Going into Depth: Learning from a Survey of Interactive Designs for Aquatic Recreation

Christal Clashing
Exertion Games Lab, Department of Human-Centred Computing, Monash University, Melbourne, Australia
christal@exertiongameslab.org

Ian Smith
Faculty of Computer Science, University of New Brunswick, Fredericton, Canada
iansmith.bwr@unb.ca

Maria F. Montoya
Exertion Games Lab, Department of Human-Centred Computing, Monash University, Melbourne, Australia
maria@exertiongameslab.org

Rakesh Patibanda
Exertion Games Lab, Department of Human-Centred Computing, Monash University, Melbourne, Australia
rakesh@exertiongameslab.org

Swamy Ananthanarayan
Department of Human-Centred Computing, Monash University, Melbourne, Australia
swamy.ananthanarayan@monash.edu

Sarah Jane Pell
Exertion Games Lab, Department of Human-Centred Computing, Monash University, Melbourne, Australia
research@sarahjanepell.com

Florian 'Floyd' Mueller
Exertion Games Lab, Department of Human-Centred Computing, Monash University, Melbourne, Australia
floyd@exertiongameslab.org

ABSTRACT

Aquatic recreation encompasses a variety of water-based activities from which participants gain physical, mental, and social benefits. Although interactive technologies for supporting aquatic recreation activities have increased in recent years, the HCI community does not yet have a structured understanding of approaches to interaction design for aquatic recreation. To contribute towards such an understanding, we present the results of a systematic review of 48 papers on the design of interactive technology for aquatic recreation, drawn from the ACM, IEEE, and SPORTDiscus libraries. This review presents an aquatic recreation user experience framework that details problems and opportunities concerning water and HCI. Our framework brings us closer to understanding how technology can interact with users and the aquatic environment to enhance the existing recreational experiences that connect us to aquatic environments. We found that designers can elicit delight, enablement, challenge, and synergy in aquatic recreation experiences.

CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); HCI theory, concepts and models.

KEYWORDS

water, aquatic, games, play, sports, physical activity, recreation, exercise

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1 INTRODUCTION: WADING IN

Water is a crucial resource for sustaining life and is also used by many as a medium of recreation. For example, 36% of American children and 15% of American adults regularly go swimming in pools, lakes and oceans [125], while many engage in other watersports such as kayaking, surfing, diving, jet-skiing or fishing. These aquatic recreation activities can be enjoyed for their autotelic qualities and also offer physical, mental, social, and emotional benefits [43]. In HCI, interaction designers seem to pay limited attention to the aquatic domain when compared to land-based recreation support, such as provided through apps for joggers [86], video cameras to support soccer players [99], heart rate monitors for skiers [123] and sports watches for tracking a wide range of recreation activities [13, 131]. However, excitingly for us, we have seen interactive designs emerge in recent years targeting the aquatic domain.

The scope of this review has focused on interaction design supporting aquatic recreation activities regardless of whether the activities are concerned with interactive technology around (e.g., water jets), in (e.g., swimming), on (e.g., surfing), or under (e.g., diving) water. While our review has revealed several interactive systems to support aquatic recreation activities; we collectively refer to them as "aquatic systems." The premise of our research was that

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there seemed to be a knowledge gap regarding guidance on how to design such aquatic systems. It was our assumption that a lack in such guidance limits the scope for interaction designers in creating better systems to support aquatic recreation. Simply applying existing land-based knowledge (such as [74, 82, 84]) to aquatic systems therefore misses out on unique characteristics of the aquatic domain such as buoyancy, drag, and safety in water, which we discuss below. Consequently, many people will not benefit from the possible opportunities that HCI can offer to support aquatic recreation activities without a structured and expansive understanding, and hence might miss out on the many benefits associated with aquatic activities.

To begin filling this gap in knowledge, we have identified the potential usefulness to collect the knowledge inherent in the many papers on aquatic systems that emerged in HCI over the years. Notably, many papers in our review often concluded with fascinating insights for the design of future aquatic systems; however, we find that these important discovery insights were often buried within the broader paper discussions [102]. Our aim was to extract these nuggets of knowledge. To achieve this, we collected and analysed prior papers concerned with aquatic systems by means of a systemised survey, and then synthesised the individual results into a higher-level framework for the design of future aquatic systems. With this review of existing aquatic systems literature, we hope that we can begin answering the research question: how do we design aquatic systems?

From our analysis, we offer the HCI community a user experience framework that articulates four different user experiences based on two dimensions: the impact of water (i.e., whether it is a “problem” or “opportunity”) on a user and technology. These user experiences can be useful for both evaluators aiming to analyse user experiences of aquatic systems, and practitioners who want to anticipate what kinds of user experiences they can expect with their designs. We also present insights derived from each user experience dimension that designers can use when aiming to create future aquatic systems. Our contribution concludes with observations and questions for design researchers in the HCI community to ponder if they seek to develop meaningful aquatic recreation experiences. We hope that our framework helps interaction designers understand how technology can be used in aquatic environments.

2 BACKGROUND: DIPPING OUR HCI TOES INTO THE WATER

The following subsections describe insights from prior work on water in HCI, particularly aquatic recreation and technology and the properties of water considered by researchers in their interaction designs.

2.1 Water and HCI

HCI researchers have increasingly engaged with water. The SWIM (Sequential Wave Imprinting Machine) has been used since 1974 to visualise wave propagation in water [58]. Designers used water for data visualization [56, 108], to replace mechanical force feedback with water jets [42, 108], to influence people's daily water intake [118], to teach water saving techniques using mobile applications [114], and as a medium for tangible interactive systems like augmented drinking cups [128, 129]. We learn from these prior works that interaction design and water can benefit from one another. However, we take a different angle on the coming together of water and interaction design by drawing inspiration from body-centric HCI developments [68, 69, 72, 75] that highlight the opportunity for interactive technology to support recreation activities. These developments have already resulted in intriguing sub-areas of HCI, such as exertion games [70, 73, 74], sportsHCI [2, 71, 83, 90, 91, 107], whole-body interaction [101], as well as related areas such as somaesthetics [40]. We learn that focusing on recreation activities can result in unique sub-areas of HCI. However, we note that so far, these sub-areas appear to mostly focus on land-based activities, such as exercise like running [76, 78, 86], physical leisure activities like climbing [46, 50] and play occurring in playgrounds [4, 8]. We believe that interaction design research can similarly benefit the aquatic recreation space by dedicated attention to the unique properties and recognition of the inherent agency of water (such as buoyancy, drag and safety, see below).

