water

MDPI

Article

Comparing Three Approaches to Estimating Optimum White Water Kayak Flows in Western Norway

Peggy Zinke [1,*], Dag Sandvik [2], Ingrid Nesheim [3] and Isabel Seifert-Dähnn [3]

[1] Norwegian University of Science and Technology, IBM, 7491 Trondheim, Norway
[2] Kayak Voss and Board Member of Ekstremsportveko, 5705 Voss, Norway; dag.sandvik@gmail.com
[3] Norwegian Insitute for Water Research, Gaustadalléen 21, 0349 Oslo, Norway; ingrid.nesheim@niva.no (I.N.); isabel.seifert@niva.no (I.S.-D.)
* Correspondence: peggy.zinke@ntnu.no; Tel.: +47-99302344

Received: 1 October 2018; Accepted: 21 November 2018; Published: 30 November 2018

Abstract: Background: Modern water management strategies aim to assess the impact of water regulation alternatives on all relevant ecosystem services, including white water (WW) recreation. Therefore it is important to estimate the optimum kayak flow range for river reaches that are potentially relevant for WW kayaking. Methods: We used the grade V run of the Teigdalselva River as an example and compared the results of three different approaches: (i) a hydro-morphological analysis of kayak runs using public data sources; (ii) a citizen science method that is based on photos and videos of kayak-activities on the web; and, (iii) interviews with elite kayakers. Results: For the hydro-morphological analysis, we found that some optimal flow ranges for WW kayak could be estimated based on empirical regional regression as a function of the natural mean flow and the geomorphic run type. The interviewed kayakers suggested a wider range of optimal flows, in particular, higher maxima. The test of the citizen science approach provided flows that ranged in the middle of the estimates made by the two other approaches for prescribing optimum kayak flow ranges. Conclusions: We recommend a combination of different methods for water management studies that are related to flow requirements for white water kayak. Estimations based on the empirical regression functions should be always complemented by at least one other approach.

Keywords: citizen science; flow requirements; optimal kayak flows; hydro-morphology; Kråkefoss; run type; stream power; Teigdalselva River; Western Norway; white water kayak

1. Introduction

White water (WW) recreation includes kayaking, rafting, and canoeing and it has evolved as global sport during the last decades. It is considered as one of the cultural and social ecosystem services provided by rivers, and it contributes to society both as direct market value and non-market values, such as recreation, socialization, and environmental aesthetics [1,2]. The potential for WW recreation can be affected by streamflow alterations that are caused by river regulation or climate change. Flows that are released for hydropower often differ from natural flow regimes with respect to the timing, magnitude, duration and rate of change [3,4]. The WW sports community has excellent expert knowledge about the suitability of boatable river reaches that is published in "kayak guide" books, e.g., [5]. In these books, expert preferences are expressed as optimal flow range or minimum and maximum flows in terms of the water level or discharge at river gauging stations that are situated close to the sport section. For flows less than the minimum kayak flow, the flow conditions are below boatable conditions, which expose too many obstacles for safe and uninterrupted navigation, whereas the maximum kayak flow represents the upper limit of stream power that is safe to navigate [1].

Optimal kayak flow ranges are mostly missing for ungauged flow reaches and for rivers that have been regulated so that they are less commonly available for WW activities due to the reduced frequency of suitable flows. This is the case for some rivers in Norway where the flow requirements for WW recreation are discussed in connection with new hydro power projects or related relicensing processes. Modern water management strategies aim to assess the impact of water regulation alternatives on all relevant ecosystem services, and they therefore require methods to assess the impacts of flow alteration on WW recreation.

Traditionally, the response of recreational navigation potential to stream flow variations has been investigated by applying expert-judgement methods [6,7]. Recent studies combine expert knowledge with hydrological and hydrodynamic simulations in order to assess the suitability for WW recreation [1,2]. Carolli et al. [8] developed a modelling-based approach to assess the recreational flow requirements and spatially distributed river suitability for white water rafting in the Upper Noce River catchment (Italy). Their approach is based on the same principles that have been adapted for habitat suitability modelling using water depth as a primary metric. Their five-step-approach includes the calculation of recreational flow ranges and a rafting-suitability index based on one-dimensional (1D) hydrodynamic simulation outcomes.

The involvement of citizens in environmental research i.e., citizen science has also a long tradition [9] and has been boosted by the spreading of internet use and mobile devices [10]. There are different types of tasks in which citizens can engage, including data-collection. Citizen or crowd-sourced science can refer to active involvement of people in collecting or analyzing data, and analyzing information provided by people (e.g., social media, images shared on the internet). The latter is relevant for WW kayaking, where the number of web-pictures and videos showing white water kayakers in turbulent rivers is constantly increasing. The photos provide visual evidence of flow conditions within the river reach. If their meta-information includes the time and date when the picture was taken, then it can be linked to streamflow data.

The suitability and difficulty of a river stretch for WW sports is closely related to a multitude of channel parameters and flow patterns, for instance, hydraulic jumps and standing waves. Kayakers have their own terminology to describe them. Important terms include white water, green water, reverse flow, chute, eddy, stopper, as well as undercut and siphon [11,12]. Most of these terms can be translated into hydraulic terms [12]. Experienced kayakers can “read” the water and its flow features, such that they are able to find the perfect line [11].

The International Scale of River Difficulty is an American system that is used to rate the difficulty of a river stretch or a single rapid [13]. It is also used in Norway [14]. The grade reflects the technical difficulty and dangers that are associated with the section of river. It is meant to give an idea of the skill level that is required for safe navigation of the specific section. The scale is useful for various water sports and activities, such as rafting, river boarding, WW canoeing, stand up paddle surfing, and WW kayaking. There are six categories, each referred to as “Grade” or “Class” followed by a number, with grade I being flat water and grade VI being at the limits for safety for experts. The scale is not linear, nor is it fixed. For instance, there can be difficult grade II, easy grade III, and so on. The grade of a river stretch may change with the level of flow.

“Runs” are stretches of rivers boatable by raft, kayak, or canoe. They can be divided into different ”run types” that are based on the average topography, gradient, and flow regime, depending on the geophysical setting [1]. WW runs occur often in the steep and laterally confined upper parts of a river catchment, where bedrock channels dominate and semi-alluvial floodplain development is limited to discontinuous areas of canyon expansion [15]. Such reaches are functional process zones with constricted hydrogeomorphic structure, which are typically unexploited with respect to other ecosystem services than recreation [16]. From a geomorphic point of view, these streams can be classified based on dominant geomorphic conditions that exist within a river reach, e.g., as bedrock, cascade, step-pool, or plane-bed channels [17].

With respect to hydrodynamics, the bedrock or boulder-bed rivers that are used for WW kayaking are characterized by a mosaic of interacting complex flow features that change depending on the flow and are not easy to capture by one or few single parameters. There is no standard flow resistance equation for the determination of mean flow velocity in mountain streams because of the morphology of mountain streams, i.e., steep slopes, large roughness elements, bed forms, and water depths of the same order of magnitude as the bed material size [18]. In artificial WW canoe/kayak courses (i.e., man-made channels for training and competition), the power surface index (PSI) is used as an indication of the course quality or difficulty for canoeists [12]. Competitive canoe or kayak slalom has its roots in upland river systems that are characterized by fast-flowing water where the key water features are formed by natural rocks and boulders [19]. The PSI value can be derived from specific stream power—a parameter that is a measure of the main driving forces acting in the channel, that is, the joint effect of channel gradient and discharge per unit bed area [20]. In addition, the occurrence and the types of hydraulic structures, such as weirs, highly affect the suitability of a river for rafting or kayaking because they can lead to the formation of very dangerous hydraulic jumps [21].

In Norway, good kayaking rivers can be found everywhere in the country. Very active white water recreation communities are centered around places like Sjoa, Voss, Kongsberg-Dagali, Oslo, Arendal, Trondheim, Oppdal, Lillehammer, Sogndal, Valdal, Evje, and Hatfjeldal. In connection with a large number of upcoming relicensing processes for hydro power [22], there is a demand to provide valid methods for the assessment of river runs for WW uses.

The present study focused on methods that allow for estimating water flows that are suitable for WW kayaking prior to completing detailed hydrodynamic studies in order to provide an estimate of the optimal kayak flow range for river reaches that are potentially relevant for WW sports. The grade V run of Teigdalselva River in Western Norway was used as example, because it was mentioned as very relevant in several interviews with local WW kayaking stakeholders. We compared the results of three different approaches: (i) a hydro-morphological analysis of kayak runs in Western Norway, using geomorphic, hydrological, and other data that is readily available from public data sources; (ii) a citizen science method that is based on photos and videos of kayak-activities on the web; and, (iii) interviews with experienced kayakers (Figure 1).

For the hydro-morphological analysis (Approach 1), our hypothesis was that WW rivers of a specified landscape or region would have similar morphological features and hydrodynamic properties, such that it would be possible to find empirical relationships for the calculation of the minimum and maximum kayak flows as function of mean flow and hydro-morphological run type. For the citizen science method (Approach 2), we tested whether photos and videos from the web together with an analysis of hydrological data could lead to reasonable estimates for WW kayak flows. The results of these two approaches were compared with flow estimates that were given by world elite kayakers during interviews (Approach 3). In the discussion, we illustrated river and flow features affecting the kayaking suitability at Teigdalselva River and two neighbor rivers (Strandelvi River and Raundalselva River) and debated the role of subjective factors such as kayaker's skills and experience.

