Using surrogate organisms in hydraulic research: guidance on their design and implementation

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ABSTRACT

When investigating or quantifying the interaction of organisms with the hydrodynamic environment, it is often necessary or desired to use surrogates instead of the prototype organisms. In order not to derogate the results, it is important to design surrogates to represent the essential properties of the prototype organism correctly. To do so, several aspects of organism behaviour and morphology have to be considered, which are rarely mentioned in studies that present work carried out with surrogates. This paper presents a guideline to the choice and design of surrogates and aims to offer support during the design phase of flume studies, particularly to researchers that (i) are not (yet) familiar with living organisms and their behaviour, or (ii) have little experience with the strengths and limitations of hydraulic facilities, in order to enhance the quality of collected data and provide meaningful results.

Keywords: eco-hydraulics; experimental facilities; flow-biota interactions; physical modelling; surrogates

1 Introduction

The interaction of organisms with hydrodynamics in aquatic environments is complex and subtle, and yet it is important for both ecological and physical processes. Studying these interactions under controlled conditions in a flume is an important task to understand the processes involved in ecosystem functioning, organism behaviour and hydrodynamic patterns. It is a challenging task to keep an organism alive and in good condition in a laboratory setting and it requires a great deal of practical management and ecological knowledge (Johnson et al., 2014a). It is often impossible to use live organisms for experimental studies, because many laboratory facilities cannot meet the minimum husbandry requirements. For instance, only very few hydraulic facilities can operate with salt

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water, which significantly limits the number of potential laboratories if the interaction of salt water organisms and hydrodynamics is of interest. Even if the facility is able to house living organisms, the need for substantial living space and the time required for feeding and cleaning of organisms and their housing tanks, can make maintaining stocks of organisms costly (Johnson et al., 2014a). And finally, there are ethical issues particularly with experiments that include animals, sometimes requiring licences and specially trained personal for animal handling.

To avoid the challenges associated with plant and animal husbandry it may be possible to use surrogate organisms without compromising on the relevance or quality of the data collected. In this context, surrogates are full or partial replicas of biota that mimic particular organism traits relevant to the aims and objectives of the study. A whole variety of physical surrogates has been used, ranging from generalised forms, e.g. hemispheres or uniform rods (Davidson et al., 1995; Bouma et al., 2005; Friedrichs et al., 2009; Paul et al., 2012), to precise replicates of morphology and texture using resin casts (e.g. O'Donnell, 2008). A regular application is the use of dead animal shells as surrogates for living equivalents (Crimaldi et al., 2002; Folkard and Gascoigne, 2009) where sometimes devices have been incorporated to mimic the siphonal currents of shellfish (Ertman and Jumars, 1988; Petersen et al., 2013); and for some studies animal movement has been mimicked with mechanical analogues (Lim and DeMont, 2009). Despite a number of practical and research benefits, there are several limitations to using surrogates instead of living organisms and thus their use has to be carefully considered.

Surrogates can be used in the field to exclude natural variability and to focus on the interaction between organisms and specific processes, whilst excluding other phenomena which may complicate interactions. However, the most common application of surrogates is in laboratories where the manipulation of hydrodynamic conditions enables fully controlled experiments to be performed, particularly where facility specific conditions prohibit the use of live organisms. While most issues addressed here can be applied to field settings, the primary focus of the guidelines is on surrogate use in hydraulic laboratory settings.

A surrogate will always be a simplified model of the real world or prototype. This renders surrogates exceptionally useful for the validation of numerical models. Often, the use of surrogates is also deemed necessary to allow for scaling when the size of laboratory facilities does not accommodate organisms and their environment on the prototype scale. But it is important that the essential behaviours and properties of the organism are retained during surrogate design. What is considered essential depends on the objectives of the particular study and the complexity of the problem under investigation. But in general, it is more important that a surrogate behaves like the prototype rather than look like it. As the definition of essential organism properties is specific to the respective science questions under investigation, these guidelines cannot provide a description of important properties to replicate. Instead, these guidelines aim to (i) help researchers make the decision whether surrogates are a suitable tool for the specific research aims (Figure 1) and (ii) provide guidance on the construction and use of inert surrogates in order to provide suitable analogues for the properties of living equivalents being studied (Figure 2) and thus achieve high quality results.