2.2 Recreation and HCI

Prior work shows how HCI can support recreation. While many aquatic activities can be classed as recreational activities [6, 16], we acknowledge that they can also be utilitarian, competitive, educational, and therapeutic in form and purpose [31]. In comparison to idleness or rest, we assume the position that recreation is an activity that can involve individual “physical, mental, social or emotional” engagement driven by internal motivation rather than extrinsic reward [43]. As recreation means to “re-create” oneself, the engagement in a recreational activity means to be refreshed enough to return to the daily tasks of life [18].

Broadly, prior work in HCI has aimed to support recreational activities where the user is seeking pleasure – even proposing that pleasure in a recreational activity is a virtue or “a desirable disposition” [83, 85]. Where motivated by the user seeking pleasure [43], the revitalisation of one's spirit, initiative and perspective on life indicates the success of a recreational activity [45]. This review has identified recommendations for methods of designing for recreation to be further developed [82]. Our work replies by focusing on design for aquatic recreation. Furthermore, we learned from prior work that while designers cannot guarantee pleasure or the refreshment of a user's spirit from engagement with an interactive recreational system [115], we can design recreational systems that offer cues and signals to promote such an outcome [61]. Hence, with our work, we considered systems that aim to facilitate such an outcome with a particular focus on aquatic systems.

Expanding our design knowledge of the intrinsic affordances of body-aquatic interactions underpins how and why we dip our (HCI) toes into recreational waters. The body of water itself directly impacts on the individual and social sense of oneself. For example, an individual's agency can be challenged, suspended, or supported by water. The experiential virtues that attract us to water are linked to the element of survival and range from pleasure known as “hydrophilia”, to a visceral terror known as “hydrophobia.” Freedivers refer to a “rapture of the deep,” underwater performers describe seeking to go beyond the Jungian psychological view of the body to "become a body of water" [97], while hydrophobics oppose such acts. Cultural theorist Virilio believes that the internal motivation towards recreational aquatic activities is a type of self "mutualism", contributing to an "aesthetic of disappearance" [105], and he warns that acts of immersion in an aquatic (or a virtual) environment are "a pitiless art" [127]. For centuries, individuals have sought to master activity in water as much as inactivity – from floating mindlessly to vigorous play – and are motivated to escape or reconnect to the natural body. In both extreme practices, it is the form and activity of the body of water itself that largely determines the extent of an individual's recreational or leisurely activity.

We, therefore, learn that designing for the water can be a complex and philosophical endeavour and existing HCI knowledge may not be sufficient to advance the design of future aquatic systems. Despite the complexity, non-digital work, such as overview articles [31], manuals [1, 51] and design guidelines for sites of aquatic activity [1, 51], which guide safety and inclusivity needs, all indicate that aquatic systems are worthy of study. We gather from these sources that our work could positively impact traditional aquatic recreation. For example, adding interactive technology to modulate the sensory aspects of water engagement through technology could be advantageous for certain populations, such as those with autism [1].

2.3 Prior Work around Technology Support for Aquatic Recreation

We also learned from prior work around technology supporting aquatic recreation. These prior works mostly highlight that water is a difficult medium to design for because it often requires waterproofing electronics [10, 20, 55, 102]. Therefore, interactive technologies can be seen as antagonistic to aquatic environments based on the high electrical conductivity of impurities in water [62]. As a result, interactive recreational systems are typically unsafe or impractical in wet environments, while wireless components have challenges of communication interference through the medium [87, 126]. Furthermore, the dynamism of water's movement adds more complexity to the body and technology than from the relative predictability of moving through the lesser density of air [104]. Therefore, we learned that prior investigations around the use of technology to support aquatic activities have typically come from technical papers detailing sensor deployment in the aquatic domain [27, 106]. As these, in the past, required extensive technical knowledge and resources, they were predominantly focused on supporting elite sporting performances [28, 38, 117]. We learn from these prior works that technology can support the aquatic domain; however, we believe that with technological advances making low-cost prototyping more feasible, not just elite athletes but also recreational activity participants should be supported. Hence, in our work, we focus on aquatic recreational activities.

2.4 Designing for Water's Properties

Our review also casts a lens on prior work relating specifically to designing for the properties of water. This is important, as recreational aquatic activities are subject to properties that are less pronounced or not even present in land-based activities, resulting in vastly different environmental conditions. Shmeis et al. listed a set of properties of water: depth, temperature, pressure, visibility, light, sound, water flow, non-open water environment and open water environment [116]. These properties change sensory perception, physical movement, and physical abilities compared to engaging in land-based recreational activities [98]. Therefore, these factors should be considered when designing for aquatic recreation; we looked out for these and noted how designers engaged with them in our surveyed papers. Prior work positioned the manipulation of sensory perception, physical movement, and physical abilities as potential constraints for the human body during recreational activity [61]; however, previous research also advocated seeing such environmental factors as opportunities [46, 50, 82]. We also see them as an opportunity for interaction design (hence our higher-level framework identified water as both a problem and an opportunity, which we describe later). Furthermore, we note that the aforementioned constraints can be dangerous in many aquatic environments when users lack the proper skill set (e.g., participants can drown if they cannot swim). We therefore believe that designers must factor in how to harness or countermeasure the impact of these properties through informed risk assessment and within acceptable margins of safety. This has led Raffe et al. to propose to see these constraints/opportunities as varying in degree depending on one's vicinity to water [103]. To help design future aquatic systems, the authors therein applied the "exertion framework" [71] to various water interactions to identify six degrees of water contact with the human body and the implication of each for interactive systems. These degrees of contact are listed as "vicinity", "sporadic contact", "on top of water", "partially submerged", "floating" and "underwater". Each degree of contact has varying impacts on human senses, homeostasis, and motor skills, which serve as unique constraints that can enhance or hamper the aquatic experience. From this work, we learned that considering the various properties of water can help us understand the resulting user experiences when supported by technology, which we considered in our framework that we present later. Although this prior work by Raffe et al. [103] provides an interesting proposal of how to think about water and interactive technology, we note that the authors themselves acknowledge that it has not yet been validated, hence our work is still needed.

