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StreamflowVL: A Virtual Fieldwork Laboratory that Supports Traditional Hydraulics Engineering Learning

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Abstract: This paper describes an innovative virtual laboratory for students of Hydraulic Engineering at an Italian university that shows water discharge measurement techniques applied in open-channel flows. Such new technology, which supports traditional practical classes, has the potential to increase students' motivation and improve their skills, as well as simultaneously reducing the costs, time, and possible dangers that continuous field experiments would involve. Thanks to this immersive and interactive experience that is carried out indoors, students learn to move around a fluvial environment, as well as work more safely and with reduced risks of accidents. Besides, the virtual lab can boost learners' interest by combining education with pleasure and making knowledge more fun. Collaboration with a group of students enrolled in the Master's degree course of the Civil and Environmental Engineering program at Basilicata University at the early stages of developing the educational tool led to improvements in its performance and features. Also, a preliminary testing procedure carried out on a student sample, verified the achievement of the students' learning objectives in terms of knowledge and skills. Such analysis indicated that students took more active role in the teaching/learning process and they showed greater interest in the topic dealt with through the new technology compared to the involvement of students observed during traditional lessons in previous years. The architecture and operational modes of the virtual laboratory as well as the results of the preliminary analysis are discussed.

Keywords: virtual laboratory; hydraulic engineering education; flow measurement technique; innovative teaching/learning approach; interactive educational tool

1. Introduction

The rapid transformations in the workforce and technological innovations due to a global knowledge-driven economy are changing the nature of engineering practice, and demand extensive expertise that can simplify the mastery of scientific and technical disciplines. The UNESCO Engineering Report [1] highlights how engineering education, curricula, and teaching methods should be more focused on logical, practical problem-solving methodologies and approaches, allowing the next generation of professionals to face new challenges and to seek new opportunities that have a positive impact on global problems such as war, pollution, poverty, or climate change. This requires constant integration between academic lessons and practical activities. The latter can improve and reinforce important concepts related to data analysis, problem solving, testing, and scientific interpretation. However, in the engineering field, the introduction of experiential learning activities in educational institutions presents some problems due to limited space, times, and financial resources.

In the last few years, many engineering universities have tried to solve these issues by integrating information and communication technologies (ICTs) with traditional teaching methods to improve the learning experience and students' level of expertise. This has led to the creation of virtual learning environments (VLEs), virtual classrooms that allow teachers and students to communicate with each other online through interactive systems (computer animations, audio and video devices, 3D graphics, on-line databases) and e-learning systems with Internet-based features (e-mail, instant messaging facilities, cyber-platforms). Over the years, these VLEs have become increasingly more efficient, and they provide shared and collaborative places where students can learn new content and deepen topics of interest [2], thus improving the quality of the educational experience and simultaneously reducing the cost and time associated with traditional teaching methods [3]. Among the different VLEs, virtual laboratories (VLs) are one of the most useful tools to engage students and build motivation and enthusiasm for engineering subjects, to help them to refine techniques and abilities and to advance more quickly in their studies, and ensuring that more and more graduates will meet the needs of the labor market [4–6].

Currently, due to the constant demand for industry-focused qualifications, various courses for Mechatronics and Industrial Engineering require that automation tasks be followed in real systems that represent different types of industrial processes (e.g., in warehouse storage, an elevator, a transport and sorting line, and a manufacturing cell). However, these real systems involve high investment and operating costs, and thus they cannot always be acquired or updated by universities.

In order to solve such issues and open up to new opportunities, virtual laboratories have been implemented to provide undergraduate students with basic robotics knowledge and postgraduate students with the skills to create industrial robots that control and monitor manufacturing processes [7–12].

Besides resolving some of the issues related to traditional in-class methodologies, the primary objective of developing virtual laboratories is to enable a more student-based learning process, which fosters not only initiative and autonomy but also more applied knowledge through a stimulating means of communication [13–20]. Virtual laboratories have become more and more interactive, transforming the student from a passive listener to an active participant in the learning process [21–26].

The technological advances and high popularity of computer games have been exploited in educational VLs in order to make the learning process more enjoyable and more connected to the students' interests outside the classroom [27–32].

Although the experiments on virtual laboratories have increased in Engineering university courses in recent years, few have been implemented in the Hydraulics Engineering field.

The present paper proposes an innovative virtual laboratory, StreamflowVL (SVL), for Hydraulics Engineering students at the University of Basilicata (School of Engineering), to support the traditional lessons. In particular, the here-developed SVL is able to communicate the methods and techniques employed in the measurement of the water discharge in open-channel flows, helping students to become familiar with sophisticated equipment and advanced methodologies.