Many of the concepts described in this guideline have been described in a recent book by Frostick et al. (2014) and for general guidance on physical modelling, we would like to refer to the "Users guide to Physical Modelling and Experimentation" (Frostick et al., 2011). Here we synthesise the provided information into a decision tree to help scientists (yet) unfamiliar with research at the interface of biota and hydrodynamics to make the right choices and hence improve the quality of their experimental work. This document is geared towards researchers across a wide range of disciplines, including biologists and hydraulic engineers, by addressing both biological and physical aspects of surrogate use and design. It should be seen as an introduction to surrogate design and implementation. For detailed information on individual aspects of this guideline, we refer the reader to the above mentioned text books and other publications provided in the reference list.

2 When to use surrogates instead of living equivalents?

The decision to use surrogates may be made based on various considerations and aspects of a study. The advantages and disadvantages of the use of surrogates are described in detail in Johnson et al. (2014b), but guidance on when to use them is still lacking. Here the most prominent aspects of an eco-hydraulic experiment that affect the choice of whether or not to use surrogates are described (Figure 1).

2.1 Define your research questions

A clear definition of the specific research questions being asked is crucial when making the decision of whether to use a surrogate. In some studies the use of surrogates may not be appropriate. For example, surrogates are unsuited for studying the behavioural response of animals to flow conditions because they rarely mimic active responses to hydrodynamic forcing. However, for many studies addressing the interaction between biota and hydro- or morphodynamics, surrogates are an adequate means to simplify and control complex natural processes.

Depending on the research question, surrogates can be abstract or realistic reproductions of the prototype. How complex a surrogate needs to be and whether its design is successful, depends on the characteristics it needs to mimic and on the parameters that will be measured during the study. For instance, the roughness and drag at a scale relevant to individual mussels will depend on shell texture, while the resulting impact of this texture on the roughness of large mussel aggregations with shells of different heights may be minimal (Coco et al., 2006). Similarly, it may be sufficient to represent vegetation with simple plastic strips if the effect of plant stiffness on flow and wave damping at a patch scale is of interest (Paul et al., 2012), but if the turbulence within the patch is being investigated, the chosen strip stiffness also needs to enable realistic surrogate posture and motion (Luhar et al., 2010).