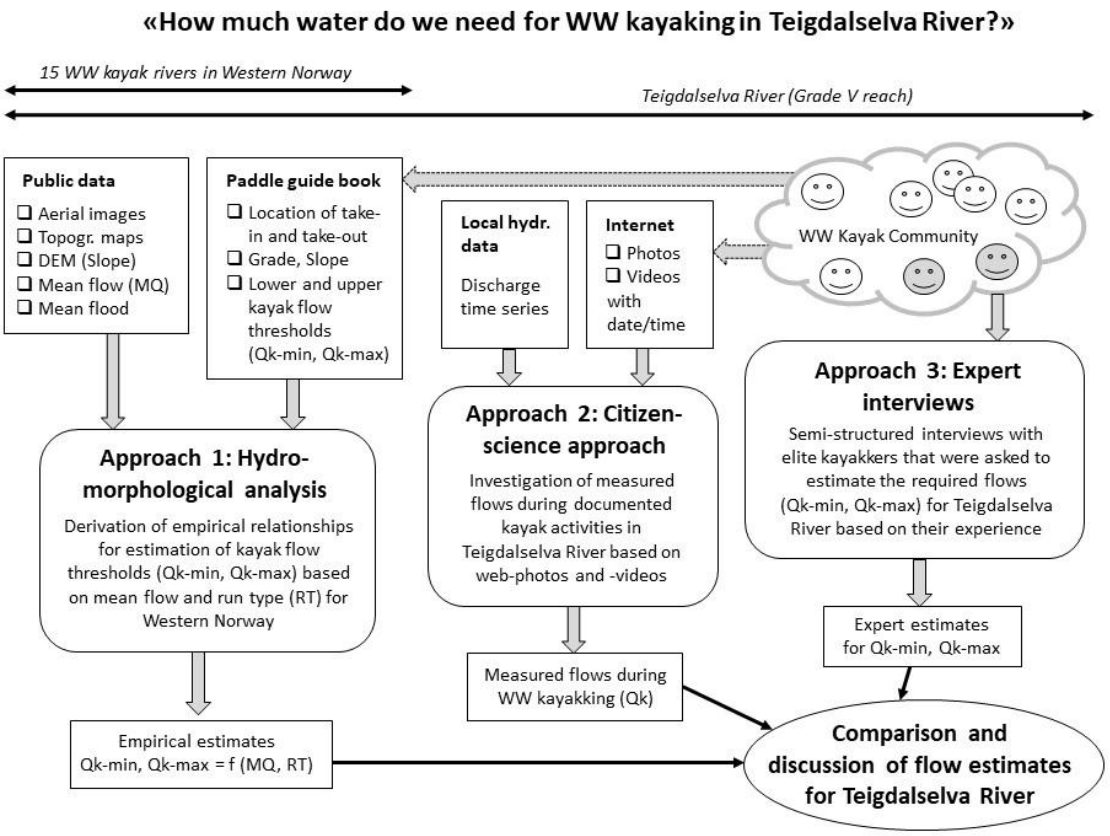

Figure 1. Visual illustration of the objective and the three approaches of the study. The empirical relationships for Approach 1 were derived based on the data from 15 WW kayak rivers in Western Norway. Afterwards, all three approaches were applied to Teigdalselva River.

2. Study Site, Materials, and Methods

2.1. Study Sites

For the hydro-morphological analysis, we analyzed the information in Tore Nossum's kayak guide "Western Norway" [23] for rivers situated in the Ecoregion "Vestlandet" (Figure 2, Table 1). Run lengths varied between 0.4 km and 10.8 km, with an average of 3.3 km. The elevation of take-outs (i.e., the lower ends of the runs) ranged from 0.8 m above sea level on the lower Valldøla river to over 700 m on the upper Smedalselvi and Ulvåa rivers. The average take-out elevation was 355 m above sea level. The difficulty of the investigated runs ranged from class I to class VI, with most of the runs belonging to class III to V.

Geologically, the investigated river runs are situated in Proterozoic or Caledonian rocks, which are comprised mostly of dioritic to granitic gneiss and migmatitt or metasandstone and schiefer. The bedrock is locally covered by moraine materials or thin humus layers [24]. Mean annual precipitation of the region ranges from about 750–1000 mm/year in the Eastern parts to more than 4000 mm/year in the high mountain zones [25]. It varies greatly with distance from the coast, elevation, and local weather patterns.

The contributing mean watershed drainage area of the investigated river runs ranged from 36 km^2 (Myklebustelva) to 829 km^2 (Rauma). The flow regime of the rivers is characterized by a spring–summer flood due to snow melting and rain (May–July) and low flows during the winter (Figure 3). The primary boating season for the smaller rivers is during the vernal snowmelt (flood runs), but rain can provide boatable flows also during autumn. Larger rivers, such as Raundalselva River, require a specific medium flow range and provide favorable kayaking conditions over longer periods also in summer.

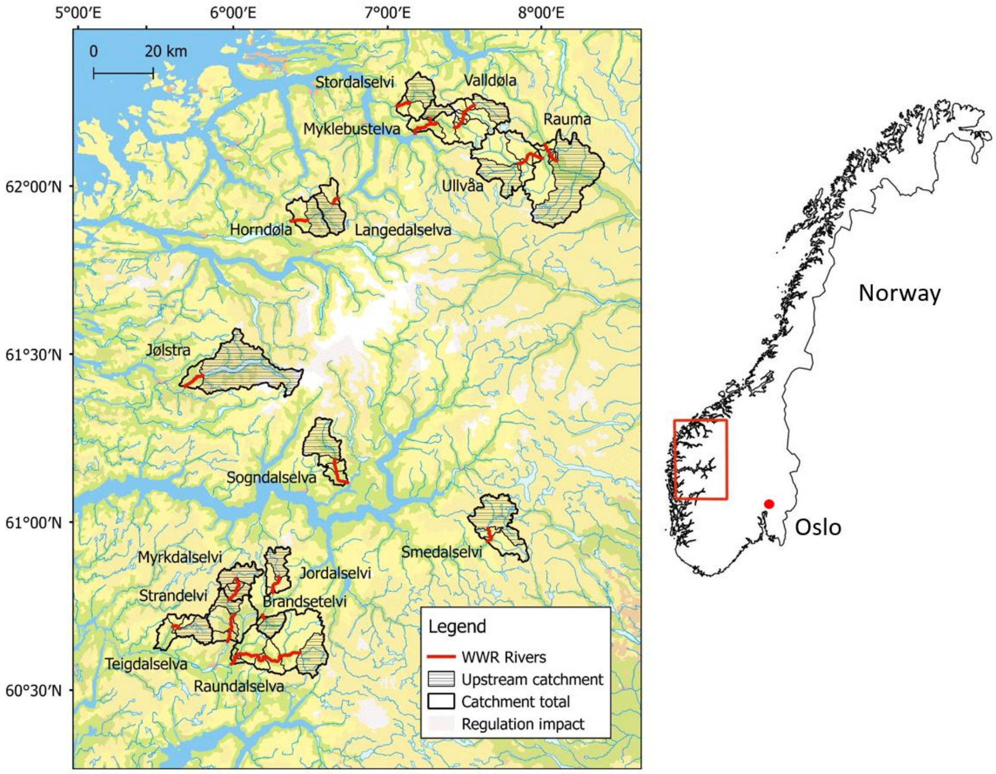

Figure 2. Overview map showing the location of the investigated river sections and their catchment areas, based on data from the State Map Agency (SK) and the Norwegian Water and Energy Directorate (NVE).

Table 1. Overview of the investigated white water (WW) rivers in Western Norway. Rivers studied in more detail are underlined. Grades for No. 2–16 according to Nossum [23]. The range of mean discharges (MQ) is given for the WW runs (not the gauge). NR = number of runs; RT = run types according to Ligare et al. [1], see also Table 2.

