# HARNESSING PHOTOGRAMMETRY FOR WHITEWATER SLALOM COURSES IN NATURAL RIVERBEDS: AN INNOVATIVE APPROACH FOR COURSE DESIGN AND ANALYSIS

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**ABSTRACT:**

Whitewater slalom, a thrilling and challenging water sport, requires carefully designed courses that provide a dynamic and engaging experience for athletes. Traditional methods of designing slalom courses in natural riverbeds have relied on manual measurements and estimations, which can be time-consuming, labour-intensive, and subject to human error. However, with the advent of photogrammetry, a cutting-edge technology that involves the use of aerial or ground-based cameras to capture and process 3D data from images, there is a new frontier in designing and analysing white water slalom courses.
This article explores the usage of photogrammetry in the context of white-water slalom course design in natural riverbeds. It highlights how photogrammetry can revolutionize the course design process by providing accurate and detailed 3D models of the riverbed terrain, which can be used for virtual simulations, rapid prototyping, and precise analysis of different design options. The advantages of using photogrammetry include improved accuracy, efficiency, and cost-effectiveness in comparison to traditional methods.
The article concludes by discussing the challenges and limitations of using photogrammetry for whitewater slalom course design, including issues related to data acquisition, processing, and accuracy. Despite these challenges, the potential of photogrammetry in revolutionizing the design and analysis of white-water slalom courses in natural riverbeds is immense, and it opens up exciting opportunities for further research, innovation, and advancement in the field of water sports.

## 1. INTRODUCTION

The development of artificial slalom courses in France, Germany and in other countries in 1970 - 1980 sought to overcome the inherent problems experienced with natural courses. If the drop in the height of a natural river along a slalom course length is measured, then it is usually found to be quite large - even as high as 20 m. If this is compared with the height difference across the course of Augsburg (Germany) about 4 m, then relatively small drops in height are very suitable for making canoe slalom courses. This is because in the artificial course the water flow is designed, whilst in the natural river it serves this purpose very inefficiently.

The following reasons for constructing artificial whitewater slalom courses have been identified:

1. To create more spectacular sites for racing and training for canoe slalom, and to extend the existing season, both of which will increase the competitors' skill level.
2. Whitewater sport, generally defined - whitewater canoeing, kayaking, rafting, or even inner tubing - has become one of the major growth sports of the 1980 and 1990's. Thus, creating more facilities for people living in densely populated area makes a lot of sense, because it increases the possibilities of participating in an outdoor sport.
3. Increase the popular appeal of canoe slalom by giving it more exposure to large numbers of spectator and television audiences. Normal slaloms, being held in remote, wilderness areas are hard to get to and thus do not attract large numbers of spectators and media coverage.
4. Protection of the environment. The creation of new facilities for water sports parks would eliminate the current tendency to hold slalom races in existing wildlife parks, which in some cases interferes with the park's aim of protecting the air, water, animal life, and foliage recourses.

### 1.1 Slalom courses expectations

The construction of an artificial slalom course is intended to serve as a recreational sports activity and to continue the tradition of water sports in the area. The course is designed to be multi-purpose and allows for the practice of several sports and activities, such as water slalom and downhill, leisurely rides on any type of vessel (canoe, paddleboard, raft, etc.).

The expectation of these courses falls into broad categories. Firsts, from the athletes' point of view, there is the expectation of an exciting, spectacular course. Secondly, from the promoters' point of view, is the expectation of a facility that is attractive to spectators and the public, who may never actually go on the water, but will often come to observe what is going on there. Thirdly, the course must be safe for all categories of users, ranging from elite to novice. Lastly, from the financier's point of view, the course must be affordable, both to design and construct initially, but also to maintain in the future.

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**1.1.1 General users** of the course break down into two categories: elite athletes, who would like to use the course for important races, such as National Championships, or World Championships, or training for events like these; and people with much less skill - let's say novices - who want a much less difficult course.