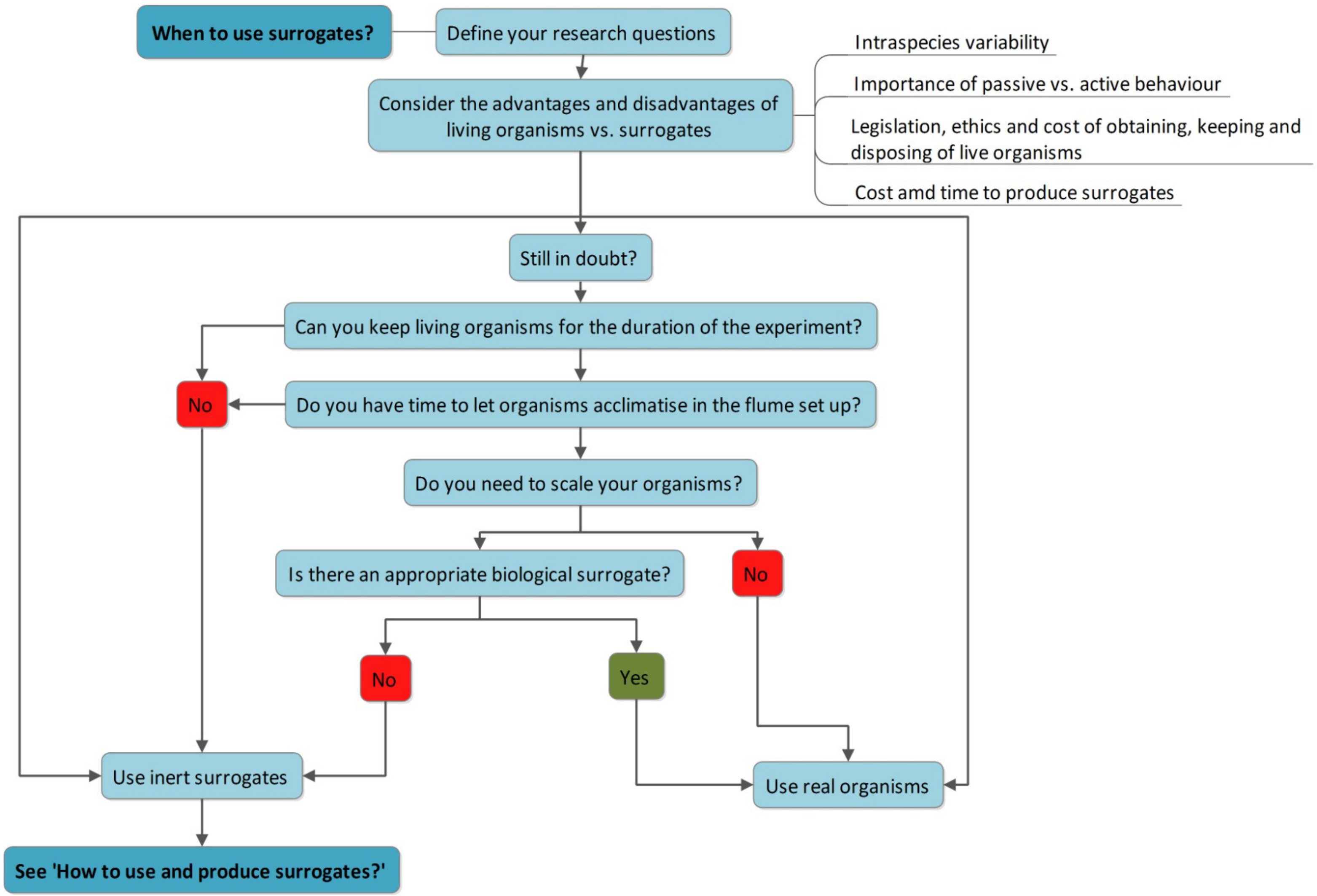

Figure 1: Flow chart informing the decision-making process when deciding whether to use surrogates in eco-hydraulic experiments

2.2 *Consider the advantages and disadvantages of living organisms vs. surrogates*

The use of surrogates can have key advantages over using real organisms. In particular, using surrogates avoids the many complications and costs of using living organisms, which are discussed in detail below and include: (i) intraspecies variability, (ii) importance of active behaviour, (iii) legislation, ethics and cost of obtaining, keeping and disposing of live organisms and (iv) cost and time to produce surrogates.

Intraspecies variability

It is possible to include intraspecies variability in morphological parameters, such as organism size and shape, in surrogate design, but the merit of such effort strongly depends on the question to be answered. For example, areas of smaller or larger mussels within a colony are likely to cause second order effects in studies of aggregation morphology or small scale turbulence, but the effect of variability in mussel size is likely to be negligibly small when considering wave propagation. For other parameters, such as vegetation stiffness or buoyancy, the effort of reproducing natural variability in surrogates can be exorbitantly high since it may require the identification and use of different materials to produce surrogates. Moreover, variability between individuals can confound the identification of important organism-environment relationships and, consequently, one of the main criteria in choosing to use surrogates may be to exclude variability in certain parameters in order to isolate, standardise or otherwise control the interaction between an organism and hydro- or morphodynamic processes. For instance, several studies (e.g. Bouma et al., 2005; Paul et al., 2012) have used surrogates to identify the effect of plant stiffness on wave attenuation, which would not have been possible in a bed of surrogates with mixed stiffness.