No.	River	Gauge	NR	Grades	MQ (m^3/s)	RTs
1	Teigdalselva	Mestad (62.17.0)	1	V	9.1 (nat.)	1
2	Horndøla	Horningdalsvatn (89.1.0)	1	IV	7.3	1
3	Langedalselva	Horningdalsvatn (89.1.0)	1	IV	6.7	1
4	Myklebustelva	Valldøla v/Alstad (100.1.0)	1	IV	1.9	1
5	Myrkdalselva	Myrkdalsvatn (62.10.0)	3	I, IV, IV–V	6.1–8.1	1, 2, 3
6	Strandelvi	Myrkdalsvatn (62.10.0)	4	III, V	13.8–20.9	2, 4
7	Songdalselva	Songdalsvatn (77.3.0)	3	I–II, IV, IV–V	9.0–10.6	1, 2
8	Raundalselva	Kinne (62.15.0)	6	III, IV, VI	13.3–28.2	2, 3
9	Rauma	Stuguflåte (103.3.0)	5	II, IV, V	10.1–25.6	1, 2
10	Jølstra	Jølstra ndf (84.15.0)	1	IV	30.8	4
11	Valldøla	Valldøla v/Alstad (100.1.0)	6	II, III, IV	3.5–15.0	1, 2, 4
12	Ulvåa	Storhølen (103.1.0)	3	II, III, IV	7.1–11.9	2, 3
13	Jordalselvi	-	3	III, IV, V	3.2–5.7	1, 3
14	Stordalselvi	-	1	V	5.4	1
15	Smedalselvi	Smedalselvi (73.10.0)	2	II, V	5.5–8.5	2, 3
16	Brandsetelvi	-	1	IV–V	2.8	1

The main focus of the present study was on the Teigdalselva River and the two neighbouring WW rivers Raundalselva and Strandelvi (Figure 4). Teigdalselva River is an appoximately 20 km long river in Voss Municipality (Hordaland) with a drainage basin of 147 km^2 at the outlet into lake Evangervatnet. It has earned ominous reputation among kayakers because of one waterfall: the infamous Double Drop [5], by the Norwegians called Kråkefoss. The 2 km long river section upstream of Kråkefoss from the intake near a goat house (Geithus) is classified as grade V–VI river. The river section downstream of the Double Drop is less used for kayaking described as "flat water", with the exception of two rapids and the more challenging river section on the last kilometer, before the river enters lake Evangervatnet [5,26]. The river section from Kråkefoss downwards is more important for fishing and is called the anadrome section by water managers, because the waterfall represents a migration barrier for the two most important species Sea trout (*Salmo trutta*) and Atlantic salmon (*Salmo salar*).

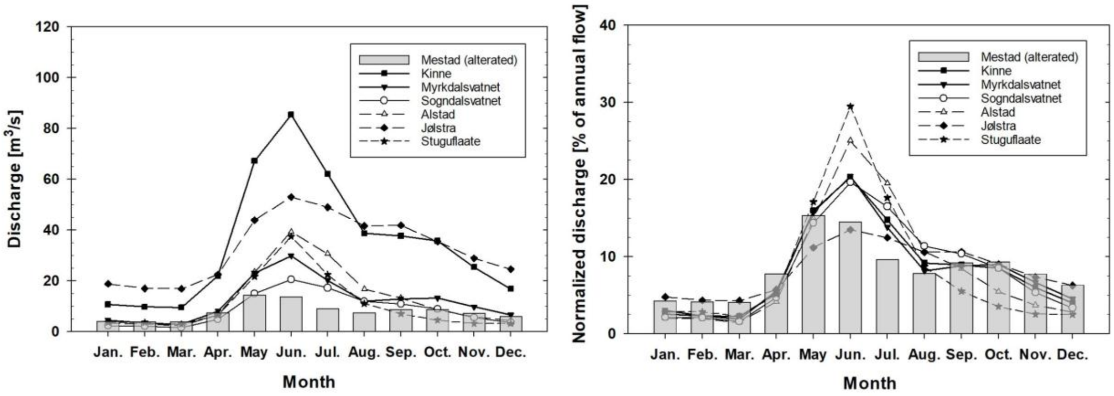

Figure 3. Absolute (**left**) and normalized (**right**) mean monthly discharges of the kayaking gauges. From NVE-database, time series 1986–2015.

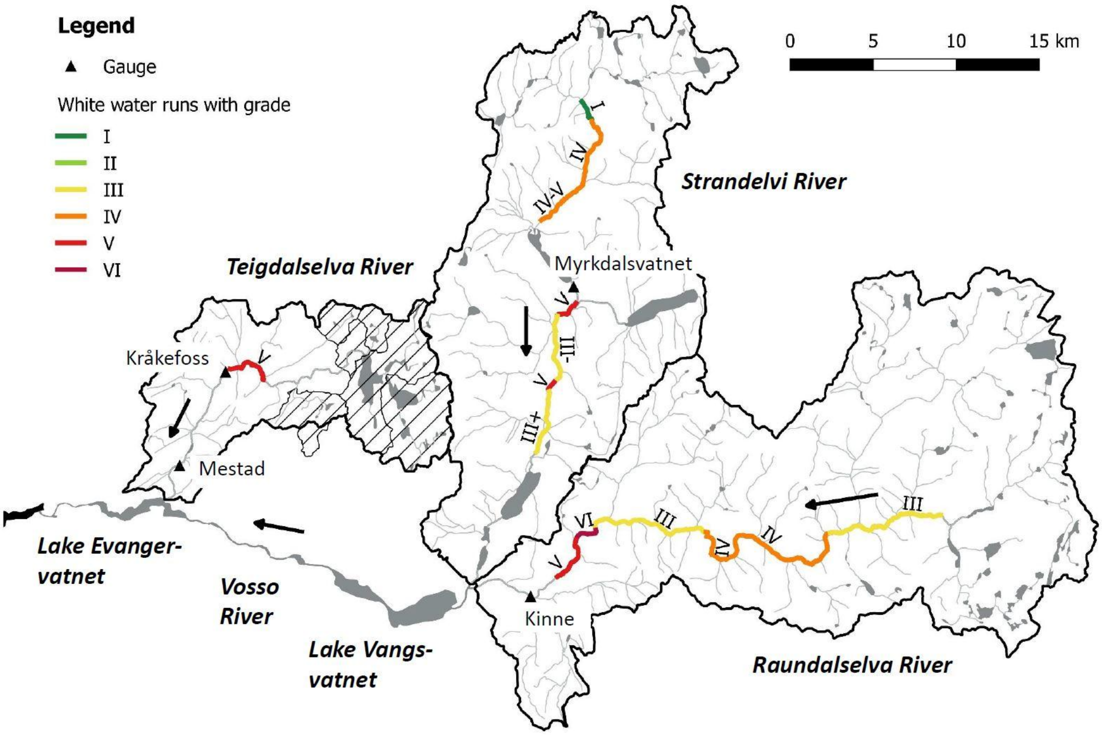

Figure 4. Overview map of the Teigdalselva, Raundalselva and Strandelvi river basins with WW runs and gauges. The upper part of Teigdalselva River basin is affected by water abstraction (hatched zones).

Teigdalselva has been affected by water abstraction for hydro power production in the upper part of the basin, which has limited the number of days that are suitable for kayaking since 1969 (cp. Figure 4). The grade V section is used by approximately 50 to 60 kayakers per year. Due to its difficulty, there are only few kayakers that are capable to run it [26]. Measurement data for Teigdalselva River is available for gauge Mestad (NVE, since 1985) and for a station of the hydro power company at Kråkefoss (since 2013).

2.2. Methods and Data

2.2.1. Hydromorphological Analysis

The length and difficulty grade of the kayak runs were taken from the kayak guide book by Nossum [23]. If the grade was given as range (e.g., IV–V), it was rounded up. The guide book [23] provided in addition the optimal flow range for kayaking, in most cases with reference to the next gauging station (Table 1). If no gauge station information were available, then estimates of the flow in the kayak river section itself were given based on kayaker's experiences, or the optimal conditions were described by comparing with other rivers.

We used publicly available data from the Norwegian Water and Energy Directorate (Norges vassdrags- og energidirektorat, Oslo, Norway; NVE) and the State Map Agency (Statens kartverk, Hønefoss, Norway; SK) for a GIS-based calculation of run-averaged slopes (S), mean discharges (MQ), and mean annual floods (MAF). The slopes were extracted from water surface elevation data. MQ and MAF were calculated using NVE's web-application NEVINA and represent the time series 1961–1990 for the natural flow regime, i.e., without the influence of dams or diversions operating in upstream areas. The mean flow was also determined for the location of the gauge stations (MQg). For kayaking runs where the maximum (Qk-max) and minimum flows (Qk-min) were provided with respect to a gauging station, the difference in catchment size between the runs and the gauges was accounted for by multiplying the kayak flow values (Qk-min, Qk-max) with the ratio MQ/MQg. This ratio ranged between 0.2 and 2.5, being 0.5 to 1.5 for 82% of the respective runs.

The data were further used for the calculation of reach-averaged values for specific stream power (SSP) in W/m^2, which is defined as

$$\mathrm{SSP} = \frac{\rho\, g\, Q\, S}{b} \tag{1}$$

where ρ is the density of water (1000 kg/m^3), g is the gravity constant (9.81 m/s^2), Q is the reference discharge (m^3/s), and b is the mean width (m) of the surface water at reference discharge. SSP-values were calculated using MAF, Qk-min and Qk-max as reference discharges. b was taken from SK-maps and represented according to the map-metadata approximately bankfull conditions.

For comparison, all runs within the database were described by the run type (RT), as suggested by Ligare et al. [1] for North-American WW rivers. These RTs are classified to describe their physiographic setting using one of the following: steep creek, creek, gorge, and river, based on the average topography, gradient, and flow regime (Table 2, Figure 5).

Table 2. Run types and their characteristics according to Ligare et al. [1]. Qk-max is the maximum flow for WW sports.

