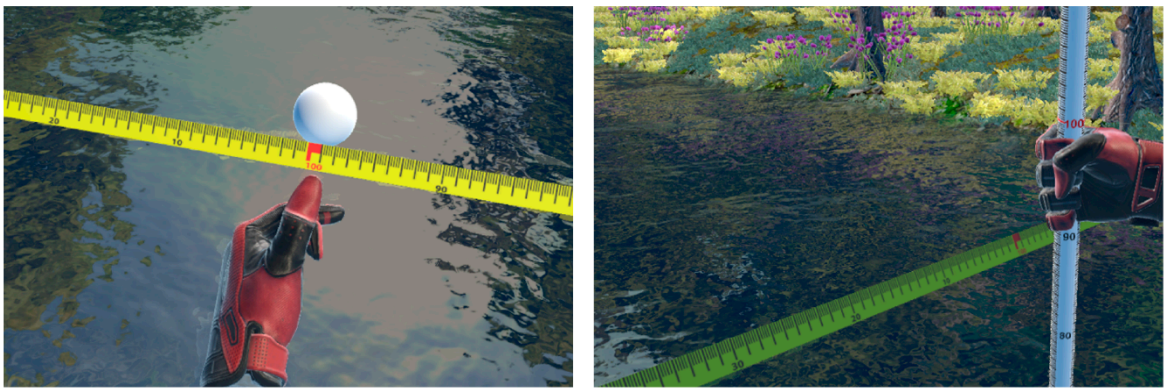


Figure 4. Measurement of the width through the graduated tape.

The virtual reality system allows the user to mark the verticals with white spheres, placed along the cross-section following the metric rope and pressing the button of the Oculus Touch controller. On the same verticals, the user detects the depth through a graduated rod in order to obtain the cross-sectional area (Figure 5a,b).



(a) **(b)**

Figure 5. (**a**) Detection of the verticals with white spheres and (**b**) measurement of the flow depth through the graduated rod.

In the last step, the user simulates the acquisition of the point velocities through two different sensors: the classical current meter and the sophisticated acoustic velocimeter (Figure 6a,b). The two instruments allow workforces to measure in field using both the traditional and the more advanced surveying technology. They were chosen because they are the most largely used for the evaluation of the water discharge in open-channel cross-sections. In particular, the current meter, besides being the easiest-to-use instrument, is also the most reliable as it has been tested on a significant amount of rivers so far. On the other hand, the Acoustic Doppler Velocimeter (ADV) provides highly accurate data in short time and gives the water discharge values directly, without the need of calibration and/or conversion formulas. The use of only two sensors avoided distracting the technicians from the main aim of the virtual tool, which was learning the water discharge measurement technique and methodology. The current meter is composed of two wading-rods, one of which slides inside the other. At the end of the adjustable rod there is a propeller, which begins to rotate as soon as it touches the water. Once the propeller is placed at the desired position, the user sets a timer and presses the start button on the handheld keypad. When the measurement is finished, the keypad produces a beep, as it happens in a real case. The Acoustic Doppler Velocimeter is the SonTek one, named Flow Tracker, which has a sensor and two rods, one of which is extendable. The sensor is attached to the extendable rod in order to allow the user to change its position along the vertical from the channel bed to the free surface. Once the sensor is placed at the selected point on the vertical, the user presses the different commands on the handheld keypad to carry out the measurement.

(a) **(b)**

Figure 6. Acquisition of the point velocities through (**a**) the current meter and (**b**) the Acoustic Doppler Velocimeter (ADV).

During the simulated measurement steps, a warning message of activity stop is triggered by the wrong actions and/or use of the equipment, which starts the application again from the beginning and so trains the worker on the correct procedure directly on the job (Figure 7a,b).

(a) **(b)**

Figure 7. (**a**) Wrong use of the ADV and (**b**) the warning message of activity stop.