**1.1.2 Elite athletes** want a course with the following characteristics:

1. It should conform to the standards of the International Canoe Federation (ICF), the international governing body of the sport, in that the course should be from the minimum length 200 m and the maximum length 400 m measured from the start line to the finish line down the center-line of the course.
2. Based on much experience of athletes, coaches and expert engineers, the width should be approximately 10 meters, with variations permissible in short sections.
3. Again, based on experience, the depth should be 0.6 m or more, to make it safe for eskimo rolling and playing. It should be noted, however, that the deeper the water, the more volume of water must be available from the reservoir, and this may be a limiting factor.
4. A rather severe drop in all or at least many sections. Experience has shown this to be in the vicinity of 3 - 5 m over the entire length of the course. These figures are based on what athletes would like, but also on the costs involved. Drops of natural rivers are usually found to be quite large, even as high as 20 m. If this is compared with the height difference on the course at Augsburg (about 4 m) it can be seen that relatively small drops in height are very suitable for making artificial canoe slalom courses. This is because in the artificial course the water flow is designed, and hence efficient, while in the natural river it is inefficient.
5. A sufficient discharge through the course. Experience had shown this to be roughly from 10 – 20 m^3/s. The lower figure would be appropriate for a training course and the higher figure would be appropriate for a top international race.

**1.1.3 Novices** want a course with the following characteristics:

1. All the above hydraulic features, but on a smaller scale.
2. Long stretches of water deep enough in which to eskimo roll, because they will often go through many attempts.
3. a safe and quick escape from the course, should they capsize and fail to roll.
4. a positioning of obstacles which permits a more direct passage down the river, unlike the elite athlete who would like a more twisting passage.

**1.1.4 Spectators** want the following:

1. An exciting course to watch.
2. A comfortable place from which to watch.
3. He wants to be able to see a lot of the course from one location.
4. Refreshments, rest rooms and other comforts.
5. Things to do besides just watch the race; he may be accompanied by small children who are easily bored.
6. SAFETY. This is included in some of the above descriptions, but the following points should be added:
7. Smooth contoured edges on all solid obstacles, such as river banks, boulders forming eddies, stoppers, etc.
8. Large enough obstacles to prevent "wrapping" a canoe around them.
9. No possibility of foot entrapment.

**1.1.5 The financier** simply needs to know that he can afford to build and maintain the facility. Thus, he needs to be able to raise the funds through governmental or commercial sources and he may want to design a program whereby users pay for using the course.

### 1.2 Natural vs artificial slalom courses

When it comes to whitewater slalom courses, the choice between natural and artificial courses is an important consideration for course designers and event organizers. Natural slalom courses are typically located on rivers or streams, utilizing the existing topography and water flow patterns. These courses offer a unique and challenging experience, as they require competitors to navigate through the unpredictable and dynamic nature of the river (Chanson, 2004). The natural environment provides a diverse range of obstacles, such as rocks, waves, and eddies, which demand quick decision-making and precise manoeuvring from the athletes. Natural slalom courses also offer a visually appealing setting, with the surrounding landscapes adding to the overall experience. However, the availability and suitability of natural riverbeds for slalom courses can vary, and it may be challenging to find suitable locations with the desired characteristics for competitive events.

In contrast, artificial slalom courses are man-made installations specifically designed for whitewater slalom competitions. These courses are constructed using concrete, plastic, or other materials, and can be built in a controlled environment, such as a purpose-built water channel. Artificial courses provide several advantages, including consistent water flow and obstacle placement, which allows for precise course design and predictability during competitions. These courses can be customized to replicate challenging river features, such as waves and eddies, ensuring a standardized experience for all competitors. Additionally, artificial courses offer the flexibility to modify and adjust the course layout based on specific event requirements or changing water conditions. However, the construction and maintenance of artificial slalom courses can be costly, and they may lack the natural aesthetics and variability of terrain found in natural riverbeds (Bémová, Pollert, 1996).