Run Type	Slope	Flow	Note
1: Steep creek	>0.025		Often at top of watershed
2: Creek	<0.025	Qk-max < 42.5 m^3/s	
3: Gorge			Having lower flow thresholds and greater difficulty than runs upstream and downstream
4: River	<0.025	Qk-max > 42.5 m^3/s	Often at lower elevations, having grades I and II

Figure 5. Examples of Norwegian rivers representing the four run types. Photos: (**a**) Steve Arns, (**b**,**c**) Øystein Bjørke, (**d**) Peggy Zinke.

2.2.2. Citizen Science Approach

For the citizen science approach, we searched for photos and videos showing kayaking activities at Teigdalselva River on the web. The webpages were accessed before 30 June 2017, which was an internal project deadline for this task. The location was identified by using the GPS-information in the file or—if this was missing—by visual identification of known river structures (e.g., Kråkefoss). Only those photos and videos where the date of the activity was either included in the photo (EXIF “Date taken”), as mentioned on the web page, or could be found out by contacting the authors, were selected for further analysis. The discharges corresponding to the date and time when the photos and videos were taken were obtained from data of the nearby gauge stations at Mestad and Kråkefoss.

2.2.3. Expert Interviews

As part of an investigation of stakeholder interests that included several interviews with paddlers [27], nine elite kayakers (i.e., kayakers competing at national, international, and professional levels) were interviewed in an informal setting during the “Kayaker’s Barbecue” on the last day of 2017’s extreme sport week (“Ekstremsportveko”) in Voss, 1 July 2017. “Ekstremsportveko (https://ekstremsportveko.com https://ekstremsportveko.com)” is the largest extreme sport festival in the world and it hosts competitions in 17 extreme sport disciplines, among them kayaking and rafting. Nine elite kayakers from seven countries being familiar with Teigdalselva River were asked about kayaking conditions at Teigdalselva River, and to estimate the optimal kayak flow range based on their personal experience.

3. Results

3.1. Hydromorphological Analysis

The average slope of the 41 investigated kayaking runs (No. 2–16 in Table 1) ranged between 0.5% and 9.8%. Higher slopes occurred typically at higher difficulty grades (Figure 6, left).

The minimum flows for WW kayak runs ranged between 3 m^3/s and 34 m^3/s and the maximum flows between 4 m^3/s and 68 m^3/s, with the highest values being found for grade III (Figure 7, top). Average specific stream power for the mean annual flood discharges in the kayak runs increased with grade and reached a maximum value of 5048 W/m^2 for the grade VI reach at Raundalselva River (Figure 6, right). Suitable kayaking flows were found to have a specific stream power in the 10 to 730 W/m^2 range (Figure 7, bottom), corresponding to PSI-values between 5 and 365 (50% of SSP for natural rivers, [12]).

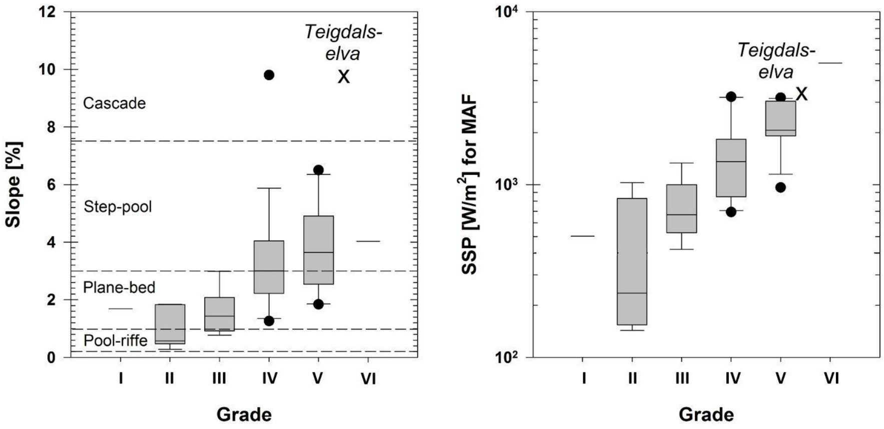

Figure 6. Box plot of the run-averaged values of slope (**left**, with stream type thresholds according to Montgomery and Buffington [17]) and SSP of the kayak runs (**right**) as function of grade. Slopes were extracted based on water surface elevations of SK's digital elevation model. Specific stream power (SSP) was calculated using mean annual floods (MAF) as reference discharge. The grade V reach of Teigdalselva River is highlighted with a cross.

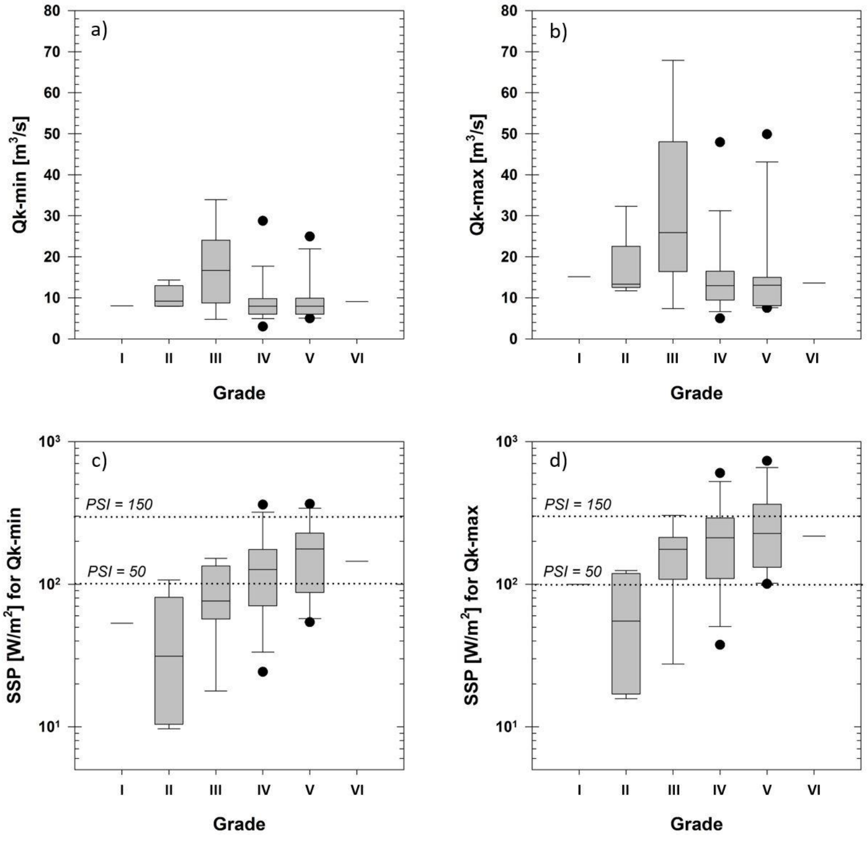

Figure 7. Minimum (**a**) and maximum (**b**) kayak flows and the respective SSP of kayak runs (**c**,**d**) as function of difficulty grade. SSP was calculated using the minimum (Qk-min) and maximum (Qk-max) kayak flows as reference discharge. The power surface index (PSI) thresholds of 50 and 150 are suggested for runs of regional significance and world championship standard, respectively.

The ratio Qk-min/MQ ranged between 0.3 and 2.2. Figure 8, (left) indicates that this ratio decreases with increasing discharge MQ for any given run type RT. A similar, but less pronounced relationship was found for the maximum flow ratio Qk-max/MQ ranging between 0.5 and 4.5 (Figure 8, right). The ratio Qk-min/MQ versus MQ showed a similar behavior for RT 1 to 3. RT 4 (river) occurred in the data set only at MQs larger than 14 m^3/s and required higher kayak flows, both for the minimum and maximum kayak flows. The regression line was derived only for RT 1 to 3 together, without including a run for Raundalselva River, which was on the transition between RT3 and RT4. This run for Raundalselva River had a Qk-max of 41.8 m^3/s, which is quite close to Ligare's threshold for RT "River" (42.5 m^3/s, cp. Table 2). Based on the regression lines in Figure 8, the minimum and maximum kayak flows for the grade V run in Teigdalselva River for MQ = 9.1 m^3/s (average *MQ* between take-in and take-out for unregulated conditions) were estimated as 9.4 m^3/s and 15.2 m^3/s, respectively.

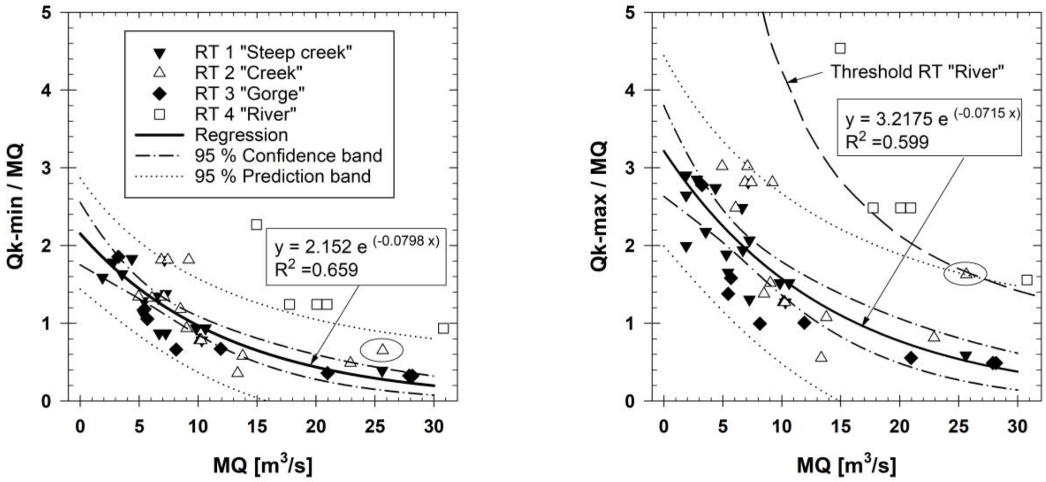

Figure 8. Ratio Qk/MQ as function of the unregulated mean discharge MQ (1961–1990) for the minimum kayak flow Qk-min (**left**) and maximum kayak flow Qk-max (**right**), specified for the four RTs. The regression functions were derived without including RT 4 "river" and the run marked with an ellipse, see explanations in text.