3. VRLab Testing Procedure

3.1. Tool Validation in Indoor and Outdoor Environment

Preliminary tests were conducted on a sample of 35 people, having different backgrounds and IT competence, among self-employed professionals and technical/non-technical employees. The latter came from private companies, in the field of hydro-infrastructures planning and building and equipment and software production for the water resource analysis, as well as from public bodies, operating in environmental control. The aim of the testing procedure was to improve the features and the performance of the here-developed virtual lab and to understand how it could efficiently help fieldworkers to reach the following specific learning objectives:

- Knowledge: learning to accurately use traditional and sophisticated equipment for the measurement of the water discharge in open-channel cross-sections and memorizing the correct sequence of measurement operations through the virtual training;
- Skills: combining the theoretical knowledge with the use of the measurement equipment and methodologies in a real fluvial environment through repetitive training in a controlled environment;
- Competence: applying quickly and autonomously the standard measurement methods and techniques for the water discharge measurement and being able to plan field activities for the river monitoring.

The testing procedure involved two phases. The first phase had four main steps: (1) preparatory lectures on the essential tool user modes; (2) theoretical explanations of the methods and techniques employed in the water discharge measurement of open-channel flows; (3) the interaction with the VRLab in a protected environment, assisted by a teacher and a technical operator; (4) and the distribution of a questionnaire to collect the users' opinions and suggestions. The second phase, instead, involved three main steps: (1) an on-the-job training path autonomously carried out by the technicians; (2) a sequence of field activities for the water discharge measurement in some cross-sections of the main rivers in the Basilicata region (Southern Italy); (3) and the distribution of a questionnaire to collect the users' opinions and suggestions.

The first questionnaire had three sections, each one with a set of questions on: (i) the system quality, (ii) the interactivity, and (iii) the performance of the training tool (Table 1). The second questionnaire, in two sections, was focused on the impact of the VRLab use in different monitoring steps in field and

on the usefulness of the training tool (Table 2). All items used a five-point Likert assessment scale, ranging from 1 ("strongly disagree") to 5 ("strongly agree").

Table 1. Questionnaire distributed to fieldworkers after the virtual experience.

Section 1—VR System Quality				
1. The 3D VR scenes accurately reproduce the real fluvial environment				
❍ Strongly Agree	❍ Agree	❍ Neither/Nor Agree	❍ Disagree	❍ Strongly disagree
2. VRLab displays the real objects in a clear way				
❍ Strongly Agree	❍ Agree	❍ Neither/Nor Agree	❍ Disagree	❍ Strongly disagree
3. The texts and the numerical data from the VRLab are well readable				
❍ Strongly Agree	❍ Agree	❍ Neither/Nor Agree	❍ Disagree	❍ Strongly disagree
4. The images from the VRLab are of good quality				
❍ Strongly Agree	❍ Agree	❍ Neither/Nor Agree	❍ Disagree	❍ Strongly disagree
Section 2—VR Interactivity				
1. VRLab allows quickly moving across the scene				
❍ Strongly Agree	❍ Agree	❍ Neither/Nor Agree	❍ Disagree	❍ Strongly disagree
2. VRLab allows fast managing the fingers gesture to activate various features				
❍ Strongly Agree	❍ Agree	❍ Neither/Nor Agree	❍ Disagree	❍ Strongly disagree
3. VRLab allows quickly grabbing and handling the equipment				
❍ Strongly Agree	❍ Agree	❍ Neither/Nor Agree	❍ Disagree	❍ Strongly disagree
Section 3—VR Performance Indoor				
1. VRLab supports the correctly placement and use of the equipment				
❍ Strongly Agree	❍ Agree	❍ Neither/Nor Agree	❍ Disagree	❍ Strongly disagree
2. VRLab provides appropriate and accurate guidance messages				
❍ Strongly Agree	❍ Agree	❍ Neither/Nor Agree	❍ Disagree	❍ Strongly disagree
3. VRLab facilitates the simultaneously execution of different actions				
❍ Strongly Agree	❍ Agree	❍ Neither/Nor Agree	❍ Disagree	❍ Strongly disagree
4. The visualisation of video tutorials enhances the knowledge of the measuring techniques				
❍ Strongly Agree	❍ Agree	❍ Neither/Nor Agree	❍ Disagree	❍ Strongly disagree

Table 2. Final questionnaire distributed to fieldworkers after the field activities.