The immersive experiences used in Hydraulics can generally be divided into two main categories: 2D virtual hydraulic circuits and 3D virtual hydraulic equipment. 2D animations have been developed using a variety of software or programming technologies, ranging from general programming languages, such as Microsoft Excel [33] and Visual Basic [34], to more professional software including Macromedia Flash [35], Matlab/Simulink [36] and the Metaio framework [37,38]. In particular, Rivas et al. [33] presented educational software based on Microsoft Excel spreadsheet, which with its built-in solver, is able to analyse and optimise systems and processes of medium complexity, whose mathematical models are expressed by means of nonlinear systems of equations. Such software allows the evaluation of the performance and the optimum design of piping networks. Wong et al. [34] designed a software application using Visual Basic, consisting of several function blocks including equation system formulation, numerical simulation, dynamic data visualisation, as well as graphical animations, to help students to visualise and understand the dynamic behaviours of fluid phenomena. This application supports the "user-in-the-loop" feature, so that students become active participants by interacting with network components while a simulation run is in progress. In 2009, in 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 implements numerical simulation algorithms to drive the virtual hydraulic circuit according to mathematical models. In this way, students can perform actions similar to those of 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. More recently, Cápková et al. [36] designed an interactive simulation tool for students in control engineering courses at the Slovak University of Technology in Bratislava that is able to control a nonlinear hydraulic plant in different configurations using a graphical user interface developed in Matlab/Simulink. These virtual experiments allow for changing the plant configuration and also applying various control structures, switching between simulations and real conditions, and implementing the control locally or via the Internet. In the water monitoring and flood events management sectors, Mirauda et al. [37,38] implemented an augmented reality mobile platform based on the Metaio framework and smartphone technology, in order to improve the technical skills of field workers. The overlaying of simple graphic elements on the real scene on a lightweight portable device makes the visualisation of the surroundings much clearer on the screen, avoiding the need for maps and technical reports, and guides users to a correct, fast method for conducting surveys during ordinary and extraordinary field activities.

Among the 3D animations, some were developed through technologies such as OpenGL [39], VRML [40,41], and other popular 3D modelling software, such as LabVIEW [42–44], creating more immersive virtual environments so as to retain more users' involvement. For example, Pieritz et al. [39] developed an interactive, Web-based virtual laboratory with OpenGL technology to simulate and study fluid flow problems. By implementing finite volume methodology in the teaching software, they significantly enhanced the learning of fluid dynamics by undergraduate and graduate students, as the software can be used at home to solve other numerical problems in support of the coursework. Due to its generality, the tool can also be used by engineering professionals. Pauniaho et al. [40] introduced a three-dimensional model in a Hydraulics course at Tampere University of Technology (TUT), in Finland, using virtual reality modelling language (VRML) to teach the structures and functions of fluid power systems and hydraulic components. This technique showed students how a slide moved inside a valve and how it affected the opening of flow orifices, thus increasing or decreasing the flow. Gao et al. [41] 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. The introduction of 3D experiments made the process of learning not only highly interactive and even more attractive, but also more effective in helping students to practise experimental operations.

Recently, at the University of Belgrade Faculty of Mechanical Engineering Hydraulic Machinery and Energy Systems Department, Nedeljkovic et al. [42,43] performed virtual experiments in the LabVIEW application for testing hydraulic pumps operating in parallel and series modes. This allowed students to improve their learning process through the analysis of various pump hydraulic curves, the study of their duty points, and the observation of the flow rates in each pipe. Sivapragasam et al. [44] involved Engineering undergraduate students in the development of virtual labs in Fluid Mechanics using the LabVIEW platform. The experiments were created to track the profile of the jet trajectory from an orifice fitted in a tank and to draw the flow net for a given velocity potential stream function. The response of the students indicated that the virtual experience gave them a better understanding of the associated advantages and disadvantages and built their confidence.

StreamflowVL, which is presented here, was built through the Unity 3D game engine and tested using a head-mounted display (HMD), called Oculus Rift, whose application was previously investigated by [45–47]. The interactivity with the real environment represents an innovative aspect of the proposed virtual laboratory compared to the VR tools developed so far in Hydraulic Engineering.

A preliminary testing phase was carried out on a sample of students enrolled in the Master's degree course of Civil and Environmental Engineering program at Basilicata University, in order to validate the features and performance of the virtual didactic tool. Their feedback led to a series of updates to the final version. The paper is organised as follows: the importance of field studies in Hydraulics Engineering courses for graduated students is discussed in Section 2; the traditional approach to teaching the water discharge measurement procedure in open-channel cross-sections is presented in Section 3; the features, the conceptual design, and learning objectives of the proposed virtual laboratory are described in Section 4; the preliminary test results of a student's sample are highlighted in Section 5; a comparison with the traditional learning approach is detailed in Section 6; and the conclusion and future work plan complete Section 7.

2. Fieldwork in Hydraulic Engineering Courses

Water is a vital resource for the survival of the planet and, as such, it must be protected. In recent years, climate change has caused significant variations in precipitation and temperature patterns, affecting the availability of water and the effectiveness of water treatment infrastructures [48–50]. In particular, water quality problems may increase where there is less flow to dilute contaminants introduced by natural and human sources [51]. Similarly, the rise in the occurrence of higher runoff increases the load of pollutants and the overflowing of sewers. Furthermore, higher flooding frequency carries a greater possibility of waterborne disease outbreaks, following the overflow of treated and untreated wastewater sewer systems; at the same time, flooding causes serious damage to properties, agricultural and economic activities, as well as human losses [52,53]. In addition, population growth, urbanisation, and significant leakages in pipe networks are enforcing rapid changes in some areas, leading to a dramatic increase in high-quality water consumption. Often this demand for water cannot be satisfied by locally available resources, while the discharge of insufficiently treated wastewater increases costs for downstream users and has detrimental effects on the aquatic systems [54]. In this context, more qualified water engineering expertise is required to develop new and advanced technologies that are able to resolve some of these issues [1]. In view of this, Hydraulic Engineering education in academic institutions might play a key role and help the students to improve and increase their skills and competences, preparing them for future professional challenges. In order to achieve these goals, these courses should be organised to give students the chance to be involved in more practical activities and real tasks, where they can learn to think more critically and to solve real-world problems.