## 2. METHODOLOGY OF ARTIFICIAL/NATURAL SLALOM COURSES

For the project of harnessing photogrammetry for whitewater slalom courses in natural riverbeds, the integration of an innovative technology called "digital twin" becomes imperative from the outset. The concept of a digital twin involves creating a virtual replica of the terrain that can be modified and validated throughout the project to ensure it meets all the necessary requirements. This technology allows for comprehensive assessments to be conducted both virtually, through techniques like 3D visualization and computational fluid dynamics (CFD) flow modeling, and physically, by generating models for visualization or employing physical modeling techniques to assess the flow dynamics. The resulting data and insights can then be utilized for project documentation purposes or even for the production of real objects with unconventional shapes. One of the key advantages of digital twin technology is the seamless connectivity and interdependence of its individual elements, providing a holistic and integrated approach to course design and analysis.

By employing a digital twin approach, designers and stakeholders can benefit from a range of advantages throughout the project. The continuous monitoring and modification of the digital twin enable real-time adjustments and optimizations, ensuring that the final slalom course aligns with the desired specifications. The virtual assessments, such as 3D visualizations and CFD flow modeling, allow for thorough analysis of the course layout, identifying potential bottlenecks, safety concerns, and optimizing the flow dynamics for enhanced performance (Streeter, Wylie, Bedford, 1998). Additionally, the physical manifestations of the digital twin, such as printing models, offer tangible representations that aid in visualization and provide a more intuitive understanding of the proposed design. The interconnected nature of the digital twin facilitates collaboration among various stakeholders, including course designers, engineers, and event organizers, fostering effective communication and informed decision-making throughout the entire project lifecycle. Ultimately, harnessing the potential of the digital twin technology empowers course designers to create innovative, well-informed, and optimized whitewater slalom courses in natural riverbeds.

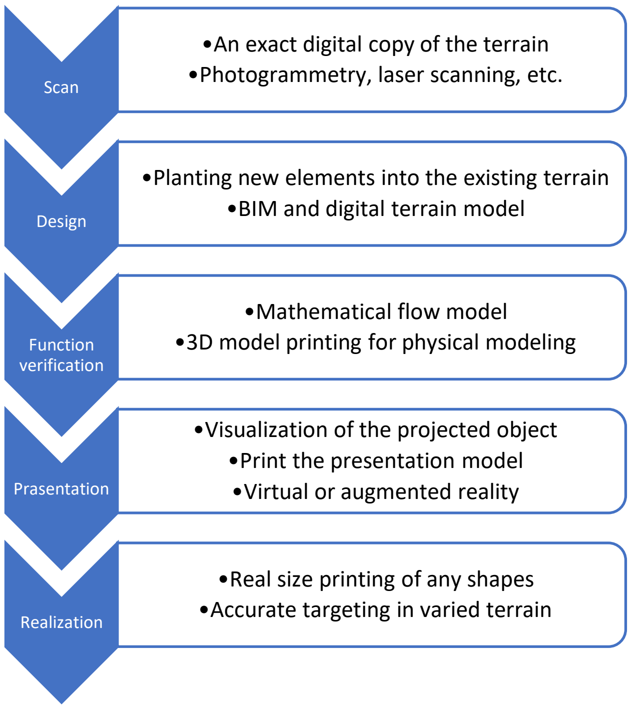


**Figure 1.** Methodology schematics.

## 2.1 Scan

The initial and pivotal step in the process of designing a whitewater slalom course in a natural riverbed involves a detailed scanning of the river terrain as previously mentioned. This phase is crucial in providing an accurate and comprehensive representation of the riverbed's current state, which is then utilized as the foundation for the subsequent design and analysis processes.