3.2. Citizen Science Approach

The citizen science approach resulted in 29 photos and two videos with known date and clear reference to Teigdalselva River. For 20 photos, the date and time were included in the EXIF information ("date taken"), for the remaining nine the date was mentioned at the web page. One of the images was sorted out as implausible. All other photos or videos belonged to five different dates between 2008 and 2017. Four of them documented kayak activities in the grade V reach upstream from Kråkefoss, while one video (1 July 2011) showed kayak training in a short reach close to the road downstream from Kråkefoss. The data documented kayak activities in the grade V reach at flows between 10 m^3/s and 21 m^3/s (Figure 9, Data sources P1–P3 and V1).

The discharge hydrograph for June 2006 (Figure 10, left) highlights the typical daily flow fluctuations that may occur in May and June. According to the information given by the local kayak experts during the interviews [27], the kayaking conditions at Kråkefoss in May and June are often best in the afternoon. Then, the flow is on its highest, after increased snow melting induced by warming of the earth surface during the day. The daily range of measured discharges on kayaking dates can vary substantially, in particular in connection with short floods after rain events. On 30 June 2011 (Figure 10, right), the discharge dropped from 80 m^3/s to 15 m^3/s at Mestad (approximately 28 m^3/s to 7 m^3/s at Kråkefoss). According to the photos, the kayaking took place in the afternoon between 2 pm and 5 pm. The video that was taken the day after documented kayak activities downstream from Kråkefoss at a discharge of about 10 m^3/s at Mestad (4 m^3/s at Kråkefoss)—most likely, because the flow conditions in the grade V reach had already become unsuitable.

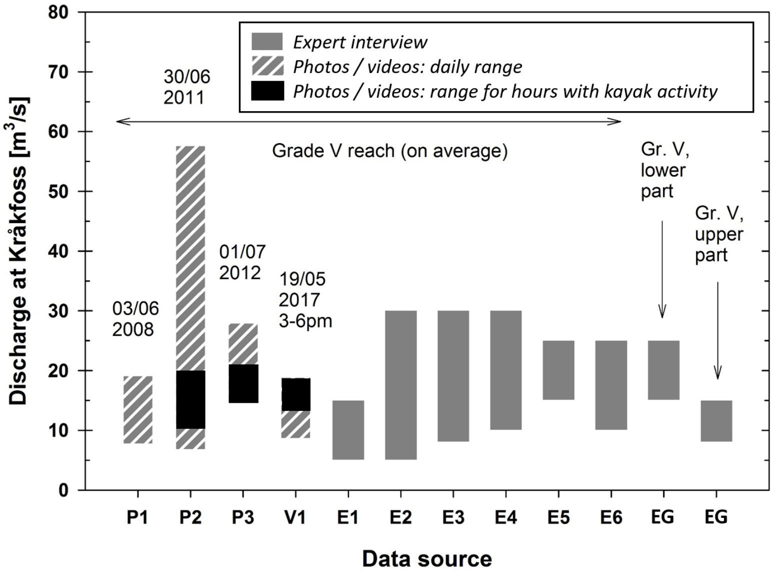

Figure 9. Overview of the estimated optimal flow ranges for the grade V reach of Teigdalselva River based on analyses of web-information and expert assessments. The data sources P1–P3 and V1 indicate the measured range of flows of kayak activities that were documented by photos (P) or video (V) on web pages. For P1, no time was available. Data sources E provide the range of flows estimated by elite kayakers. E1–E6 represent the opinion of single experts, while EG stands for an expert group of three experts that agreed on separate estimates for the upper and lower part of the grade V reach.

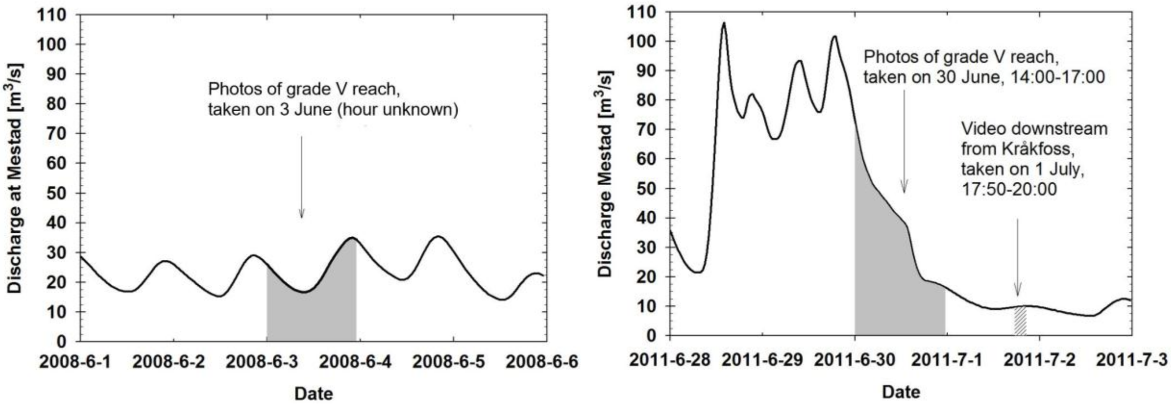

Figure 10. Measured discharges at Mestad during three documented kayaking periods. Data from BKK, time resolution 1 h (2008, **left**) and 0.5 h (2011 **right**). The date of the photo is marked in grey.

3.3. Expert Interviews

The elite athlete interviews during the Kayaker's Barbecue revealed a range of suitable kayaking flows between 5 m^3/s and 30 m^3/s for the grade V reach in Teigdalselva River (Figure 9, Data sources E1–E6 and EG). The minimum kayak flow estimates varied between 5 m^3/s and 15 m^3/s. A value of 5 m^3/s was hereby mentioned by only two experts, and they characterized it as the absolutely lowest flow that should be avoided. The maximum flows ranged between 15 m^3/s and 30 m^3/s. Flows between 10 m^3/s and 20 m^3/s were considered as optimal by several experts, while flows between 25 m^3/s and 30 m^3/s were regarded as extreme ("very full, but runnable"). An expert group of three people preferred to give different flow estimates for the upper part and the lower part of the grade V section. For the section upstream from Bjørndalen, they suggested 8–15 m^3/s, while the recommended flow range for the lower section downstream from Bjørndalen to Kråkefoss was 15 m^3/s to 25 m^3/s (Figure 9).

4. Discussion

Based on the regression functions that were found from the hydromorphological analysis (Approach 1), the suitable flow range for kayaking in the grade V reach upstream of Teigdalselva River was estimated to range between 9 and 15 m^3/s, with a large uncertainty (95% prediction intervall $0.44 - 2.77 \times MQ = 4–25\ m^3/s$). The flows that were obtained from the analysis of the photo and video data (Approach 2) covered flows between 10 m^3/s and 21 m^3/s. The nine athletes that were interviewed during the Voss extreme sport week mentioned 5 to 30 m^3/s as potentially suitable, with a core range between 8 m^3/s and 25 m^3/s that was supported by most of the experts (Approach 3).

One reason for the discrepancies between flow estimates derived from Approach 1 or 2 and the interview results (Approach 3) could be the uncertainty that is involved when kayakers estimate flows based on their "experience" or watching just the flow patterns in a river where no discharge data is available. In that case, the kayakers estimate the flows by creating mental images of similar rivers where they have paddled and knew the flows. Experiences from interviews [27] suggest that elite athletes are better able to assess the suitability of flow conditions for kayaking and relate it to flows. The typical recreational kayakers, in contrast, rely to a high degree on the experiences and recommendations from other kayakers or guide books. To ensure a fun and safe kayak experience, it is therefore essential for the WW community to have access to high-quality discharge data from gauge stations.

The optimal kayak flow range for the Teigdalselva River derived from the regression line for Nossum's Guide book [23] was more narrow (9–15 m^3/s) and had lower maximum flows than those that were recently suggested by the experts or documented by kayaking activities from the web search. The WW guide book by Klatt and Obsommer [5] suggests an even lower flow range of 6–12 m^3/s as kayaking flow for the grade V reach of Teigdalselva River. The interviewed elite kayakers mentioned that they regarded the flows given in this book and in other guide books that were published more than 10 years ago as somewhat too low, as seen with today's experience. This was their experience with several rivers. The mentioned possible reasons were that more people are kayaking today, and that the boats have changed. The recommendation for the upper-limit flow in the book would therefore be (too) low in order "to be on the safe side" for all readers (i.e., kayakers with wide-ranging skill-levels from novice to expert), while experienced kayakers could handle higher flows [28].