In summary, we have learned from prior work that interaction design can support recreational activities, and that initial investigations into the design of aquatic systems has begun; however, our understanding of how to design such systems is still underdeveloped. In response, to begin filling this gap in our knowledge, we aim to answer the question of how to design aquatic systems.

3 METHOD: DIVING DEEP INTO THE LITERATURE

Following previous survey papers in HCI [41, 48, 111, 122], we implemented a process of browsing, screening (in which we acknowledge limitations), final appraisal, analysis and synthesis of papers to identify emergent themes. The processes and results are outlined visually in Figure 1

3.1 Browsing

As prior surveys in HCI seem to focus on ACM and IEEE [41, 48, 111, 122], we also decided to also start there. Our past experiences (the first author has prior degrees in sports studies and the second author has coached competitive swimming for 11 years) suggest that sports science research can also often produce interesting interactive systems for recreation. We hence included SPORTDiscus, a large and popular sports and recreation database, to cover additional papers typically not found in HCI-relevant databases. We might also make more interaction designers aware of this underutilized resource for HCI by including this database.

We conducted a keyword search that used both compound words around recreation and water (e.g., water play) as well as logical AND/OR combinations (e.g., "water AND sports AND (device OR technology)"). We also employed keywords associated with water recreation such as swimming, kayak, and surfing.

An initial ad-hoc search revealed that any interactive systems before 2010 appeared to be mostly being discussed in terms of their usability for managing water (such as usability of water management systems in pools), probably because only more waterproofing efforts such as splash proof mobile phones have seen wide-spread adoption more recently [38]. Hence, we have limited our search to publications newer than 2010. This resulted in a reasonable result size (aligned with prior similar searches [41, 48, 111, 122]) yielding 830 entries in the ACM Digital Library, 274 entries in IEEE Xplore, and 408 entries in SPORTSDiscus, for a total of 1512 papers to be screened.

3.2 Screening

Across the ACM, IEEE, and SPORTDiscus database searches, we included original, peer-reviewed research and excluded workshop proposals, newsletters, commentaries, summaries, posters, magazine articles, and student theses. The focus on full texts may have excluded other developing bodies of work. Moreover, each database runs the potential of bias inherent in their search algorithms obscuring relevant papers. Furthermore, we acknowledge that we have collected predominantly system papers for the development of our framework, e.g., IEEE focuses mostly on technical contributions. Screening was a two-step process. In the first step, we included only papers that involve recreational activities around water. We decided to thoroughly investigate interactive systems that utilise water for recreation. For example, our search yielded papers that modelled the flow of waterways but did not relate to human recreation [11, 39]. In the second step, we filtered our papers to only those presenting a feedback loop between the interactive system and the user. This excluded, for example, systems that analysed swimming technique offline and did not offer the athlete any output [32].

The initial 1512 ACM, IEEE, and SPORTDiscus papers were screened by the 1st, 2nd and 3rd author to exclude topics such as sustainability, hydration, conservation, physiology (e.g., sweat), water management and virtual reality (VR)/augmented reality (AR) simulations of water that did not involve any contact with physical water (e.g. VR to simulate the underwater diving experience [44]). These screenings resulted in 212 papers. To account for important works published earlier than 2010 or outside the scope of our databases, we employed backward-chaining to this paper set, examining all papers referenced by these 212 works against the

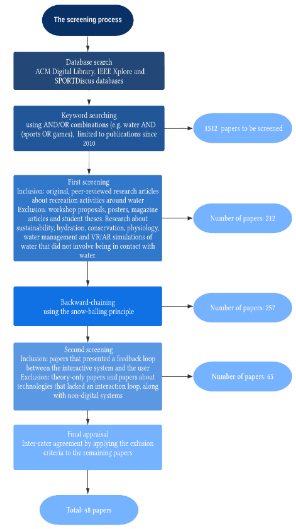

Figure 1: The paper screening and selection process.

inclusion and exclusion criteria (snow-balling principle [132], see Figure 1).

This process identified papers as far back as 1996 and yielded 101 additional papers. Removing duplicates, 257 papers remained for further screening. We acknowledge there are systems that have been developed prior to 1996 that were not captured in our screening. In the second step of screening, we excluded theory-only papers and papers about technologies that lacked an interaction loop with their users (e.g., computer vision algorithms, wireless communication assessments, development of physiological or biomechanical models [19]) along with non-digital systems (e.g. more efficient swimsuits [7]). This process resulted in a set of 65 papers.

3.3 Final Appraisal

After the second screening step, the 2nd and 3rd authors measured their inter-rater agreement by applying the exclusion criteria to the remaining paper titles and abstracts, along with full texts when important details about the interactive systems were ambiguous. Their 82.4% accordance indicates a substantial inter-rater agreement [63] with κ =.674 (95% CI, .60 to .80). Discrepancies were discussed on a per-paper basis, and their consensus led to a final set of 48 papers (Figure 1). The 1st author was left out of the process to mediate any discrepancies; however, their input was not needed as all discrepancy discussions led to unanimous agreement.