To capture the physical attributes and nuances of the riverbed, two primary scanning technologies are employed: photogrammetry and laser scanning. Both of these technologies offer distinct advantages and are selected based on the specific requirements and constraints of the project. Photogrammetry uses perspective geometry to create 3D models from 2D images, captured by drones or on-ground cameras. Laser scanning, or LiDAR, utilizes pulsed laser light to measure the precise 3D coordinates of the river terrain. Both methods offer unique advantages and are chosen based on project-specific requirements.

Following data acquisition, the data sets are integrated and processed to create a "digital twin" of the riverbed. This accurate 3D model forms the foundation for subsequent design and analysis phases, ensuring the creation of a slalom course tailored to the unique characteristics of the natural riverbed.

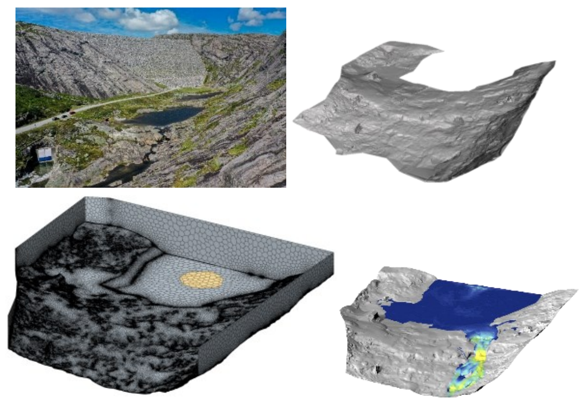

**Figure 2.** Examples of riverbed scans.

## 2.2 Functional model

The actual design process takes place when the scan has been finally prepared for it. The riverbed model can be utilized at this point for a CFD simulation of the initial state as well as possible rearrangement ideas: various obstacles configurations, riverbed leveling, etc. The result of this step of the process is one or a set of designs for a new artificial slalom course in the riverbed in which planed encroachments are modelled in different layers in a 3D graphical editor (Figure 3). This layering allows for a quick and precise definition of volume of earthworks needed.

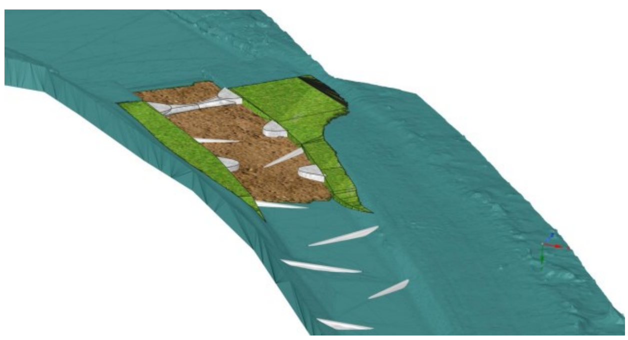

**Figure 3.** "Jez Svaté pole" artificial slalom course in natural riverbed.

### 2.2.1 Obstacles in natural whitewater slalom course:

When working with whitewater courses, it is crucial to utilize obstacles in a sparing and effective manner. The obstacles come in three standardized but irregular shapes: trimmed cylinders, boulders, and a connector located at the beginning of the course (Figures 4-6). The shape of these obstacles varies due to the fluctuation in water flow. During low flows, the obstacles are less submerged and generate a meandering flow, while during high flows, they become more submerged, resulting in undulating or cylindrical water terrain. This variability allows for operation under different flow conditions. In certain areas, the obstacles are positioned in proximity to create a water jump effect. When the obstacles are placed alternately, they generate a meandering flow pattern with return currents on the sides, making it suitable for sectional training.