In the last decade, with the creation of the European Higher Education Area [55], university education across Europe has undergone a deep transformation regarding the structure, methodology, and philosophy of technical instruction. In this phase of renewal and convergence, the new European Credit Transfer System (ECTS), which measures not only the in-class contact hours but also the total amount of study needed to meet educational goals, has increased both the students' autonomous work and their experimental and practical work, which now amounts to over 50% of the entire course. Therefore, practical training is becoming more and more essential for students to better understand various physical phenomena and to improve research methods and analysis techniques that are explained during face-to-face lessons. In particular, students can learn about the complexities of real observations, to work with advanced methodologies and equipment, and can learn the extent to which careful planning can help resolve many issues in the testing process. Such activities are also important to illustrate real professional situations and the complex interactions among all engineering and non-engineering constraints [56].

However, such activities are not often repeatable because some courses have limited duration and are mostly taught in the winter season, when weather conditions limit regular practical classes. In addition, such activities can involve a large number of students who, when monitored by only one teacher, could get easily distracted and acquire incorrect or inaccurate concepts. Finally, open-air activities can sometimes be dangerous, which can be due to limited territorial knowledge; also the use of sophisticated equipment and complex measurement techniques adds further difficulties.

3. Water Discharge Measurement in the Traditional Classroom

At the University of Basilicata in southern Italy, Applied and Fluvial Hydraulics courses are included in the Civil and Environmental Engineering curricula. Both courses are held in the first year of the Master's degree and typically attract 15–35 students. They are structured to guide learners from the knowledge of basic principles of fluid mechanics to their applications in real-world problems. During the course, different topics are discussed: the dynamics and kinematics of steady and unsteady free surface flows; filtration phenomena in groundwater; laboratory and field experiments on flow fields in open channels; potential and turbulent flows; bed and suspended transport; pollutant diffusion and dispersion; and fluid-structure interaction. The expected learning outcomes are represented by the ability to solve and analyse simple and complex hydraulic problems using analytical, numerical, and graphical models, as well as the technical ability to plan and perform laboratory and in situ experiments. In fact, some problems can be solved in the classroom by applying standard textbook techniques, whereas many of the problems do not lend themselves to such an analysis. Frequently, they require numerical and physical modelling to provide experimental data for design or validation. In addition, model testing requires some experience of experimental techniques, flow measurement equipment, data logging and elaboration. Therefore, the experimental activities are designed to develop these specific skills that cannot be obtained during formal lessons.

Applied and Fluvial Hydraulics courses, according to the ECTS, include 54 contact hours, roughly divided into 25–30 h of theoretical lessons, 10–12 h of tutorials, and 14–17 h of experimental work. Assessment is a combination of end-of-semester examinations and practical coursework. The total experimental component is about 45% of the overall assessment, of which the field activities, here discussed, comprise 25% of the subject assessment. In particular, such activities are mainly focused on the measurement and analysis of water discharges in open-channel cross-sections. Such data are an important input for the analytical and numerical resolution of equation systems, in order to analyse complex phenomena such as the fluid-structure interaction [57], the diffusion and dispersion of pollutants in rivers and estuaries [58], the propagation of flood wave along open channels [59], the morphological evolution of rivers [60,61], as well as the sediment transport in rivers and lakes [62]. The evaluation of water discharge is introduced in the classroom, where the standard measurement methods are explained, as well as the use of simple and advanced equipment [63–65]. Subsequently, students carry out a sequence of procedures in situ ranging from the selection and demarcation of the cross-section to the acquisition of flow velocities (Figure 1). In the first step, the students select the measurement site, according to specific requirements, and after traversing some reaches of the river. Then, they detect the width, with graduated tape or marked wire, and divide the area into several verticals, where the flow depths are measured with a sounding rod or line.

Simultaneously, observation of the velocity are made with classical current meters or sophisticated acoustic sensors at a given number of points on each vertical between the water surface and the channel bed. Once the velocities have been acquired, the students evaluate the water discharge using both analytical and graphical methods in the classroom.

During field activities, the students need to know not only how to correctly use the equipment and follow the different measuring steps, but also how to move within the river, which requires a large number of field surveys not always possible due to the variable weather conditions in the autumn and winter months.

(**a**) (**b**)

(**c**) (**d**)

Figure 1. Traditional practical lesson in the field: (**a**) selection and demarcation of the cross-section; (**b**) measurement of width with graduated tape; (**c**) detection of different verticals for the velocity acquisition, and (**d**) placing of the current meter at the desired location.

To overcome these issues, an innovative virtual laboratory has been developed here in order to reproduce a real fluvial environment to support traditional practical work in situ, which allows the students to familiarise themselves with the measuring techniques and equipment before the field surveys. The reproduction of a river is not an easy task, due to the large number of variables affecting the flow. Therefore, for educational purposes, the architecture and features of the tool were kept to the minimum, in order to provide a simplified interface to the students and to facilitate the learning process.

4. Proposed Virtual Laboratory

4.1. Hardware and Software Architecture

StreamflowVL is a virtual reality laboratory that was created to simulate the measurement procedure of the water discharge in an open-channel cross-section. It was developed through the Unity 3D game engine and tested using the Oculus Rift HMD, which visualises 3D VR scenes with a resolution of 1080 × 1200 pixel, a field of view of 110 degrees, and a refresh rate of 90 Hz. The SVL interaction was allowed through the Oculus Touch motion controllers, which let the user move within the virtual river environment to extended distances and detect hand and finger motion to activate other features during the simulation.