3.4 Analysis and Synthesis

The final set of 48 papers went through an open coding process, with the first three authors noting observations regarding the activity they addressed, the system's feedback loop, and how water was incorporated. Common themes were aggregated from these observations and iterated over for internal consistency. These initial themes included "interfaces encouraging socialisation" and "proximity to water influences technological integration," along with activity-based categorizations such as "fitness/sport." Through these themes it became clear that water presented unique challenges and opportunities for interaction when compared to similar land-based scenarios. The 1st and 2nd author positioned each paper in a 2-dimensional space with each axis ranging from "water as a problem" to "water as an opportunity" for either users or technology (Figure 3). These axes were determined by the coding process, where prevalent issues such as waterproofing indicated water as a problem. Conversely, other papers sought to leverage water dynamics, thus viewing water as an opportunity. The position of each paper along these axes was determined by considering to what degree a system's design considered water as a problem or an opportunity. The 3rd author determined the position of any papers that the 1st and 2nd authors did not firmly agree on; there were no drastic disagreements, only small shifts in terms of opportunities in the five papers.

Clustering was attempted over interaction characteristics such as type of activity and degree of contact with water. These efforts failed to draw meaningful insights into the design of aquatic interactions, so the opposite approach was taken by looking for commonalities between the papers in each quadrant of the space. We identified an overarching user experience for each quadrant and considered how systems might be redesigned to transition their interaction from one experience to another.

4 RESULTS: RISING TO THE SURFACE

We first provide an overview of the application of technologies to various types of aquatic recreation over time. We then identify the properties of water engaged within aquatic systems which sets the foundation for concepts covered in the discussion. Our framework brings us a step closer to understanding how technology can interact with users and the aquatic environment to enhance the existing recreational experiences that connect us to aquatic environments. We offer the HCI community a user experience framework that articulates four different user experiences based on two dimensions: the impact of water (i.e., whether it is a "problem" or "opportunity") on a user and technology. These user experiences can be useful for evaluators aiming to analyze user experiences of aquatic systems and practitioners who want to anticipate what kinds of user experiences they can expect with their designs. Summarising the insights of each user experience are design considerations that designers can use when aiming to create future aquatic systems. Our contribution concludes with observations and questions for design researchers in the HCI community to ponder if they seek to develop meaningful aquatic recreation experiences.

4.1 A Historical Overview of Aquatic Recreation in HCI: Changing Tides

Our analysis revealed that there has been an evolution of technology supporting interactive aquatic recreation over the last 25 years (Figure 2). Across the 48 publications investigated, four general types of technology are observed in their aquatic systems. These include water vessels, tracking technology, robotic systems, and extended reality (XR). Water vessels refer to systems that control the flow or containment of water such as pumps [29, 42, 56, 57, 95, 96, 108], low-frequency speakers [60], and receptacles [17, 37, 49, 56, 57, 60, 98, 120]. Tracking technologies assess the user's movements through inertial sensors [3, 22, 23, 38, 47, 52–54, 98, 102, 110], pressure sensors [55], RFID tags [15], GPS [104], cameras [112], and computer vision technology [42, 49, 60, 67, 92, 124, 135]. Robotic systems explore human-robot interaction in recreational settings [88, 98, 124], while XR includes augmented [9, 10, 12, 14, 20, 21, 49, 60, 93, 94, 135] and virtual reality applications [26, 102] that also feature tracking, but focus on the user's perspective rather than body movements. These systems are used within aquatic recreation at various points across a span of four decades (the 1990s, 2000s, 2010s, and 2020s), which we detail next.

Rapid Scout, the lone interactive system of the 1990s in this review, explored aquatic recreation in the natural environment using tracking technology for white water rafters [104]. The systems at the start of the 2000s utilised water vessels or pumps to provide interactivity to users [56, 57, 95, 96]. Later that decade, tracking technologies [3, 34] came back into use and AR was introduced to recreational settings [12]. The 2010s have thus far seen the most activity in applying technology to aquatic recreation. Water vessels were used predominantly at the first half of the decade [29, 37, 42, 60, 98, 108, 120] whereas tracking systems were used primarily in the latter years of the 2010s [15, 22, 23, 47, 53, 67, 92, 102, 110, 112, 135]. Extended reality systems were used sporadically but became more popular moving into the 2020s [14, 20, 21, 26]. Robotic systems appeared the least – we see two applications in 2013 [98, 124], then later in 2018 [89] and 2019 [88]. This could hint at the difficulty of designing and waterproofing complex robotic systems.

These changes in technological tides demonstrate that as technologies evolve, so does their application to the aquatic environment. The extended reality publications of 2019-2021 [14, 20, 21] detail an AR system in open water, signaling a full circle of systems returning to the natural environment that marked the start of the 25-year period with Rapid Scout [104]. This indicates that extended reality technology may have advanced sufficiently enough to move beyond controlled environments, like that of a pool, to the more dynamic environments of lakes, rivers, and oceans. This can have implications for greater real-world applications of aquatic technology, including commercialisation and further research in more hostile environments.

Given the development of technology and its application to aquatic environments in the recreational sphere, we became interested in the properties of water that make aquatic interactivity different from that on land. We explore how water's properties have been engaged within the publications reviewed in the following sections.

4.2 Properties of Water Incorporated in Prior Work: Trickling Down

We found aquatic systems that have been designed with explicit considerations of how the properties of water could affect or enhance the system [29, 57, 98, 102]. Our analysis identified various such properties that act as a challenge or an opportunity in aquatic systems compared to their on-land counterparts. Water is a "liquid", so users can deform or move it around a space without changing