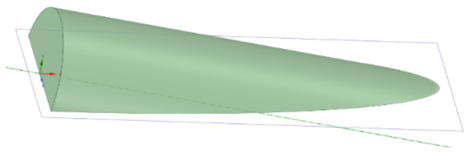

**Figure 4.** Trimmed-cylinder-shaped obstacle.

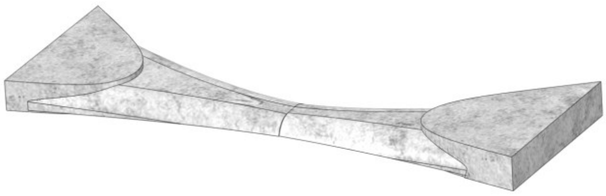

**Figure 5.** Connector obstacle.

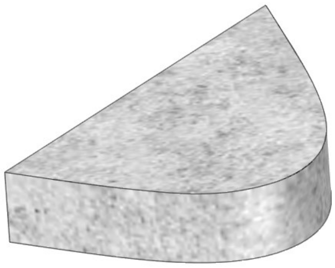

**Figure 6.** Boulder shaped obstacle.

### 2.3 Functional verification

The functional verification phase is vital in the design process of a whitewater slalom course. Once the "digital twin" model has been generated, it needs to be assessed to determine whether it accurately represents the physical characteristics of the natural riverbed and the potential modifications needed for the slalom course. This stage involves virtual simulations using advanced CFD models to analyze the river flow dynamics. Through these simulations, the water flow behavior around the proposed artificial obstacles is examined under different flow conditions. This process helps identify how different flow rates affect the course's operation, including the creation of different water flow features such as waves, eddies, and stoppers.

The functional verification phase also evaluates the energy loss associated with the proposed course design. By using smooth-shaped obstacles, the design aims to create a diverse range of water flow features with minimal energy loss, thus maintaining the river's natural flow characteristics as much as possible.

Additionally, the CFD model allows for the testing of different course layouts and obstacle placements virtually. It enables designers to optimize the course design for both elite athletes and novices, ensuring that the course is challenging yet safe.

### 2.4 Realization

The realization phase marks the transition from digital design to tangible implementation, turning the meticulously verified digital twin model into a functioning, real-world whitewater slalom course.

Our approach to the realization phase leverages the advancements in 3D printing technology. Using the 3D model, we 3D print the concrete obstacles (Figure 7) and, in some cases, even parts of the riverbank. The objective is to achieve a natural shape that not only accurately reflects the model but can also be adjusted as necessary to achieve optimal results with minimal encroachment on the natural riverbed. Concrete 3D printing allows for the production of obstacles and terrain modifications of any shape, mirroring the intricate details of the digital twin model. This is particularly advantageous in varied terrain where achieving the desired result through traditional construction methods might be challenging. This work is typically outsourced to a company specializing in 3D concrete printing. Their expertise ensures that the 3D printed elements accurately represent the digital twin model, offering the best possible approximation of the theoretical design.

**Figure 7.** 3D printed obstacle made out of concrete.

The accurate targeting of the 3D printed elements in varied terrain is facilitated by advanced geolocation technologies. These technologies ensure precise placement of the printed obstacles and terrain modifications, aligning the real-world course with its digital twin. The realization phase underscores the symbiosis between cutting-edge technology and ecological responsibility, bringing to life a whitewater slalom course that combines competitive challenge, safety, and respect for the natural environment.

## 3. CASE STUDIES

Our methodology has been successfully applied in various scenarios, showcasing its versatility and effectiveness. We'll explore its application through three different case studies: the Norway Feasibility Study, the Whitewater Course in Kadaň, and the Svaté Pole River Weir project — both in the Czech Republic.

### 3.1 Norway Litleåna River Feasibility Study

The Norway Litleåna river Feasibility Study demonstrates how our approach is used to assess the possibility of transforming a section of the Litleåna river for a broad range of water sports. Using photogrammetry, we created a 3D model of the river, which served as a basis for CFD analysis. This information allowed us to propose improvements such as oval-shaped obstacles made of local stone and concrete. With these modifications, the river could potentially host a range of sports, from swimming and canyoning to whitewater slalom and rafting, throughout the year. This case study showcases how our methodology can contribute to sustainable river redesign, enhancing the recreational potential while minimizing environmental impact.