Figure 2 shows an accurately reproduced, detailed 3D VR scene of a fluvial reach so that the user feels completely immersed in the river environment. In particular, the geometry of the open channel and surrounding area was generated through the Unity 3D terrain editor, while the movement of the water in the river was created with the AQUAS Unity 3D asset. The latter is also able to recreate free surface waves and light refraction phenomena as well as manage the water colour, bank fade, bank and depth transparency, flow velocity value and direction, and other characteristics. The vegetation along the banks was realised through the Unity 3D asset named Vegetation Studio and a plugin called "speed tree" provided very detailed sets of the main tree and grass types found in nature. All equipment such as an acoustic Doppler velocimeter, current meter, sounding-rod, graduated tape, hammer, and pickets were modelled with Autodesk 3D Studio Max 2019 and Adobe Photoshop CC 2018. In particular, the use of the tape was implemented through the "simple cable" Unity 3D asset, which allowed reading the centimeters and meters clearly in real-world scale.

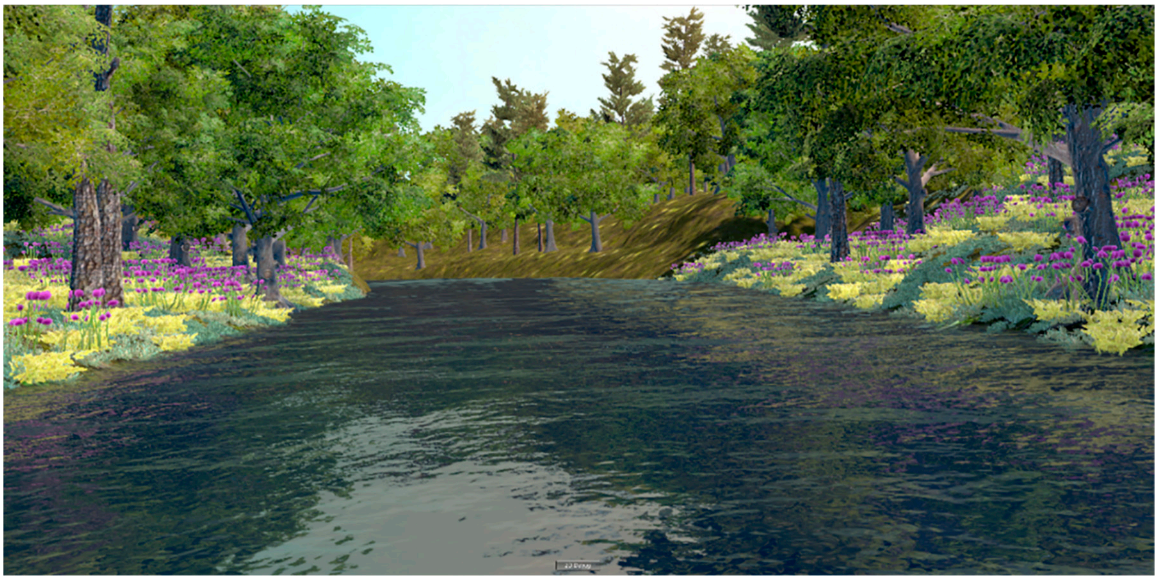
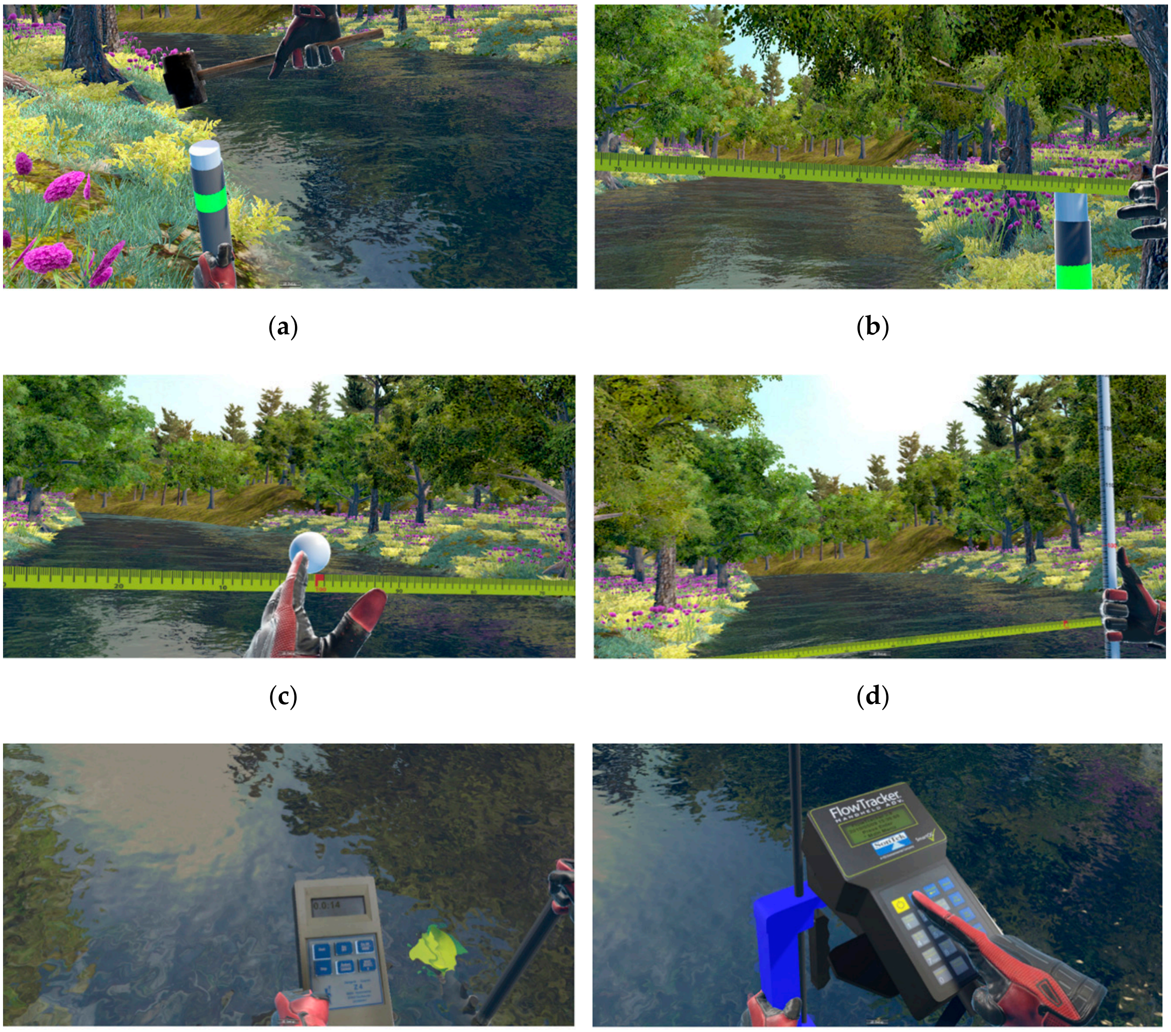