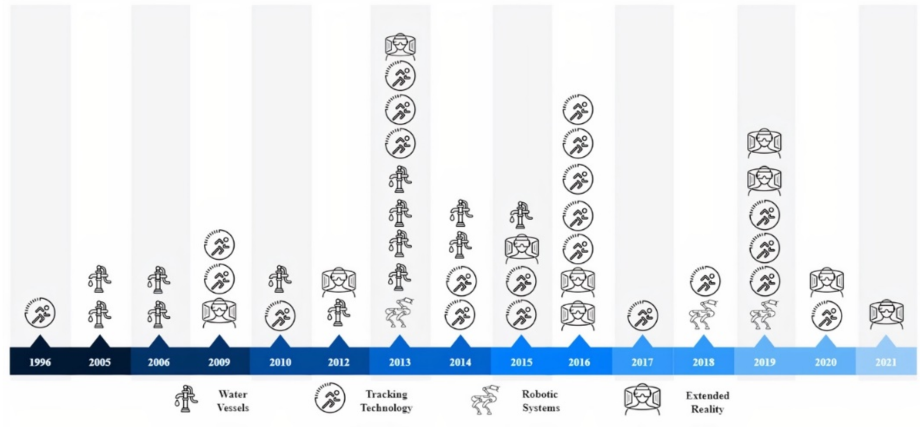

Figure 2: A timeline of aquatic systems papers over 25 years. We highlight four key types of technology being used: water vessels, tracking technology, robotic systems, and extended reality (XR).

its volume [17, 37]. When not disturbed, it settles into a "smooth curved surface" between itself and the air, maintaining this boundary through "surface tension" [120]. This presents opportunities to delineate two different usable regions of air and water [52, 60] while also
presenting an issue of limited or distorted "visibility" through the surface [3, 14, 20, 21, 47, 120, 121, 124]. This is always present due to refraction of light at the air-water boundary but may be worsened underwater due to limited light penetration at depth or opacity from particles and dissolved materials [67, 135]. Immersion in water changes the "forces" experienced by a user [134], resulting in "pressure" increasing with depth [55] to offset gravity with "buoyancy" [3, 25, 34, 67, 102, 113]. Without the need to support oneself on the ground and a general "lack of obstacles" around them, people have more "freedom of movement" [5] while immersed in water. Although buoyancy limits the effort people need to exert in aquatic endeavours, water features more "drag" than air, resisting a person's body movements [102]. The "inertia" and "viscosity" of water that causes this drag also presents an opportunity for "propulsion" by paddling or propellers [53, 89, 110], along with "tactile feedback" or "wetness" when someone is sprayed with a jet of water [42, 56, 57, 108] or feels its "weight" when lifting water [49, 60]. Jets and currents represent flux of water rather than a constant quantity, so the "flow" rate can be used much in the same way as electrical current [17, 29, 56, 57, 95]. Despite this similarity, water's "electrical conductivity" can dampen wireless network communication and damage or render useless any circuitry it contacts that lacks sufficient waterproofing [9, 94]. Users are not safe from the dangers of water either: access to life-sustaining "air is limited" in many aquatic contexts [55, 94]. These properties have implications for technology that helps to facilitate interactive recreational experiences with particular attention to health and safety.

Having noted the evolution of recreational aquatic systems over time and having identified some of the properties of water that recreational aquatic systems have utilised, we are interested in the impact of water, positively or negatively, on the user and the technology. We detail our findings in the subsequent sections.

5 DISCUSSION: INTO THE DEEP

Our results indicate that technological aspects garnered much attention in the literature regarding aquatic recreation. However, we are equally interested in the user experiences of these systems. We offer the HCI community a framework that articulates four different UXs based on two dimensions: the impact of water (i.e., whether it is a "problem" or "opportunity") on a user and on technology. These can be useful for evaluators aiming to analyze UXs of aquatic systems and practitioners to anticipate the UXs that may be elicited by their designs. We then summarise the insights of each UX by articulating design that designers can use when creating future aquatic systems. Our contribution concludes with observations and questions for design researchers in the HCI community to ponder if they seek to develop meaningful aquatic recreation experiences.

5.1 Water as a Problem and an Opportunity: Ebbs and Flows

Based on our analysis, we articulate four key user experiences featuring water as a "problem" or an "opportunity" for both users and technology. This allows for anticipation of certain user experiences in future systems. Figure 3 depicts the dichotomies on two axes. From the user's perspective, "water as a problem for the user" means that the air supply for breathing is restricted within the recreational activity. "Water as an opportunity for the user," on the other hand, uses the properties of water, such as buoyancy, to create a more engaging experience; for example, by facilitating floating. "Water as a problem for technology" generally refers to technology requiring some form of waterproofing due to the electrical components (although we acknowledge that fluidic computers could address this [65]). On the other hand, "water as an opportunity for technology" refers to the system aiming to leverage properties unique to water that are not present for land-based systems, such as water's tactile properties (e.g., wetness, weight, and temperature).

The interplay between problems and opportunities of water for users and technologies creates different aquatic user experiences across the axes. The following sections detail the characteristics of these user experiences per quadrant of the axes (Figure 3).

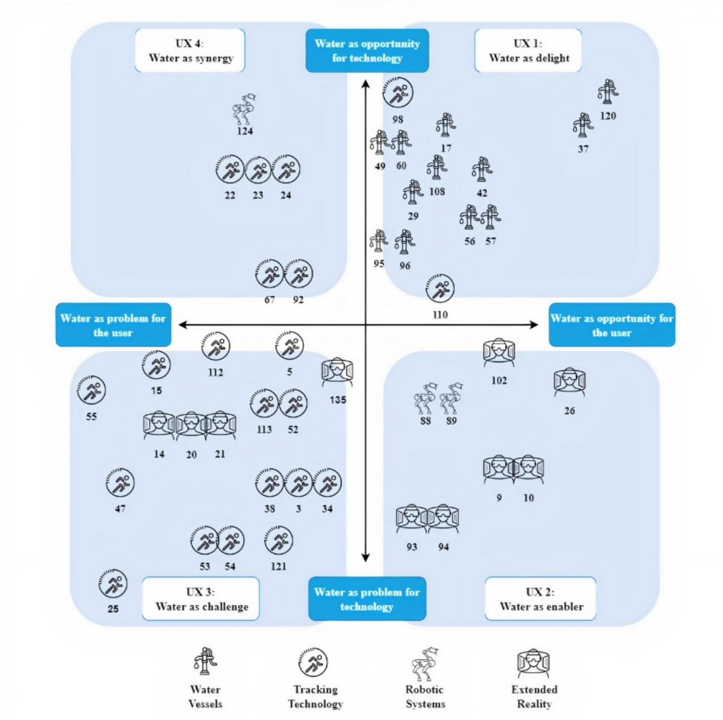

Figure 3: Interactive systems plotted against water as a problem or opportunity for users and technology. Systems are further grouped by common user experiences (UX) that we found in our analysis: The first quadrant: water as delight; second quadrant: water as enabler; third quadrant: water as challenge; fourth quadrant: water as synergy.