Section 1—VRLab Impact on Field Activities				
1. VRLab allows easily moving within river cross-sections				
❍ Strongly Agree	❍ Agree	❍ Neither/Nor Agree	❍ Disagree	❍ Strongly disagree
2. VRLab allows quickly handling equipment in field				
❍ Strongly Agree	❍ Agree	❍ Neither/Nor Agree	❍ Disagree	❍ Strongly disagree
3. VRLab supports the correct use the sensors during the different monitoring phases				
❍ Strongly Agree	❍ Agree	❍ Neither/Nor Agree	❍ Disagree	❍ Strongly disagree
Section 2—VR Training Achievements				
1. VRLab trains on the methods and techniques for an accurate measurement procedure				
❍ Strongly Agree	❍ Agree	❍ Neither/Nor Agree	❍ Disagree	❍ Strongly disagree
2. The autonomous training contributes to improving the practical skills in field				
❍ Strongly Agree	❍ Agree	❍ Neither/Nor Agree	❍ Disagree	❍ Strongly disagree
3. VRLab trains to think more critically for a better understanding some fluvial processes				
❍ Strongly Agree	❍ Agree	❍ Neither/Nor Agree	❍ Disagree	❍ Strongly disagree
4. VRLab helps to acquire know-how and abilities to work in the water monitoring sector				
❍ Strongly Agree	❍ Agree	❍ Neither/Nor Agree	❍ Disagree	❍ Strongly disagree

In general, all participants, both technical and non-technical, expressed great enthusiasm for the VRLab, rating it very highly, and showed more and more interest during the implementation of the simulated procedure.

According to the obtained results from first questionnaire (Table 3), the users felt completely immersed in the river environment (mean value μ = 4.20 and standard deviation σ = 0.96), thanks also to the presence of free surface waves and light refraction phenomena, the water transparency in depth, and additional sound effects such as the water flowing along the channel, the rustle of leaves, and the chirp of birds. Moreover, they found the virtual objects visualization very clear (μ = 4.07, σ= 0.94), the texts and numerical data well readable (μ = 4.10, σ = 1.03), and the images of high quality (μ = 4.20, σ = 0.96). The rating of the VRLab interactivity was instead slightly lower because the users showed some difficulties in moving in the river for long distances (μ = 3.40, σ = 1.04), in managing the fingers gesture through the controllers (μ = 3.17, σ = 1.15), and in quickly grabbing and handling the equipment (μ = 3.07, σ = 1.05). For example, for most users it was not simple to grab the post with one hand and hit its top with the hammer in the other hand, or to hold the sensor with one hand and the handheld keypad with the other. A possible explanation of these low values, as it was expected, is the little familiarity with Virtual Reality technology, being almost all participants non-digital natives (born before 2000). In fact, they were not accustomed to using the most modern and continuously upgraded interactive applications and this extended the times of the virtual experience. However, thanks to the high VRLab performance, the users were well supported to correctly place and use the instruments (μ = 4.23, σ = 1.04), were guided from appropriate messages to accurately carry out the sequence of the measurement steps (μ = 4.33, σ = 1.06), and were also facilitated to complete the various actions following only the main phases of the complex procedure (μ = 4.27, σ = 1.05). In addition, the simultaneous visualization of video tutorials also increased their knowledge and let them improve their practical measuring techniques (μ = 4.40, σ = 1.07).

Table 3. Mean, μ, and standard deviation, σ, values based on the scores obtained from the questionnaire.

No.	Question	μ	σ
1.1	The 3D VR scenes accurately reproduce the real fluvial environment	4.20	0.96
1.2	VRLab displays the real objects in a clear way	4.07	0.94
1.3	The texts and the numerical data from the VRLab are well readable	4.10	1.03
1.4	The images from the VRLab are of good quality	4.20	0.96
2.1	VRLab allows quickly moving across the scene	3.40	1.04
2.2	VRLab allows fast managing the fingers gesture to activate various features	3.17	1.15
2.3	VRLab allows quickly grabbing and handling the equipment	3.07	1.05
3.1	VRLab supports the correctly placement and use of the equipment	4.23	1.04
3.2	VRLab provides appropriate and accurate guidance messages	4.33	1.06
3.3	VRLab facilitates the simultaneously execution of different actions	4.27	1.05
3.4	The visualisation of video tutorials enhances the knowledge of the measuring techniques	4.40	1.07

The rating of the second questionnaire underlined how the users considered the experience with the VRLab very interesting and useful because it allowed them to learn the standard methods and techniques mostly used by the international community for the measurement of water discharge in open-channel flows (Table 4).