Figure 2. 3D virtual reality (VR) scene of a fluvial reach.

4.2. Tool User Modes

Figure 3 reports the different steps to follow during the water discharge measurement operation in an open-channel cross-section, without the real data collection, which should be carried out in the field. In detail, Figure 3a shows the demarcation of the site with the installation of posts on the two banks used as clearly visible and readily identifiable markers. In this scenario, the user/operator can grab a post with one hand and the hammer with the other, hitting its top and so simulating hammering in the post. Figure 3b depicts the measurement of the channel width with a graduated tape, which was fixed on one post and unrolled along the entire cross-section until it reached the post on the other bank. The measurement of the flow depth requires dividing the cross-section into a series of verticals, chosen close enough to define the profile accurately. In order to do so, the VR system enabled the user to mark the verticals on the graduated cable by using white spheres (Figure 3c). Each sphere could be placed along the cross-section following the metric rope through the Oculus Touch controller button. The depth was acquired with a sounding rod, see Figure 3d, which can be immersed in the water. The user can interact with the rod and grab it in order to move and place it on the desired vertical point indicated by the white sphere. The technical functioning of the depth measurement is based on the detection of the collision between the rod and the channel bottom, in which case the penetration of the rod is blocked and the value can be taken in an accurate way. Finally, both a classical current meter (Figure 3e) and a sophisticated acoustic sensor (Figure 3f) were used as velocity sensors. The first instrument 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 was placed at the desired position, the user set a timer and pressed the start button on the handheld keypad. When the measurement was finished, the keypad produced a beep, as happens in the real case. The second instrument is an acoustic velocimeter of SonTek, named Flow Tracker, which has a sensor and two rods, one of which is extendable. The sensor was 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 was placed at the selected point on the vertical, the user pressed the different commands on the handheld keypad to carry out the measurement. The velocities that appear on both the displays are empirical values that are only useful to give feedback and to help the student understand the user modes of the sensor.



(**a**) (**b**)

(**c**) (**d**)

(**e**) (**f**)

Figure 3. Different steps for the computation of the water discharge through StreamflowVL: (**a**) demarcation of the site; (**b**) estimation of width; (**c**) identification of measurement verticals; (**d**) acquisition of depth; velocity visualisation with (**e**) the current meter and (**f**) the Acoustic Doppler Velocimeter.

An explanative video, which shows the main steps carried out by a user in the virtual environment is enclosed in https://www.dropbox.com/s/6u4lkz5ic235kfp/StreamflowVL.mp4?dl=0.

4.3. Conceptual Design and Educational Objectives

SVL was developed in order to supplement the in-field activities, but mainly to support the theoretical lessons in the Applied and Fluvial Hydraulics course for the Master's degree in Civil and

Environmental Engineering at Basilicata University. Such courses were designed to teach students to use the basic principles, acquired in previous years, to resolve real-world problems and to increase their knowledge of some hydraulic phenomena and processes, for which the combination of theory and practice is fundamental. Besides, although repetitive practical lessons in field are required to master certain skills, the difficulties encountered during the years in organising open-air lessons have led the authors to research innovative methodologies that are able to limit these difficulties without reducing the quality of the educational experience. Therefore, the framework of the proposed virtual laboratory represents a first experience of the sort that is common in the hydraulic field, and that is presented in the academic environment.

The general learning objectives on which the planning and design of the SVL are based, include:

1. Improving the understanding of theoretical concepts illustrated in the classroom.
2. Preparing the students for forthcoming practical activities.
3. Increasing the students' interest in the academic subject.
4. Boosting the students' curiosity, critical thinking, and problem-solving, while developing related soft skills and increasing motivation.

The specific, subject-related objectives are:

- Knowledge: familiarising students with the traditional and sophisticated equipment employed for the measurement of the water discharge in an open-channel cross-section and memorising the whole sequence of measurement operations through the use of the virtual laboratory.
- Skills: combining the theoretical knowledge with the use of the measurement equipment and methodologies in a protected fluvial environment through repetitive training.
- Competence: learning to accurately and autonomously apply the standard measurement methods and techniques in a real fluvial environment, with the possible support of innovative technology.

5. Preliminary Testing Procedure

Preliminary tests were conducted on a sample of 30 students enrolled in the Master's degree course of the Civil and Environmental Engineering program at Basilicata University in order to improve the features and the performance of the here-developed virtual lab, and to understand how it will help in achieving the specific objectives. The testing procedure consisted of four consecutive steps: (1) the preparatory lectures on the essential tool user modes; (2) the theoretical explanation of the methods and techniques employed in the water discharge measurement of open-channel flows; (3) the interaction sessions with the VL in a protected environment, assisted by both a technical operator and the teacher in order to address potential doubts or issues; and (4) the final questionnaire, which was used collect the students' opinions and suggestions.