The construction of paddle sport crafts has indeed evolved over time, meaning that they are generally lighter and more robust due to a rugged design. This facilitated the descent of waterfalls and previously "un-runnable" rivers [29]. The understanding of the biomechanical properties, kayaking design characteristics, and pre-conditions for successful paddling performances have increased as well [30]. As a consequence, it would be necessary to correct the flow range that was obtained from the regressions with a factor accounting for the higher maximum kayak flows that experienced kayakers can handle today.

However, general recommendations on the optimal kayak flow range are difficult, because the flow preferences are individual and they change with growing experience. Outdoor adventure activity participants have wide-ranging skill levels, motivations, and risk behaviour [31]. They apply a range of behavioural strategies to achieve and maintain their preferred experience in changing environments [32]. Some kayakers may prefer flows at the lower end of the boatable flow range while the elite athletes are able to handle more complicated conditions at the upper flow limit. The difficulty level of the river is known to rise with rising flows [33]. A flow on the higher end of the boatable range will provide a greater challenge, and this is why elite kayakers can be expected to enjoy the higher flows within the boatable flow range.

The appearance and flow structures at Kråkefoss vary depending on the flow (Figures 11 and 12). The experienced kayaker likes to see a continuous and strong "flow curtain" (skimming flow over the rough bedrock steps) at each of the two drops, together with a sufficiently large whitewater landing zone. For too low flows, the flow curtains are shorter and split into several steps, such that the kayaker would hit the rocks (Figure 11). The occurrence of large white water curtains or landing zones is essential, because the aerated water is experienced as "soft" and secure, in contrast to the "hard" green water. The extent of the white water zones increases with increasing flow, such that the suitability for kayaking increases. At the maximum flow, however, the curl of the white water becomes too large and the so-called stoppers may develop, swirling the kayaker around like in a washing machine (Figure 12).

Figure 11. Double Drop at Kråkefoss at different flows in July 2017, for unsuitable low (**left**) and suitable (**right**) kayaking flows. Photos: Peggy Zinke.

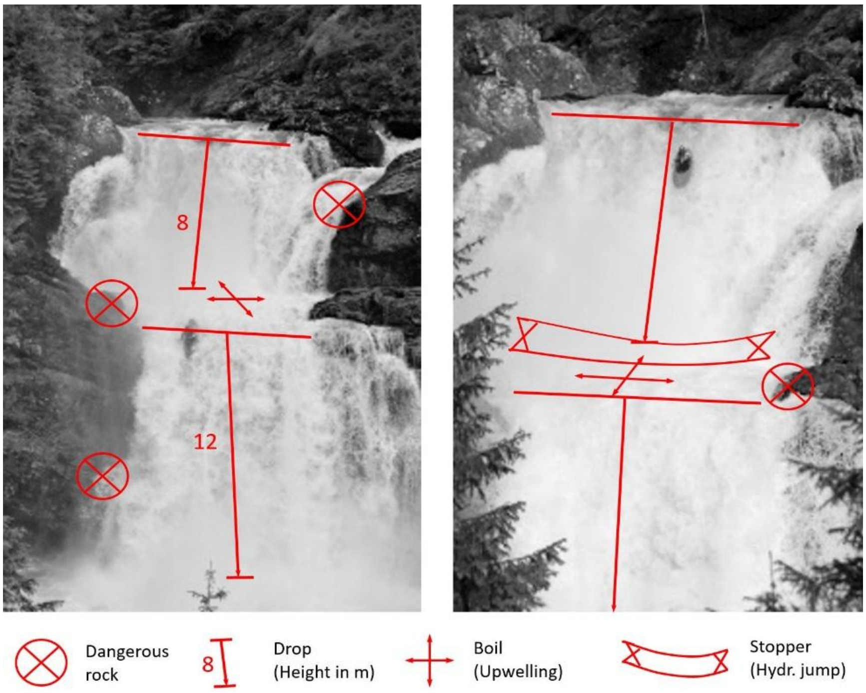

Figure 12. Double drop with kayaking activities during high flows. The left situation is suitable for many skilled kayakers, while the flow conditions on the right photo can only be managed by few world class experts. Photos: Steve Arns (**left**) and Benjamin Hjort (**right**).

The four WW run types, as suggested by Ligare et al. [1] for the western part of USA, appeared as a useful classification also for the description of WW suitability in the investigated Norwegian rivers. In our study, the function Qk/MQ vs. MQ shows a grouping that can be largely explained by the differences between RT 1–3 (steep creeks/creeks/gorges) at one hand and RT 4 (rivers) at the other hand. RT 1–3 seems to represent mostly bedrock rivers, i.e., rivers with little to no alluvial sediment mantling the bedrock over which it flows, while the few investigated runs with RT 4 are boulder bed channels (Figure 5). There are indications that RT 2 can be regarded as transition type, which may have reaches or features of semi-alluvial channels and a higher flow demand for kayaking. The flow of Qk-max = 42.5 m^3/s that was set as class limit for RT 4 by Ligare et al. [1] has empirical character and it may be different for other regions.

The interviewed elite kayakers distinguished also between two main river types: "bedrock rivers" and "boulder rivers". They claimed that most rivers with bedrock could be paddled with a lower flow, as compared to a boulder river. At higher flows, the creeks could be dangerous and there would be a risk for the occurrence of stoppers (hydraulic jumps) [28]. In our study, we found that the highest kayak flows were on average required for grade III rivers (Figure 7, top). This suggests that the majority of runs with grade IV and V were bedrock channels, while grade III runs may have longer reaches with plane-bed boulder channels (Figure 6, left). Future studies should include the investigation of substrate and stream type. A larger number of runs, including other geographic regions in Norway, needs to be studied, in order to derive more representative regression functions and a run type classification that accounts for regional conditions for RT 1–3, which represent the majority of WW runs. For RT 4, which has often a more regular bed roughness and is less dominated by white water flow, we recommend to consider the application of one- or two-dimensional hydrodynamic modelling tools.

A WW run may and does often contain reaches of different slope and geomorphic conditions, such that the assignment of one RT to the entire run is a simplification. The length of a river section that is called a "run" and assigned a specific grade depends not only on the geomorphic features, but also on other activity-related aspects, such as the accessibility (possibility for take-in and take-out) and the duration of the kayak excursions that can be undertaken. The difficulty grade of a WW run is not an exactly defined parameter, but rather a summarized assessment of the paddling conditions as a whole for a given run. The grade V section in Teigdalselva River contains some easier and slower parts near Brekkhus village, which is also reflected in lower SSP values (Figure 13). This part has a difficulty corresponding to grade II or III and gives the kayaker some time to recover after the first demanding section, before the next challenges come. All together, however, the entire section is regarded as a grade V run, and the elite athletes agreed that is not necessary to distinguish different grades for some shorter reaches that are less difficult. The flow requirements for a given kayaking run may therefore represent bottleneck reaches or drops that require more water than others.

The calculated SSP values allow for deriving the PSI value used for the indication of course difficulty in artificial canoe courses for the purpose of comparison. For those courses, a PSI value of 100 is considered as average and of national importance, 150 indicate a world championship standard, and 50 will suggest a course of regional significance [12]. Artifical canoe courses have often grade III. The PSI values in the grade V run of Teigdalselva River exceed the world championship limit by far (apart from the reach near Brekkhus, Figure 13), which underlines the outstanding role of this kayak run for the international WW sports community.