Table 4. Mean μ, and standard deviation, σ, values based on the scores obtained from the final questionnaire.

No.	Question	μ	σ
1.1	VRLab allows easily moving within river cross-sections	4.57	0.73
1.2	VRLab allows quickly handling equipment in field	4.40	0.89
1.3	VRLab supports the correct use the sensors during the different monitoring phases	4.43	0.83
2.1	VRLab trains on the methods and techniques for an accurate measurement procedure	4.20	1.06
2.2	The autonomous training contributes to improving the practical skills in field	4.27	1.01
2.3	VRLab trains to think more critically for a better understanding some fluvial processes	4.30	0.95
2.4	VRLab helps to acquire know-how and abilities to work in the water monitoring sector	4.00	1.05

In particular, thanks also to the constant autonomous work of training, the users declared easiness of movement within the river (μ = 4.57, σ = 0.73) and quick handling of the equipment (μ = 4.40, σ = 0.89), even overcoming the fear of dropping or damaging it. Additionally, they realized they were progressively more prepared to the correct use of the sensors (μ = 4.43, σ = 0.83). They stated that the VRLab tool guided them towards an accurate measurement procedure (μ = 4.20, σ = 1.06) and that the frequent use of the tool autonomously contributed to improve their practical skills in field (μ = 4.27, σ = 1.01). Furthermore, during the simulations in field, the users found themselves facing different issues which led them to think more critically and to increase their knowledge of some hydraulic and physical processes in rivers (μ = 4.30, σ = 0.95). Finally, they declared that the virtual experience provided them further tools and ability to better manage the water monitoring activities, which could help in their career development and to seek new job opportunities in the water sector (μ = 4.00, σ = 1.05).

3.2. Comparative Evaluation with and without VRLab

A further test was carried out to assess the positive effects of the virtual laboratory on the technicians' learning experience including 24 people, of the same categories used before, who were split into two groups in a random manner. The first group underwent the following steps: (1) theoretical explanations on the methods and techniques employed in the water discharge measurement of open-channel flows; (2) preparatory lectures on the essential tool user modes; (3) the interaction with the VRLab in a protected environment, assisted by a teacher and a technical operator; (4) an autonomous on-the-job training path using VRLab; (5) field activities for the water discharge estimation in some open-channel cross-sections. The second group, instead, followed the traditional approach, and thus only steps 1 and 5, without steps 2, 3, and 4.

Three performance indicators were chosen to detect the effectiveness of the new didactic methodology and the level of achievement of the specific learning objectives:

1. completion time of the measurement procedure;
2. number of mistakes made in following the whole measurement procedure;
3. number of times in which the sequence of the different measurement steps was carried out accurately.

In order to avoid the loss of concentration during the field experience, as well as the excessive and ineffective repetition of the same action, a maximum time for the completion of the whole measurement procedure (3 h) and the maximum amount of possible mistakes (5) before the teacher's intervention were set in advance for first and second indicator, respectively.

The comparison between the times employed for the completion of the whole measurement procedure obtained from both groups is reported graphically in Figure 8. It is interesting to note how for the first group the mean value is only 12% lower than the one detected for the group without the virtual training, while the standard deviation shows a higher reduction of about 60%. This underlines how the total time employed is not significantly decreased on average but most fieldworkers complete the procedure faster, thanks to the use of the VRLab. In order to know the step that slowed down the

field activity, completion times for (a) the demarcation of the cross-section, (b) the measurement of the width with the metric rope, (c) the measurement of the depth with the graduated rod, and (d) the measurement of the velocity through both the current meter and the Acoustic Doppler Velocimeter were evaluated. As observed in Figure 9 and Table 5, the use of the velocity sensors took more time in comparison with the other phases and the training with VR does not seem to have increased the quality of the action implementation that much. On the contrary, the cross-section width and flow depth measurements recorded higher differences between the mean values of two groups. This shows a clear improvement of the workforces' technical skills after the virtual training, especially for the easiest operations.