The first two steps involved all 30 students together while the last two steps were carried out individually. The questionnaire had four categories with a set of questions on: (i) the system quality, (ii) the interactivity, (iii) the performance, and (iv) the usefulness of the didactic tool (Table 1). All items used a five-point Likert assessment scale, ranging from 1 ("strongly disagree") to 5 ("strongly agree").

Table 1. Final questionnaire on students' satisfaction.

Category 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
Category 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
In case of disagreement, please indicate what is not simple to grab and/or handle: …
Category 3—VR Performance
1. VRLab supports the correct placement and use of the equipment
○ Strongly Agree ○ Agree ○ Neither/Nor Agree ○ Disagree ○ Strongly disagree
In case of disagreement, please indicate what is not simple to use: …
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
Category 4—VR Didactic Usefulness
1. VRLab is complementary to the teacher's explanation during the theoretical classes
○ Strongly Agree ○ Agree ○ Neither/Nor Agree ○ Disagree ○ Strongly disagree
2. The use of virtual resources is a more effective methodology than the traditional learning approach
○ Strongly Agree ○ Agree ○ Neither/Nor Agree ○ Disagree ○ Strongly disagree
3. VRLab trains on the methods and techniques for an accurate measurement procedure
○ Strongly Agree ○ Agree ○ Neither/Nor Agree ○ Disagree ○ Strongly disagree
4. VRLab trains to think more critically and better understand some fluvial processes
○ Strongly Agree ○ Agree ○ Neither/Nor Agree ○ Disagree ○ Strongly disagree
Further comments and suggestions: …

After the questionnaires were collected, the results helped the technical expert to modify some functionalities and characteristics of the virtual tool and to make it easier to use, as well as to enhance the learning process. In fact, the students answered positively to the first category of the questionnaire (Table 2), highlighting how VRLab is well able to reconstruct the fluvial environment (μ = 4.23, σ = 0.82) through high quality images (μ = 4.00, σ = 0.74) and the clear visualisation of different objects (μ = 4.20, σ = 0.89), allowing simple interpretation of texts and numerical data (μ = 4.13, σ = 0.90). They also made comments and suggested ways to further improve the realism and immersivity of the VR application through:

- Increasing the light refraction, the free surface waves, and the water transparency in depth (Figure 4).
- Modifying the colours of some objects.
- Fading the bright intensity in the distance.
- Adding sound effects such as the water flowing along the channel, the rustle of leaves, and the chirp of birds.

Table 2. Values of mean, μ,and standard deviation, σ, based on the scores obtained from the questionnaire.

No	Question	μ	σ
1.1	The 3D VR scenes accurately reproduce the real fluvial environment	4.23	0.82
1.2	VRLab displays the real objects in a clear way	4.00	0.74
1.3	The texts and the numerical data from the VRLab are well readable	4.20	0.89
1.4	The images from the VRLab are of good quality	4.13	0.90
2.1	VRLab allows quickly moving across the scene	4.07	0.87
2.2	VRLab allows fast managing the fingers gesture to activate various features	3.97	0.93
2.3	VRLab allows quickly grabbing and handling the equipment	3.87	1.04
3.1	VRLab supports the correctly placement and use of the equipment	4.27	0.91
3.2	VRLab provides appropriate and accurate guidance messages	4.67	0.61
3.3	VRLab facilitates the simultaneously execution of different actions	3.77	0.94
3.4	The visualisation of video tutorials enhances the knowledge of the measuring techniques	3.90	0.80
4.1	VRLab is complement to the teacher explanation during the theoretical classes	3.63	1.27
4.2	The use of virtual resources is a more effective methodology than traditional learning methods	3.80	1.13
4.3	VRLab trains on the methods and techniques for an accurate measurement procedure	3.97	1.03
4.4	VRLab trains to think more critically and better understand some fluvial processes	4.37	0.81

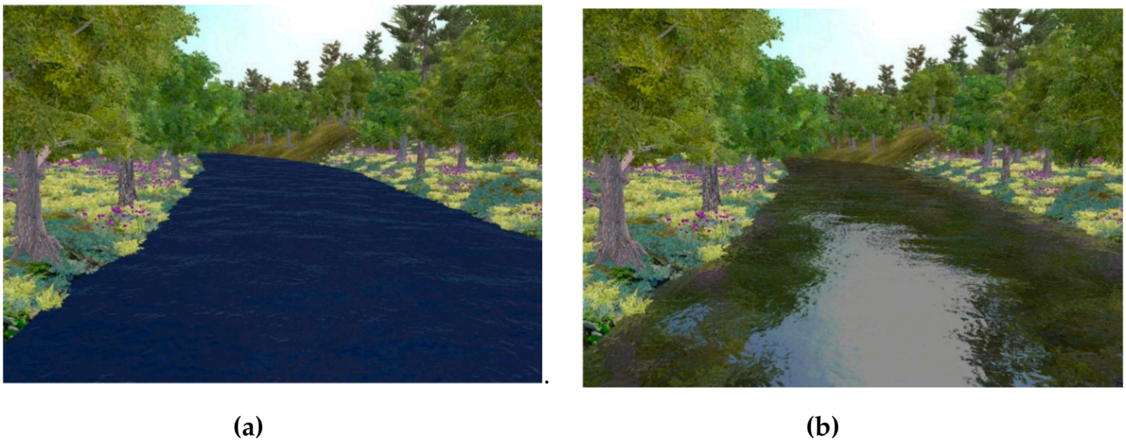
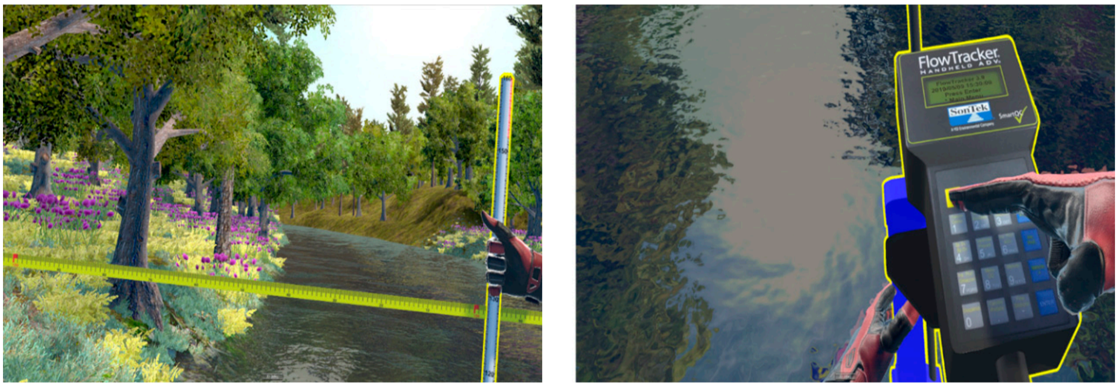