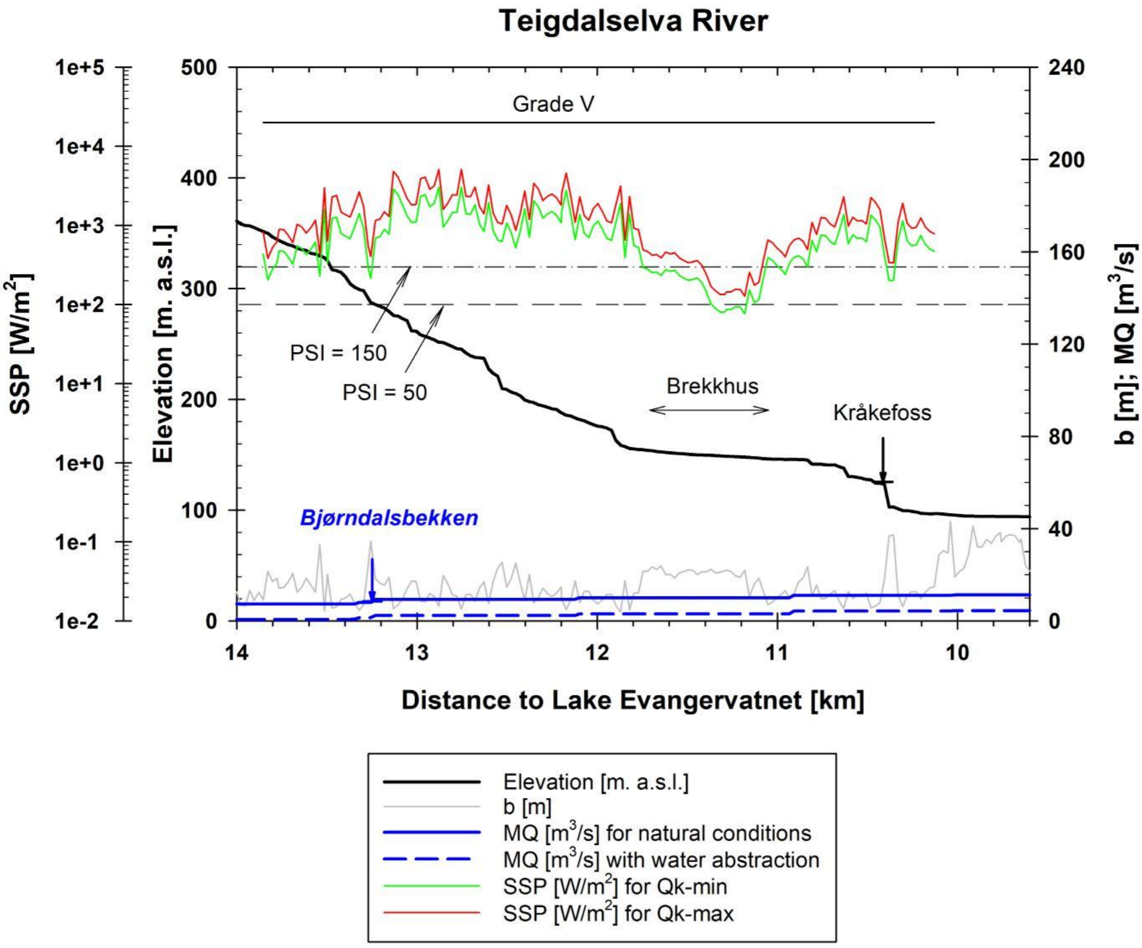

Figure 13. Longitudinal section of the grade V reach at Teigdalselva River. The following optimal kayak flow ranges are shown: upstream from Bjørndalsbekken 8–15 m^3/s, downstream 15–25 m^3/s.

The longitudinal section for Strandelvi River highlights relatively low SSP values in the entrance section of the upper (grade V) run at Strandelvi River (Figure 14). Higher SSP values in the "grade V" order of magnitude are only found near the outlet of the section. This reflects the fact that the upper part of the section is not as difficult, but the reach qualifying for grade V comes in the lower part of this section. A section is classified as grade V if there is at least one grade V rapid, as it is the case here. In Raundalselva River, the low SSP values in the upper grade III section correspond to flat zones. Relatively high SSP values were found for the lower grade III section, the so-called Play Section (Figure 14). This section has many rapids (among them class IV rapids), but in between reaches corresponding to class II. Therefore, it is in summary a grade III run, even though it would be not classified as grade III if one would look at single points.

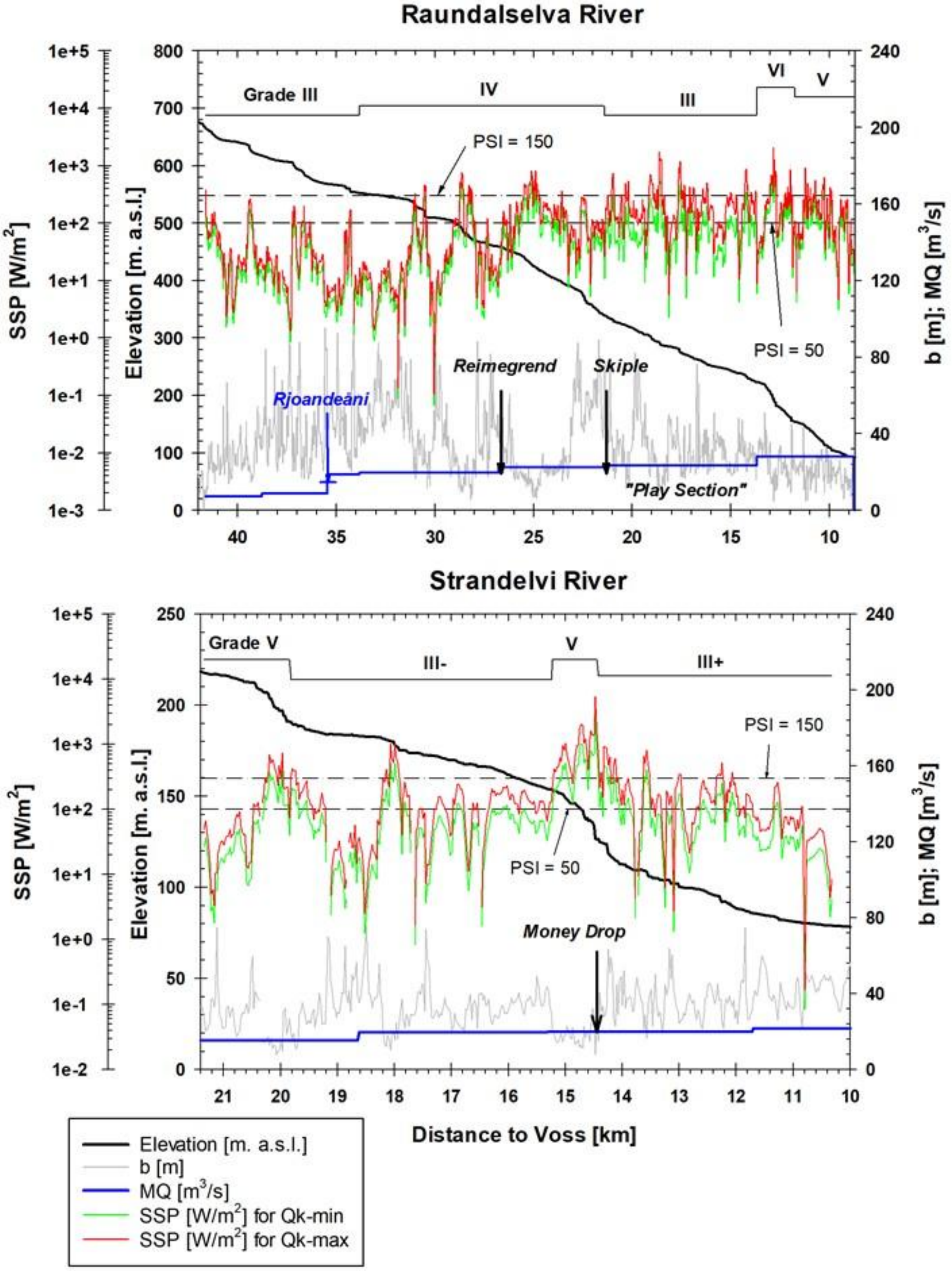

Figure 14. Longitudinal section of the known kayaking reaches at Raundalselva River (**top**) and Strandelvi River (**bottom**), including mean discharge, grade, and SSP.

5. Conclusions

We compared three different approaches for estimating the optimum flow ranges for WW kayaking in Western Norway.

For the hydro-morphological analysis, we analyzed data of 41 WW runs in Western Norway from a kayak guidebook, together with publicly available morphological and hydrological data. Overall, our results support our hypothesis that the optimal kayak flow range for WW kayak of a given geographic region can be estimated based on empirical regression as function of the natural mean discharge MQ (time series 1961–1990) and the four geomorphic run types that were suggested by Ligare et al. [1]. MQ is a parameter that can be easily obtained from public data sources in Norway (NVE's NEVINA-tool). The assignment of the run type requires information about the river slope and the sequence and difficulty of runs along the river. This assessment should be done by or in cooperation with experienced kayakers, if no other information is available. The empirical regression curves for the minimum and maximum flows of the combined run types 1–3 were derived based on a small data set that showed considerable scatter. A larger number of runs in Norway need to be investigated, in order to derive more representative and region-specific regression functions that account for the varying hydrological conditions throughout the country.

As a citizen science approach, we tested whether photos and videos of kayak-activities on the web together with an analysis of hydrological data can lead to reasonable estimates for WW kayak flows. By a manual web search before 30 June 2017, less than 30 photos and videos with known date and a clear reference to Teigdalselva River were found. They could be related to kayak activities in the grade V reach at four different dates. The measured discharges during these dates ranged in the middle of the estimations that were made by the other methods. Despite the fact that a large number of WW kayak photos were available on the web, most of them were not sufficiently documented for scientific analyses. Information about the date/time and location of the images or videos was often missing. Nowadays, more and more photos are taken by cameras or mobile electronic devices where date, time, and location information are automatically included, making them much more suitable for analysis. The method has therefore a large potential for automated data mining methods. In addition, the kayak community should be involved more actively into crowd sourcing data collection, for example, by mobile applications where kayakers actively can send in location, time and date of their activities.