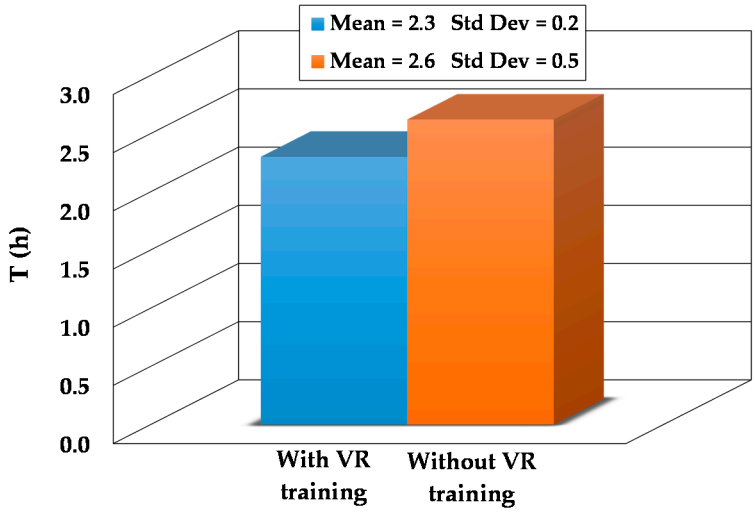


Figure 8. Completion time of the measurement procedure with and without virtual training.

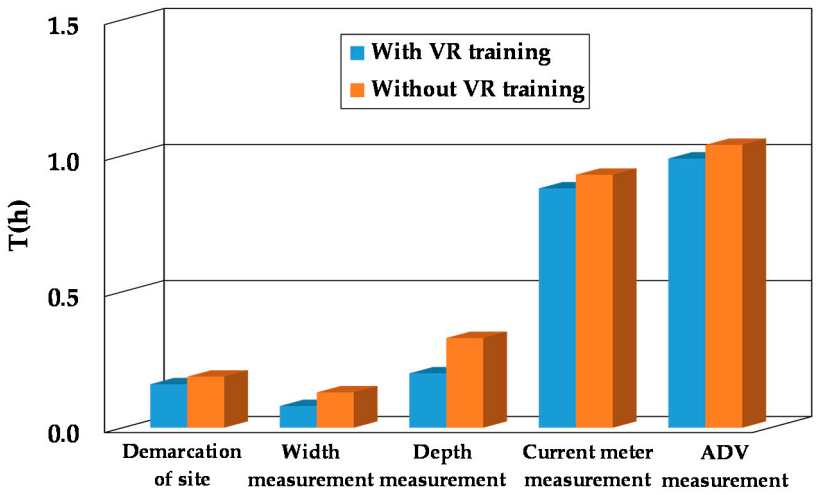


Figure 9. Completion times of the different measurement phases.

Table 5. Mean values and standard deviations of each step completion time.

Monitoring Step	Completion Time with VR Training		Completion Time without VR Training	
	Mean	Std. Dev.	Mean	Std. Dev.
Demarcation of the site	0.16	0.03	0.19	0.03
Measurement of the cross-section width	0.08	0.02	0.13	0.04
Measurement of the flow depth	0.20	0.04	0.33	0.1
Measurement of the velocity with the current meter	0.88	0.05	0.93	0.07
Measurement of the velocity with the ADV	0.99	0.06	1.04	0.06

The number of mistakes on the whole procedure has a higher mean value and dispersion without VR training (Figure 10). This is due to a greater number of teacher's interventions for the second group. Looking closely at the mistakes in each step, the ones with a higher mean value are the tasks perceived as more difficult (Figure 11 and Table 6). In particular, for the installation of the posts on two banks, the mean value and the level of dispersion are nearly 6% lower than the ones without virtual training, due to the type of ground not always easily penetrable. Even the use of ADV has a small difference between the mean values and standard deviations (about 8% and 5%, respectively), because of the difficulty in memorizing the functions of the different buttons on the handheld keypad.