(a) (b)

Figure 4. 3D VR scene of the fluvial reach (**a**) without and (**b**) with the light refraction and the water transparency in depth.

With regard to the technical features of the VL, the students were able to quickly move around in the virtual scene (μ = 4.07, σ = 0.87) and manage the finger gestures to activate various features (μ = 3.97, σ = 0.93). However, the first students showed some problems with grabbing the equipment and placing it correctly, especially in hammering the posts in and accurately using the velocity sensors. To remove the first problem, the technician enabled each object to be highlighted in yellow at the user's touch (Figure 5). To simulate the correct use of the instruments, a control light was inserted on each of them. Therefore, when the operator starts the simulation by interacting with an instrument, its control light is red until the instrument is placed in the desired position; when the correct position is achieved, the control light turns green in order to generate user feedback on the correct execution of the task. For example, while marking the site along the banks, the user will keep hitting the top of the post with the hammer until the green light is displayed (Figure 6). These improvements introduced in the VRLab increased the rating of question 3 in category 2 and question 1 in category 3 ($\mu = 3.87$, $\sigma = 1.04$; $\mu = 4.27$, $\sigma = 0.91$).



(a) **(b)**

Figure 5. Examples of (**a**) the sounding rod and (**b**) the Acoustic Doppler Velocimeter highlighted in yellow at the user's touch.

(**a**) (**b**)

Figure 6. (**a**) Misplaced post and (**b**) correctly placed post.

Another technical problem observed during the simulated measurement procedure was the abandonment of the instruments and their fall into the water, see Figure 7a, which increased the time of the students' virtual experience. To avoid the inconvenience of having to look for and recuperate the tools in the river, the VR expert introduced a warning message to stop activity in the application, enabling them to start again from the beginning (Figure 7b).

(**a**) (**b**)

Figure 7. (**a**) An abandoned instrument in the water and (**b**) a warning message.

This also allowed the users to be corrected and to be trained to use the measurement equipment properly. The students also proposed some improvements to enhance the technical performance of the virtual tool:

- They advised the addition of further video tutorials and guidance messages as well as more virtual equipment assembling/disassembling practice to fully exploit the application potential.
- Regarding the complex steps of the water discharge measurement procedure, which were meant to be carried out simultaneously, they suggested the simplification of secondary actions while keeping the main phases as they were.
- Regarding the efficient use of the sensors, they suggested the improvement in their visualisation (Figure 8).

(**a**) (**b**)

Figure 8. Handheld keypad with (**a**) flat buttons and (**b**) lifted buttons.

With regard to the achievement of the specific objectives, they were preliminarily verified in terms of knowledge and skills, through a qualitative analysis carried out by the authors, who continuously observed the students' behaviour during their use of the SVL, and through the quantitative assessment in the last category of the questionnaire. In the future, competence will be evaluated after a more extended testing procedure in a virtual and real environment.

In the first case, the authors observed that by using the virtual environment, the students achieved a deeper knowledge of the topic compared to previous years when only theoretical lessons supported field activities. This was apparent in the more active role of students in the teaching/learning process and in more interaction between the students and the teacher. Furthermore, it was observed that the duration of the water discharge measurement procedure decreased in time (from roughly 2 to 1 h) and mastering the tool improved daily (with learners reducing their mistakes and remembering the procedure, without asking for support). The authors also noticed that the students resolved some issues faster than in previous years and had greater awareness of how important the acquisition of certain technical skills were. In addition, the students started to see the field activities not only as a new didactic experience but also as a useful opportunity to satisfy the curiosity that arose during the simulation with the virtual laboratory.

The quantitative analysis highlighted the great enthusiasm expressed by the students for the VL, who showed increased motivation while using the new technology as compared to traditional methods (μ = 3.80, σ = 1.13) and they acknowledged its didactic usefulness, especially when combined with the classical lessons (μ = 3.63, σ = 1.27). In particular, they stated how the VR Lab contributed to improving their knowledge of the methods and techniques for water discharge measurement in open-channel cross-sections (μ = 3.97, σ = 1.03). Moreover, it allowed them to look more critically at some aspects of applied hydraulics and to better understand some fluvial processes (μ = 4.37, σ = 0.81).