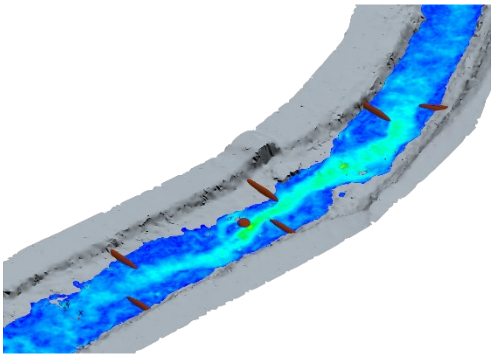

**Figure 8.** CFD Simulation in Litleåna 3D model with obstacles.

### 3.2 Whitewater Course in Kadaň, Czech Republic

The Whitewater Course in Kadaň represents a unique application of our methodology, with the proposal to create one of the world's first 3D printed whitewater slalom course. Our methodology informed the proposal, with our digital twin model guiding the 3D printing process. This case highlights the potential of the methodology for innovative construction techniques and its adaptability to diverse contexts.

Firstly, the riverbed was drone scanned to create a 3D model for CFD simulations. Secondly, a scaled physical model of the river's stretch was locally 3D printed. Finally, the physical model was connected with the CFD results by projecting the results on the running model with augmented reality (AR) goggles. That way an engineer has a much easier time assessing the designs. Currently, the implementation of the course is being processed by the local authorities.

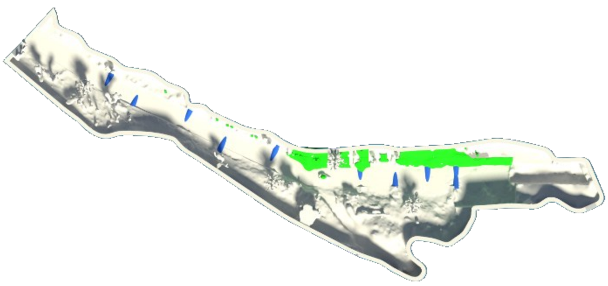

**Figure 9.** Model of the river stretch in Kadaň made from the scans.

### 3.3 Svaté Pole River Weir, Czech Republic

In the Svaté Pole project, we employed drone technology to scan the riverbed and surroundings, transforming the raw data into a 3D model. This model then served as a basis for CFD simulations, enabling us to propose modifications for a canoe slalom course. This case demonstrates the integration of our methodology with advanced technology like drones and its application for river management and whitewater sports infrastructure design (Figure 3).

Each case study underlines the versatility of our methodology, its adaptability to diverse contexts, and its potential for sustainable and innovative river redesign.

## 4. CONCLUSIONS

In this work, we have detailed a comprehensive methodology for designing and implementing whitewater slalom courses, from initial feasibility studies to the final realization. We have shown how advanced technologies, such as photogrammetry, computational fluid dynamics, and 3D printing, can be integrated into the process, allowing for precise modeling, analysis, and construction. The case studies presented illustrate the flexibility and adaptability of this approach. In the Norway feasibility study, we saw how the methodology could be used to assess a river's suitability for a wide range of water sports, and plan for environmentally friendly, yet effective improvements. The whitewater course in Kadaň showcased the potential for 3D printing in the construction of slalom courses, guided by our accurate digital twin models. The Svaté Pole river weir project demonstrated the integration of drone technology into our methodology, enabling detailed scanning of river terrain for precise model creation and simulation.

The methodology presented in this paper offers a robust and versatile solution for the design and implementation of whitewater slalom courses. It addresses the complexities of such projects, adhering to international canoe slalom rules, and IOC requirements, while taking into account constraints such as limited construction areas and environmental impacts. By incorporating advanced technologies and a systematic approach, it paves the way for more sustainable, innovative, and effective slalom course design, ultimately contributing to the growth and accessibility of whitewater sports.

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