5.1.1 User experience 1: water as delight. HCI has defined the user experience of delight as the combination of pleasure and surprise elicited from a user's interaction with a system [64]. Similarly, we call user experiences in the upper-right hand of the design space "water as delight" because the system elicits a combination of pleasure and surprise when the user interacts with water.

Delight is elicited when "water as opportunity for users" involves interaction with the water in novel and unexpected ways [120]. For example, the Splash Controllers [37] and Water Ball Z [42] systems use water's wetness and "messiness" along with visual and auditory feedback to stimulate multiple senses and delight users.

Water's viscosity and ability to communicate information tangibly make it an appealing medium for playful interactions. Systems incorporate water's ability to be splashed [42, 56, 57], spilled [37], and manipulated by physical movements [37, 120] to promote playfulness. Furthermore, we believe that the experience of getting wet from a distance [42, 95, 96] or being partially submerged [49, 60, 98] opens up additional opportunities for delight.

We found that many "water as delight" systems mostly elicit pleasure and surprise by taking advantage of water properties, such as surface tension, to create tactile interactions on land. For example, LiquiTouch [108] facilitates delight by enhancing feedback via a graphical interface through water jets. Water jets convey haptic information via their intensity and breadth on a fingertip [108] that traditional GUIs cannot. The project Fl.UIs [17] demonstrates that different water colours can trigger events in an aquatic system that responds to various touch pressures. Additionally, Splash Controller [37] shows how direct physical movement of the water in a vessel can be used as a game controller, the novelty and messiness of which appear to facilitate delight. Furthermore, pressurized water can facilitate delight by providing audible feedback [56, 57], with the feedback becoming louder at higher pressures [42].

Prior work in HCI has already argued that supporting multiple senses can elicit "delight" in users [79]. We extend this previous work by adding that water can be utilized as an often easily-implemented way to stimulate multiple senses. In summary (Table 1), we see an opportunity for designers to consider the use of the sensorial nature of water in novel and unexpected ways to facilitate "water as delight".

5.1.2 User experience 2: water as enabler. We call the user experience associated with systems that sit in the lower-right hand quadrant of the design space (where water is an opportunity for the user, but a problem for the technology) "water as enabler". In HCI, "enabler" means offering support through interactive means for the execution of a task [33, 59, 100], most often for persons with special needs [30].

Water is an enabler primarily because it is a medium that can give users an increased sense of agency over their bodies [77]. For example, the system Shark Punch [102] utilises buoyancy to support the user's punching tasks in the water, allowing users to have greater movement support than they would on land. However, water is a challenge for the technology, as suggested by the immense development effort invested by the creators of the Shark Punch system to get its motion sensing to work underwater [102].

Another example system in this quadrant is the game Aquaticus [88, 89]. It employed robots to support humans in a game of capture the flag where water is the enabler for a novel play experience. Water is an opportunity for the user to capture a flag in an alternative space to land, while water is a problem for the technology as suggested by the extensive technical development of the required sensor and input device [88, 89].

In terms of "water as enabler", we see an opportunity to support users' greater freedom of movement of the body within water and, thereby, enable empowerment of the body's abilities. Buoyancy is a property that allows for greater freedom of movement within water compared to air in many cases. Although buoyancy levels are higher in salt water than in fresh or pool water, all bodies of water offer buoyancy and the associated greater freedom of movement has been used in interactive systems to enable empowerment. For example, VR systems in water have been using buoyancy to reduce users' perceptions of fatigue when they engage in repeated punching or pointing actions [26, 102]. These systems enable greater endurance in the water, whereas participants would get tired more quickly on land.

Additional examples of systems in the "water as enabler" quadrant are the Dolphyn and AREEF projects [9, 10, 93, 94]. They allow users to carry an augmented reality tablet into the water and learn about ocean species while diving. Here, the opportunity for the user is to experience situated learning [109], while the technology problem is to get the augmented-reality camera to work despite the impacts of underwater light reflection [133]. Indeed, the designers of Dolphyn [9, 10] reported that their design process necessitated careful waterproofing considerations and extra effort to consider limited input options such as joysticks and buttons that could operate while immersed in water.

With our "water as enabler" quadrant, we extend previous work on interactive systems as enablers [33, 59, 100] by highlighting that the water medium (in contrast to the often prevalent "air" medium in HCI) can be used by interaction designers to enable the (better) execution of a particular task. Furthermore, our focus on water expands the ubiquitous computing concept to include water as an environment for the placement of interactive devices that "enable" interactions [130]. We also extend prior HCI work on the usefulness of greater freedom of movement for bodily empowerment, including whole-body interaction [101]. In summary (Table 1), we propose that HCI has an opportunity to consider "water as an enabler" as it can provide greater freedom of movement and empowerment of the body.

5.1.3 User experience 3: water as challenge. We call the user experience associated with systems that sit in the lower-left hand quadrant of the design space (where water is a challenge for the user and for the technology) "water as challenge". When it comes to HCI, the notion of challenge has probably most often been discussed regarding "flow," or the "optimal experience" [25]. When a user's abilities match the challenge of an activity, a positive state of "flow" can occur [25]. Conversely, if the user's abilities exceed the needs of the activity, boredom may occur, and if the user is under-skilled, they may feel frustration and anxiety [43].

In this quadrant, both the user and the technology experience water as a problem. For the user, the efficient movement through water and the need for air in a timely manner present themselves as challenges. Interactive systems aim to address these challenges by providing visual and auditory feedback to develop more efficient swim strokes [3, 22, 25, 34]. However, implementing technological feedback has not been easy. For example, network issues are a common challenge when streaming swim stroke data to analysis systems. While streaming data is not usually a problem on land, there are significant penetration and reliability issues when attempting to stream wirelessly under water [53, 54, 121].