Finally, the main advantages underlined by the students, which confirmed the teacher's qualitative evaluation, were:

- The opportunity to attentively follow all the steps individually or in small groups.
- The opportunity to carry out the entire measurement procedure end-to-end.
- The real-time response by the teacher to their doubts.

6. Comparison of the Innovative VL with the Traditional Approach

The choice of an open-air site suitable for experiments is never easy, especially in winter months and bad weather conditions. Even during the course, the site can sometimes become inaccessible, which forces teachers to conduct field work activities in a shorter period of time and students to try and acquire knowledge and skills more quickly, inevitably leaving out some aspects of the whole measuring procedure.

Following this teaching experience, the authors propose the use of an indoor virtual environment that is not subject to time or space limitations and is always accessible during the course. This way, the learning process takes just the right amount of time and allows all students to individually practise the entire measurement procedure, which is often impossible with traditional methods. Other limitations overcome by the StreamflowVL are: problems of transport and accommodation in the case of distant sites; considerable equipment and organisational costs; risks of accidents in field; and the wearing out and breaking of misused equipment and the subsequent interruption of the activities. In particular, from an educational point of view, traditional field lessons alone carried out with large groups of students have never been completely effective, since they increase the students' waiting time for their turn to perform the experiment, distracting them and preventing them from completing all the phases of the water discharge measurement procedure. These are the main reasons why StreamflowVL, being a one-to-one teaching method, allows students to be in control, use their initiative and master unfamiliar topics while being supported when needed, and to take pleasure in the learning process itself.

The latter could also be a disadvantage in the future in the case of excessive enthusiasm in the "gaming" aspect of the VL, which can lead to distraction. SVL does not require the same level of discipline and caution that is necessary in field. However, this effect could be reduced if monitored by teachers, who can underline the seriousness of the activity, as they would do in any learning environment. The lack of hands-on contact with devices and equipment in SVL could be another limitation as it does not improve the manual skills that are acquirable by working with real-life equipment. Another disadvantage of StreamflowVL is that it must include complex mathematical models in order to take into account all the details of a real experiment.

In view of this analysis, the proposed innovative approach, which combines virtual and field lessons, seems be the most effective learning process and it is able to fill the gaps in the traditional method.

Table 3 shows a comparison between the approach proposed in this paper and the traditional one.

Table 3. Comparison between the proposed approach and the traditional one.

Main Features	Traditional Approach	Proposed Approach
Accessibility of the experimental site	Not always	Always
Level of immersion and interactivity	Weak	Strong
Level of discipline and caution	Higher	Lower
Contact with the real world	More frequent	Less frequent
Technical and organisational costs	Higher	Lower
Duration of experimental activity	Longer	Shorter
Experimental risks	High degree	Low degree

7. Conclusions and Further Development

In this paper, the authors proposed an innovative teaching/learning process through the introduction of a virtual laboratory in Hydraulic Engineering courses for simulating field experiments on water discharge monitoring in open-channel flows. StreamflowVL was developed through the Unity 3D game engine and tested using the Oculus Rift HMD. It was planned to support the traditional theoretical and practical lessons, and especially the continuous field activities that are often hard to organise within a course due to variable weather conditions (mainly in the winter period) and the poor safety or inaccessibility of certain places. By realistically reproducing a reach of river in an indoor and well-monitored environment, the VL allowed students to learn to move around a natural channel, increase their skills, and familiarise themselves with the use of sophisticated equipment and complex measurement techniques in order to avoid continuous lessons in field.

Previous studies have highlighted that the design and application of virtual environments in the classroom are more important than the type of educational technology used to fully exploit their teaching potential.

In view of this, the present virtual didactic tool was implemented through a collaborative process involving the teacher, the VR expert, and the learners. StreamflowVL has undergone several updates from its initial version up to the final one, thanks to the comments and opinions of the student sample, who contributed to the improvement of the virtual application features and performance to obtain knowledge of the water discharge measurement procedure in open channels. The qualitative and quantitative analysis, although in a preliminary phase, verified that students achieved the learning objectives in terms of knowledge and skills, while the achievement of competence will be evaluated in the future after a more extended testing procedure in a virtual and real environment. In particular, the qualitative analysis highlighted the more active role of students in the teaching/learning process and their greater interaction with the teacher. During the simulation with the virtual laboratory, the authors noted that the students achieved a deeper knowledge of the topic compared with the previous years and a greater awareness of how important the acquisition of certain technical skills were. Additionally, the quantitative analysis underlined the students' enthusiasm and interest in the topic taught through the new technology compared to the involvement observed during traditional lessons. In addition, students stated how VRLab improved their knowledge of methods and the techniques for the water discharge measurement in open-channel flows. Therefore, the use of StreamflowVL will allow diversification and change the instruction pattern from teacher-centered, passive education to student-centered, active education and from a one-to-all simultaneous learning model to a one-to-one demands learning model.

In order to further support this conclusion, further testing procedures will continue to be conducted to include similar learners in other universities, possibly implementing other virtual modules, such as flood events, the addition of structures/infrastructures within the river and other more complex situations, which could assist students in better planning and to perform field activities more autonomously. Furthermore, the combination of StreamflowVL with numerical simulation software will lead to higher standards and will have a deep influence on other application fields. In addition, the creation of new virtual environments addressing other measurement procedures, such as the bed and suspended solid transport or water sampling for quality assessment, might become the objective of other courses.

Based on the improvements following the testing phase and the subsequent extension to other modules, StreamflowVL will eventually be freely available to the Hydraulic Engineering education community.

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