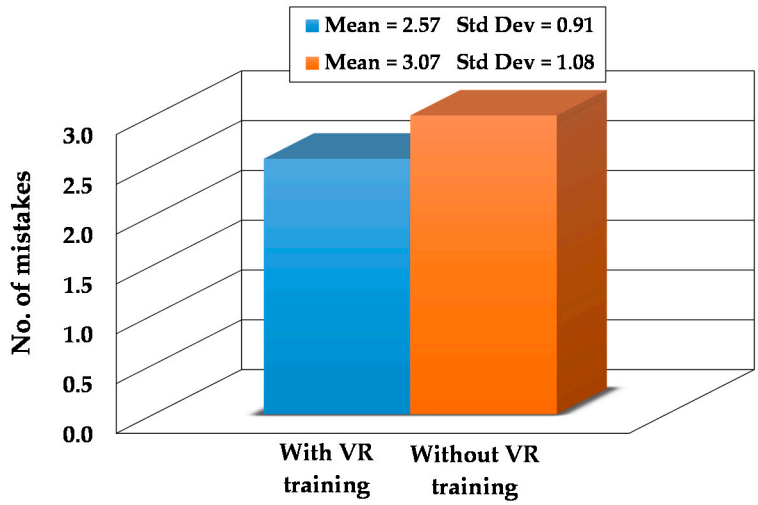


Figure 10. Total number of mistakes.

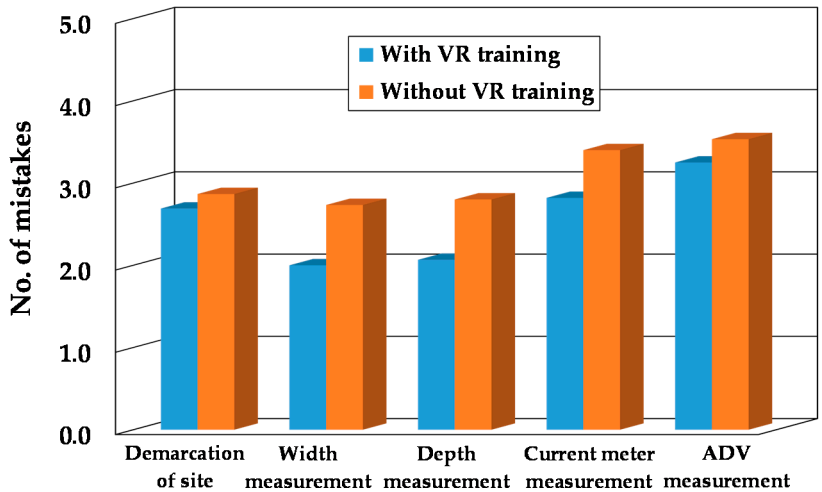


Figure 11. Number of mistakes in the different monitoring steps.

Table 6. Mean values and standard deviations of the number of mistakes in each monitoring step.

Monitoring Step	No. of Mistakes with VR Training		No. of Mistakes without VR Training	
	Mean	Std. Dev.	Mean	Std. Dev.
Demarcation of the site	2.69	1.22	2.87	1.30
Measurement of the cross-section width	2.00	0.65	2.73	0.96
Measurement of the flow depth	2.07	0.52	2.80	0.77
Measurement of the velocity with the current meter	2.82	1.21	3.40	1.35
Measurement of the velocity with the ADV	3.25	0.97	3.53	1.02

Overall, the mean values of the first group are lower than the ones of the second group with a reduction ranging from 5% to 40%. Finally, as shown in Figure 12, the number of times in which the

workforces carried out the correct sequence of the monitoring steps is higher in the first group (8 out of 12) than one of second group (5 out of 12). This highlights how the use of the virtual reality tool allowed technicians to better memorize the different measurement phases.