In terms of "water as challenge", we see an opportunity to consider reducing movement challenges by using hardware that produces minimal drag in water. Although "water as challenge" highlights that water seen as a challenge can be beneficial for the user experience, we contend that designers can consider reducing movement challenges to allow other challenges to come to the fore. In other words, we believe that the system's interactions should not obstruct the primary task of moving through water (in situations where recreational activities involve movement through water). Attaching hardware to the body, such as tracking devices, often creates more drag than they would in land-based activities. Therefore, minimizing drag resistance can support less obtrusive interactions between the user and the water. We found that designers mostly considered three methods for reducing drag in the water: smaller wearable systems, placement of wearable systems, and embedding interactive technology in the environment.

We note that designers have aimed to limit wearable systems' impact on water drag or movement resistance by considering placement and making the hardware smaller. For example, designers have placed interactive systems along the lower back [3, 53, 54] that minimizes drag when swimming breaststroke or freestyle because the lower back is slightly above water. Designers have also considered incorporating sensors into existing equipment, such as embedding LEDs within existing swimming goggles to avoid water drag effects [3, 34, 38, 47]. Furthermore, designers have considered embedding interactive technology in the environment to avoid water drag effects on the water movement challenge. For example, a project placed LEDs along the length of the pool [121] to provide feedback without drag effects. Similarly, designers have used an ambient RFID system that only requires the user to wear small wrist-based tags [15]. In addition, designers have created immersive media swimming experiences with images projected on pool walls [135] to avoid attaching hardware to the user so as to not avoid drag. While these systems show great benefit, we note that they are typically implemented in controlled environments, such as swimming pools, and may be more challenging to implement in open water settings.

In addition to drag, context-switching for direct interaction with a device can distract users from their primary aquatic task. Systems such as SwimMaster [3, 34] and Clairbuoyance [47] minimize this issue by only offering feedback to the user when adjustments are required. This feature allows users to swim normally (i.e., as if they were not engaged with the system) while they are performing adequately. Other technologies support mobility by easing users' concerns for safety, such as drowning prevention measures [55], or by notifying blind users of hazards [67, 92]. Visually impaired users can also be supported by having a system control their navigation entirely; CoOp empowers blind paddlers to focus on their paddle strokes by having a sighted partner remotely controlling the canoe's direction [5].

With "water as challenge", we speak to prior HCI work from the games community that highlighted how games use challenges to achieve a flow state [119]. However, most of these challenges come in the form of digital challenges added to the game. Bodily games have already extended such an understanding of challenges by suggesting using the physical environment as an additional challenge element [74, 80, 81]. We extend this prior work, highlighting that designers can also use water to facilitate user challenges that lead to flow experiences. Furthermore, prior HCI work finds that placing hardware on the user can affect how they move through their environment because it changes their perceptions of how they are seen by others [36]. We also extend this prior work, highlighting that designers of aquatic devices can consider how their designs affect movement in the water through added drag, promoting the user experience of "water as challenge." In summary (Table 1), in terms of "water as challenge", we see an opportunity to consider modulating movement challenges in water through system design to facilitate flow experiences.

5.1.4 User experience 4: water as synergy. We call our final user experience "water as synergy". This user experience sits in the upper-left quadrant of the design space. In this respect, we refer to user experiences where the interaction between the properties of the aquatic environment and the interactive system produces a combined effect greater than the sum of their parts [66].

In this quadrant, systems often use the aquatic environment to address "water as a problem for the user." These problems include limited auditory feedback options because of ear submersion. However, new developments around waterproof headphones may help to alleviate this issue [35]. Reviewed systems also see "water as a problem," especially for vision-impaired users, because the water makes seeing more difficult. In response, designers used computer vision added to a wearable smartphone, along with guiding audio, to allow blind swimmers to swim more independently [67, 92]

We found that patterns of aquatic activities use rhythms to provide the predictability that technological systems benefit from to create synergistic experiences. This includes the rhythms of the body navigating the water, especially during swimming activities when the head is submerged without additional breathing apparatus such as a snorkel or SCUBA tank. We also note that the immersed swimmer's regular need for air can be seen as a pattern that is best met by the rhythm of a swim stroke. Systems such as Swimoid [124] and Moby Dick [23, 24] are synergistic in that they utilise patterns and rhythms within the aquatic activity to provide technological support to the user. For example, Swimoid [124] shows users suggestions for improving their technique on a screen below them while their face is in the water during the head down phase of a swim stroke. As seen in the swim-based audio game Moby Dick, users time their surfacing to breathe with game events [23, 24, 52]. As fatigue sets in, users will take more frequent gasps for air. These gasps could be tracked and predicted so that game events can be triggered and synchronised to guide the user's actions. Synergy is then created by the synchronised cooperation between the technology and the user's actions and responses.

We also identify that many systems in this quadrant take advantage of a swimming pool's predictable and unchanging structure (as opposed to land-based outdoor systems, for example), presenting "water as an opportunity for technology." For example, lap pool characteristics such as lane length are often uniform and designed with distinct features (such as black lines). Technology, including cameras, can deal quite easily with this and utilize these characteristics. This is particularly true for the projects Swimoid [124], Goby [67], and the Wearable Electronic Swim Coach [92]. To function effectively, these systems rely on predictable and unchanging pool characteristics such as length, black lines in a lane pool, and known water depth. Similarly, the project MobyDick [23, 24, 52] uses the predictable, smooth surface of the swimming pool water for its game's breaststroke sensing.

Predictable patterns are not limited to aquatic structures such as a pool. Patterns can often be found in natural aquatic environments, too, such as rivers that have both rapids and smooth sections. Rapid Scout [104] takes advantage of these river patterns and encourages white-water paddlers to utilize the smooth sections of the river to engage with the user interface of the system.