The results of optimum flow estimates from the hydro-morphological analysis were compared with flow estimates for Teigdalselva River given by world elite kayakers during an interview. They suggested a wider range of suitable flows, in particular higher maximum flows and mentioned that maximum flows that are provided in old kayak guide books can be somewhat too low, due to a larger number of highly skilled athletes today and lighter, more robust crafts. However, flow preferences are individual and change with growing experience. Some kayakers prefer flows at the lower end of the boatable flow range, while highly skilled elite athletes are able and find joy in handling more complicated flow conditions. Another reason for the discrepancies between flow estimates are the uncertainties that are involved when kayakers estimate flows based on their visual impressions and experiences. This issue should deserve more attention in future studies, where a large number of kayakers with different skill levels could be interviewed regarding their preferences in rivers of different grades.

For studies about the flow requirements for WW kayak in the context of water management, we recommend the use of a combination of different methods. Estimations based on the empirical regression functions should be always checked and confirmed by kayaking experts knowing the river under investigation or photos and videos documenting kayak activities for known hydrological conditions.

Author Contributions: Conceptualization and methodology, P.Z., I.N., I.S.-D.; Data Analysis, P.Z.; Kayaker Interviews, P.Z.; Data Acquisition Web-Data, P.Z. and I.S.-D.; Writing—Original Draft Preparation, P.Z. with input from all co-authors, in particular D.S.; Writing—Review & Editing, all authors; Visualization, P.Z. and D.S.

Funding: This research was funded by the ENERGIX programme of the Norwegian Research Council (NRC) as part of the interdisciplinary project "SusWater" (Sustainable governance of river basins with Hydropower production, No. 244505/CEDREN 193818) and inspired by the NRC-funded project iResponse (247884/O70).

Acknowledgments: We would like to thank all interview partners, in particular the kayak experts that have shared their knowledge during the Kayaker's Barbecue on 1 July 2017. Special thanks to Steve Arns (www.liquidlore.com), Øystein Bjørke and the family of Benjamin Hjort (who died in 2016) for the permission to use their photos. We are grateful to BKK for the provision of gauge data.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ligare, S.T.; Viers, J.H.; Null, S.E.; Rheinheimer, D.E.; Mount, J.F. Non-uniform changes to whitewater recreation in California's Sierra Nevada from regional climate warming. *River Res. Appl.* **2012**, *28*, 1299–1311. [CrossRef]
2. Carolli, M.; Zolezzi, G.; Geneletti, D.; Siviglia, A.; Carolli, F.; Cainelli, O. Modelling white-water rafting suitability in a hydropower regulated Alpine river. *Sci. Total Environ.* **2017**, *579*, 1035–1040. [CrossRef] [PubMed]
3. Bizzi, S.; Pianosi, F.; Soncini-Sessa, R. Valuing hydrological alteration in multi-objective water resources management. *J. Hydrol.* **2012**, *472–473*, 277–286. [CrossRef]
4. Poff, N.L.; Alan, J.D.; Bain, M.B.; Karr, J.R.; Prestegaard, K.L.; Richter, B.D.; Stromberg, J.C. The natural flow regime. A paradigm for river conservation and restoration. *BioScience* **1997**, *47*, 769–784. [CrossRef]
5. Klatt, J.; Obsommer, O. *The Whitewater Guide. Der Wildwasserführer*; La Ola Verlag: Köln, Germany, 2003.
6. Shelby, B.; Whittaker, D.; Roppe, J. Controlled flow studies for recreation: A case study of Oregon's North Umpqua River. *Rivers* **1998**, *6*, 259–268.
7. Brown, T.C.; Taylor, J.G.; Shelby, B. Assessing the direct effects of streamflow on recreation: A literature review. *JAWRA J. Am. Water Resour. Assoc.* **1991**, *27*, 979–989. [CrossRef]
8. Carolli, M.; Geneletti, D.; Zolezzi, G. Assessing the impacts of water abstractions on river ecosystem services: An eco-hydraulic modelling approach. *Environ. Impact Assess. Rev.* **2017**, *63*, 136–146. [CrossRef]
9. Miller-Rushing, A.; Primack, R.; Bonney, R. The history of public participation in ecological research. *Front. Ecol. Eviron.* **2012**, *10*, 285–290. [CrossRef]
10. Bonney, R.; Shirk, J.L.; Phillips, T.B.; Wiggins, A.; Ballard, H.L.; Miller-Rushing, A.J.; Parrish, J.K. Next Steps for Citizen Science. *Science* **2014**, *343*, 1436–1437. [CrossRef]
11. Gerlach, J. *Der Kajak. Das Lehrbuch für den Kanusport*, 4th ed.; Delius Klasing Sport: Bielefeld, Germany, 2015.
12. Goodman, F.R.; Parr, G.B. The design of artificial white water canoeing courses. *Proc. Inst. Civ. Eng. Munic. Eng.* **1994**, *103*, 191–202. [CrossRef]
13. American Whitewater Association. International Scale of River Difficulty. Available online: https://www.americanwhitewater.org/content/Wiki/safety:internation_scale_of_river_difficulty (accessed on 10 January 2018).
14. Norges Padlerforbund. Gradering. Available online: http://www.padling.no/elv/sikkerhet/gradering/ (accessed on 30 April 2018).
15. Tranmer, A.W.; Tonina, D.; Benjankar, R.; Tiedemann, M.; Goodwin, P. Floodplain persistence and dynamic-equilibrium conditions in a canyon environment. *Geomorphology* **2015**, *250*, 147–158. [CrossRef]
16. Thorp, J.H.; Flotemersch, J.E.; Delong, M.D.; Casper, A.F.; Thoms, M.C.; Ballantyne, F.; Williams, B.S.; O'Neill, B.J.; Haase, C.S. Linking ecosystem services, rehabilitation, and river hydrogeomorphology. *BioScience* **2010**, *60*, 67–74. [CrossRef]
17. Montgomery, D.R.; Buffington, J.M. Channel-reach morphology in mountain drainage basins. *Geol. Soc. Am. Bull.* **1997**, *109*, 596–611. [CrossRef]
18. Aberle, J.; Smart, G.M. The influence of roughness structure on flow resistance on steep slopes. *J. Hydrol. Res.* **2003**, *41*, 259–269. [CrossRef]
19. Naish, C.; Dungworth, D.; Doyle, T. Delivering London 2012: The Lee Valley White Water Centre. *Proc. Inst. Civ. Eng. Civ. Eng.* **2012**. [CrossRef]
20. Bizzi, S.; Lerner, D.N. The use of stream power as an indicator of channel sensitivity to erosion and deposition processes. *River Res. Appl.* **2015**, *31*, 16–27. [CrossRef]
21. Environmental Agency Wales. Weir Assessment System. Environmental Agency Wales, Wales (UK). 2009. Available online: http://www.swiftwaterrescue.at/downloads/R3UK_WeirAssessment_Online.pdf (accessed on 2 May 2017).

22. Sørensen, J.; Brodtkorb, E.; Haug, I.; Fjellanger, J. Vannkraftkonsesjoner som kan revideres innen 2022. Nasjonal gjennomgang og forslag til prioritering. 2013. NVE Rapport 49/2013, 316p. Available online: http://www.miljodirektoratet.no/Documents/publikasjoner/M49/M49.pdf (accessed on 15 March 2018).
23. Nossum, T. Western Norway. Available online: http://elveguide.netrunner.nu/guider/tore-nossum-s-guider (accessed on 27 March 2017).
24. Maps of Bedrock and Soil in Norway. Geological Service of Norway. Available online: https://www.ngu.no/en/topic/applications (accessed on 11 December 2017).
25. Map of Normal Precipitation (1971–2000). Geodata AS. Available online: www.senorge.no (accessed on 15 January 2018).
26. Sandvik, D. (Voss, Norway). Site information provided during the field trip to Teigdalselva River and Eksingedalsvassdraget in July 2017. Personal communication, 2017.
27. Nesheim, I.; Sundnes, F.; Barkved, L. Hvordan kan regulerte vassdrag tilrettelegges for flerbruk? Et studie av vassdragsfunskjoner og brukerpreferanser. *Vann* **2018**, *2*, 181–191.
28. Ellard, A.; Sutton, J.; Ramazza, M.; Deguli, E.; Bartak, K.; Farkas, D.; Kodada, M.; Kopecny, J.; Sandvik, D.; Interview information during the Kayaker's Barbecue at the Voss Extreme Sports Festival on 1 July 2017 (Voss, Norway). Personal communication, 2017.
29. Wilson, I.; Folland, J.; McDermott, H.; Munir, F. White-Water Paddlesport Medicine. *Extreme Sports Med.* **2016**, 289–304. [CrossRef]
30. Michael, J.S.; Smith, R.; Rooney, K.B. Determinants of kayak paddling performance. *Sports Biomech.* **2009**, *8*, 167–179. [CrossRef]
31. Pomfret, G.; Bramwell, B. The characteristics and motivational decisions of outdoor adventure tourists: A review and analysis. *Curr. Issues Tour.* **2016**, *19*, 1447–1478. [CrossRef]
32. Aas, Ø.; Onstad, O. Strategic and temporal substitution among angler and white-water kayakers: The case of an urban regulated river. *J. Outdoor Recreat.* **2013**, 1–8. [CrossRef]
33. American Whitewater Association. Safety Code of American Whitewater. Available online: https://www.americanwhitewater.org/content/Wiki/safety:start (accessed on 22 May 2018).