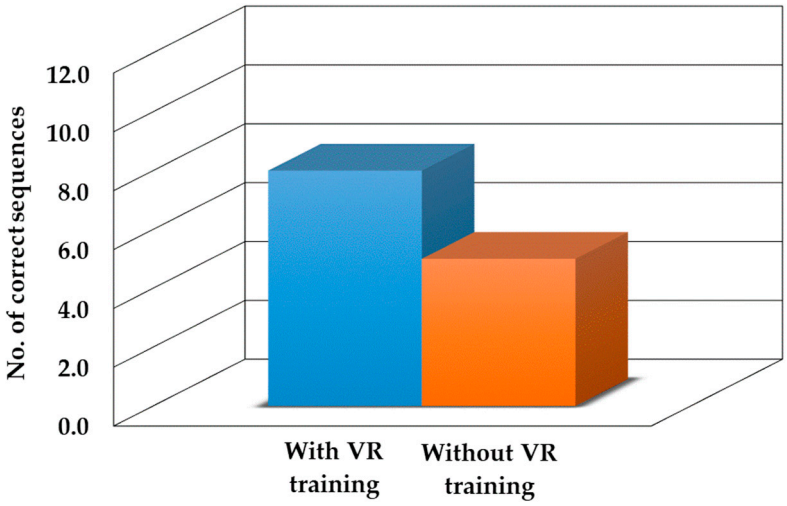


Figure 12. Number of correct sequences of the measurement steps.

3.3. VRLab Limits, Challenges, and Solutions

From the analysis of the testing results, the total time employed for the completion of the whole measurement procedure seems to have decreased, even if not significantly. In particular, the training with VR has not improved the quality of the actions involving the use of the current meter and Acoustic Doppler Velocimeter for the measurement of the flow velocity. Even the small difference between the mistakes made with and without the VRLab highlights the difficulties of the technicians in memorizing the various functions of the different buttons on the handheld keypad of the two sensors. This experience confirms how the creation of complex and interactive 3D objects still represents a challenge for the VR technology. These issues could be reduced in the future by using more and more high-fidelity 3D models of the equipment and by including further modules within the virtual laboratory specifically devoted to explain the different user modes of the sensors. For example, designing an avatar able to follow and help the operator in different phases of the assembly and use of the instrument might be an interesting development, maybe even involving the companies dealing with the sale and customization of equipment and software for water resource monitoring and analysis.

An additional reason for the small difference in the procedure completion time and quality with and without VR training is the type of target audience, which is not accustomed to using the most modern and continuously upgraded interactive applications and thus needs more time in order to become familiar with the navigation commands. Furthermore, the employment of Oculus Touch motion controllers made some measurement actions more difficult, such as the grabbing and hammering down of the posts during the demarcation of the cross-section as well as holding the velocity sensor with one hand and the handheld keypad with the other during the velocity measurement phase. A possible solution could be to substitute the controllers with pinch gloves, which enable a more natural interaction with the 3D objects, since they use hand-signs to execute actions. In addition, they continuously track the motion of the user's hand and limb and give the correspondent signals to the transmitter.

Observing the mobile workforces' behavior while using the VRLab, it was noted that some technicians required more guided training in order to completely understand the different functions and user modes of the virtual tool and thus become more independent. In order to minimize the presence of a teacher in the initial stages, a solution could be to design a simulated work phase within the virtual laboratory, which would support the technician step by step through the use of symbols and

voice commands and allow his/her, thanks to use of special sensors, to reproduce the measurement action previously displayed. This phase should precede the autonomous simulation, in which the user would have to repeat the operations previously learned on his/her own. The simulator, through a complex algorithm, should verify the technician's learning by returning feedback to that effect. In this way, the user would be able to repeat the necessary simulation cycles until full learning.

Looking at the limits due to the automatization of the measurement procedure, coming from the frequent and repetitive employment of the VRLab, the operators could avoid getting bored over time with the use of a virtual tool based on different levels of competence, exactly like the ones of a video game. In other words, if the technician is able to perform some actions accurately, he/she can move to the next level and accumulate or lose points according to the completion time of the different measurement steps and/or the number of mistakes made, with the same logic of a virtual competition. However, despite the more stimulating environment, an excessive gamification of the virtual laboratory could lead the user to get distracted and thus take the whole procedure less seriously.