Prior HCI work has already highlighted that considering rhythm can be beneficial for recreational interactive systems [71]. We extend this prior work, highlighting that designers can consider the rhythm of the aquatic environment as a resource to facilitate synergy experiences. In summary (Table 1), in terms of "water as synergy", we see an opportunity to consider using tracking technology to leverage aquatic patterns to facilitate synergy.

Earlier in this paper, we identified a gap in knowledge when it comes to guidance on how to design aquatic systems, and, therefore, sought to begin answering the research question of how to design such systems. From our analysis, we see that designers produced a range of systems that we interpret as approaching water as either a problem or as an opportunity for both the user and for the technology. Taking our framework, we can identify where most design investigations are situated and also see underexplored areas in the design space. We detail our observations in regard to where we see opportunities for future work in the following section.

6 FUTURE WORK: BEYOND THE HORIZON

Based on our observations, we propose that the HCI community can consider several trajectories where future work can take place. We make observations from the timeline (Figure 2), identify opportunities within the framework (Figure 3) and discuss potential design approaches that we believe are not considered or articulated regarding the development of recreational aquatic systems.

Our timeline of aquatic interaction (Figure 2) prompts us to ask three primary questions. First, we identified that the 2010s saw most activity in the publishing of aquatic systems; in particular, 2013 seems to be the height of that activity. We believe that we are the first to articulate this anomaly and question what was it about 2013 that made designing aquatic systems a popular year, and why there has been a general downward trajectory from that point onwards. Secondly, we note that extended reality technologies that can provide more immersive experiences have moved beyond controlled

Table 1: A summary of characteristics and implications of each quadrant.

User Experience	Definition	Opportunity or problem for the user	Opportunity or problem for technology	Design considerations
Delight	Systems that experience water as an opportunity for technology and for the users. Systems that elicit a combination of pleasure and surprise when the user interacts with water.	Opportunity to use the sensorial nature of water in novel and unexpected ways to facilitate "water as delight".	Opportunity to use water's wetness and "messiness" along with visual and auditory feedback to stimulate multiple senses.	Incorporate water's ability to be splashed, spilled, and manipulated by physical movements. Take advantage of water's properties such as tension and pressure.
Enabler	Systems that experience water as a problem for technology but as an opportunity for the users. Systems offering support through interactive means for the execution of a task.	Water is a medium with greater freedom of movement giving users an increased sense of agency over their bodies.	Problems due to immense development effort invested to get sensors and actuators to work underwater.	Incorporate water's buoyancy to support user's movement. Incorporate technology, such as robots and VR, to support user's task.
Challenge	Systems that experience water as a problem for technology and for the users. Systems designed to provide solutions for challenging activities in water, such as swimming.	Problems for users in terms of regular need for air and efficient movement through the water.	Problems because of difficulties implementing technological feedback due to networking issues and data streaming.	Take advantage of wearable systems to reduce any task obstruction or embed interactive technology in the environment. Use the physical environment as an additional challenge element.
Synergy	Systems that experience water as an opportunity for technology and a problem for the user. Systems that explore the interaction between the properties of the aquatic environment and the technology to produce a combined effect greater than the sum of their individual parts.	Problems for user due to auditory feedback options because of ear submersion, and visual impediments because the water makes seeing more difficult.	Opportunity for technology to leverage patterns and rhythms of aquatic activities to provide predictability.	Take advantage of patterns, for example to utilise computer vision. Consider using tracking technology to leverage aquatic patterns to facilitate synergy.

pool environments and we speculate that this may because of more robust waterproofing. However, we ask if simply waterproofing is limiting imagination and creativity in the creation of novel aquatic systems. Thirdly, we note that robotics appears the least in the reviewed systems. We question if this reflects a difficulty in building and waterproofing complex robotic systems. If that is the case, we wonder if this is even more reason to design beyond waterproofing, and instead harness the unique properties and nature of the water environment.

Based on the 48 papers plotted within the quadrant (Figure 3), we have considered water as a problem and opportunity for both users and technology. Following our analysis, we have three key observations that researchers, designers, and theorists may want to consider questioning and exploring as a community within the HCI domain.

In our first observation, we note that water vessels seem to be most conducive to delight and have not been used much for synergy, challenge, and enablement. We are interested in finding out how we can make aquatic systems in other user experience quadrants more delightful. For this, we might need to combine technologies, for example, combining robots, tracking technology and extended reality systems with water vessels. However, how to design such systems is still an open question. However, answering such a question might open a new realm of delightful aquatic systems.

Secondly, we observe that extended reality systems seem to approach water as a problem to be mitigated against as they fall in the bottom halves of the quadrant. Instead of seeing water as a problem, what if there was a paradigm shift of seeing the water's unique properties as opportunities for novel immersive experiences that are difficult to achieve on land? To an extent, this is already happening with VR experiences in floatation tanks that support weightlessness during a VR session [102]. However, these experiences are low-hanging fruit and we believe that much more can be explored.

Thirdly, we also observe and acknowledge that tracking technology allows for versatile use in and around aquatic environments due to its presence in three of the four quadrants, the water as enabler being missing. That tracking technology is more prevalent on the left side of the design space where water is a problem for the user strongly points to an opportunity to explore tracking technology where water is an opportunity for the user. In this way, tracking technologies could better support and augment more delightful and enabling experiences. We suggest the community asks how that transition can be best achieved.

7 CONCLUSIONS: WADING OUT

In this article, we aimed to dive deep into the literature surrounding interactive technologies for aquatic recreation and surfaced with our contribution to the field of HCI. From our analysis, we offer the HCI community a user experience framework that articulates four different user experiences based on two dimensions: the impact of water by design (i.e., whether it is a "problem" or "opportunity") on a user and on technology. Our framework brings us closer to understanding how technology can interact with users and the aquatic environment to enhance the existing recreational experiences that connect us to aquatic environments. In sum, we found designers can elicit delight, enablement, challenge, and synergy in aquatic recreation experiences.

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