Finally, the inability of making real mistakes in VRLab, because all controlled components have limits predefined and checked by the environment, and the lack of hands-on contact with the concrete devices and equipment could represent further limitations. In fact, the mobile workforces could lose the level of discipline and caution, necessary when the same experiments are carried out in field, and thus be exposed to greater risks and hazards. This could be reduced alternating the use of the virtual tool with training in field, which allows working with real-life equipment.

4. Conclusions

Fast population growth carries with it great issues related to clean and accessible water which, together with the impacts of climate change, make the sustainable management of this resource ever more challenging. A real-time and accurate monitoring activity of open-channel flows can play a key role in the reduction of the degradation and contamination phenomena and in planning efficient measures and actions addressed to a correct use of water. Although there are sophisticated and advanced measurement sensors and methodologies, the technical staff of public and private bodies responsible for the control of the territory are not always adequately trained on their use. In addition, most of the times such personnel is not able to apply traditional methods and techniques.

In view of this, the present paper proposed an educational tool based on Virtual Reality able to train the fieldworkers on how to accurately carry out water discharge measurement in open-channel flows. The performance of the virtual environment was preliminarily verified on a sample of about 60 people, among self-employed professionals and technical and non-technical employees, working for private and public companies in the environmental sector.

The first part of the validation involved 35 technicians who were trained in the virtual environment and tested before and after the field activity. The results underlined the quality and the clearness of the system and the high realism of the reproduced fluvial environment, despite low initial interactivity because the users were not accustomed to working with interactive software. Subsequently, the involvement of the same workforces in the water discharge measurement of some Basilicata rivers, after a continuous VRLab autonomous training on the job, highlighted an improvement of their technical skills and an increase in their knowledge on standard measurement procedures. In particular, the technicians demonstrated their ability to move more easily within the river, as well as to accurately use the equipment and sensors in field.

The second part of the testing procedure involved 24 people split in two groups, one assessed with and the other without the virtual training. The analysis was carried out considering three quantitative performance indicators regarding the completion time of the whole field activity and of each measurement phase, the number of mistakes made during the different tasks, and the number of correct sequences of the monitoring steps. The comparison of the obtained results showed a reduction of the completion time, especially of some measurement phases, and a greater number of correct actions and sequences, thanks to the employment of the virtual tool.

Therefore, according to the testing results, the validation of the VRLab highlighted reduced time and cost of the monitoring activities, the need of less-specialized technical personnel, the users' increased knowledge of hydraulic phenomena, and improved decision-making processes.

To furtherly improve the performance of the proposed training tool, the virtual interactivity and the sense of full immersion in the real fluvial environment could be increased, also thanks to the growing advancement in VR technologies and software. In particular, the use of sophisticated mathematical models could take into account all details of an existing physical system and all aspects of a given experiment and/or phenomenon, while the use of graphics software and of headsets, gloves, and other devices would give the technicians the amplified perception of being in a real river.

Although the current VRLab was designed only to learn the measurement procedure of the water discharge in open-channel flows, it would be easily extensible and scalable, up to, and including, other educational modules on water surveys and more complex scenarios, able to simulate extreme conditions of the fluvial environment such as flooding and droughts. This would allow building further capacity in managing some of the most critical issues and raising awareness on the risks and hazards of real situations. At the moment, the use of the virtual training provides citizens with a highly qualified service which, at low costs and in real-time, can guarantee accurate and reliable data on the flow regimes of open channels. In the future, the introduction of other educational modules and scenarios within a more interactive and motivating environment capable of providing immediate feedback could help mobile workforces even more with:

- identifying solutions at minimum cost and energy use in order to solve some water-engineering problems;
- implementing methodologies and techniques for an even smarter monitoring and management of the water resource;
- assessing efficient and reliable measures for the water protection and defense against environmental degradation and the reduction of pollution sources in watersheds;
- detecting actions to contain the damaging effects of population growth and climate change on the demand and supply of clean and safe water;
- choosing strategies to guide citizens towards the right use of water resources.

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