Importance of active behaviour

Physical surrogates are well suited to mimic morphology and, to a certain extent, flexibility in plants. However, they lack the ability to represent physiology or behaviour that affects hydrodynamic conditions, but is dependent on other environmental parameters. The latter applies particularly to animals where, for instance, the physical roughness may be modelled accurately in surrogate mussels, but the additional roughness associated with siphonal jets or the effects of filtering activities on boundary layer flow development may not necessarily be incorporated. Some studies have, however, incorporated this feature in surrogate design (Ertman and Jumars, 1988; Crimaldi et al., 2007; Petersen et al., 2013). Equally, if animal locomotion (e.g. the effect of crayfish motion on sediment distribution; Johnson et al., 2011) is of relevance, the use of surrogates may not be feasible. Whilst surrogates can provide excellent replicas of passive reconfiguration of organisms to hydrodynamic conditions, animals may also respond actively, for example, by changing their behaviour, which surrogates are not well suited to study.

Costs, legislation and ethics of obtaining, keeping and disposing of live organisms

Obtaining live organisms can be expensive if the organism of interest is not readily available in the vicinity of the laboratory where experiments will take place. If the organisms have to be sourced elsewhere, this is likely to be associated with purchase costs and transport expenses. Some species may only be available abroad, requiring consideration of import restrictions and regulations before planning the experiments, and it is possible that use or import of some selected species will be prohibited. Legislations may also apply with regards to keeping live organisms, particularly vertebrate animals, and disposing of organisms at the end of experiments. For instance, species that are considered invasive to the region where the laboratory is located cannot be released into the wild and will need to be disposed of professionally, which leads to additional costs. Even if organisms can be sourced locally and released locally afterwards, they may not be easily available at large enough quantities to run the planned experiments. Seagrass meadows, for instance, are globally protected ecosystems (IUCN, 2010) and cannot be excavated and transported to a laboratory without immense administrative effort, if at all. Once organisms have been obtained, the cost of aquaria and related equipment to maintain biota in ethically acceptable conditions, such as water filters, aeration devices and temperature regulation or suitable pumps, must also be considered (Johnson et al., 2014a).

Ethical questions in this context mainly apply to experiments with live animals, which always require careful consideration. In most countries legislation regarding animal testing tends to be limited to vertebrates (e.g. fish, reptiles) and cephalopods (e.g. squid, octopus) and frequently researchers require a permit and need to be qualified to run experiments with these animals. However, it is good practice to consider whether tests involving live animals are absolutely essential, even if it concerns invertebrates (e.g. shellfish, crustaceans) that do not fall under any regulations.

Cost and time to produce surrogates

The material used to construct surrogates will strongly depend on the organism parameters that need to be modelled, but material costs and time to produce surrogates may play a role in the decision-making process. In particular, if large quantities of surrogates are needed, for example when studying wave attenuation by salt marsh vegetation under storm conditions at full scale, the material costs and construction time may be prohibitive. In such cases, cost and effort may be better spent attempting to use natural salt marsh vegetation. Once surrogates are produced, however, it is possible to store them once the experiments are completed to either repeat the experiments at a later stage or re-use them again for another study.

2.3 Can you keep living organisms for the duration of the experiment?

Living organisms have specific biotic and abiotic requirements that determine their fitness, well-being and general survival. A detailed review with regards to husbandry issues is given in Johnson et al. (2014a), but the key concerns are the provision of sufficient oxygen, light and food and maintaining a suitable temperature and salinity. Moreover, the facility (including tanks, pumps and pipe works) needs to be free of toxic materials, which is often difficult to realise; copper piping, for instance, is very common in experimental facilities. Most organisms can cope with sub-optimal conditions for a certain time and, in some cases, provision of one factor can mitigate the negative effects of the lack of another. It has been observed for the brown macroalgae *Laminaria digitata* that provision of excess light can reduce stress caused by elevated water temperature (Paul, pers. obs.). However, if sub-optimal conditions are maintained for too long, organisms will deteriorate to a state where their behaviour cannot be considered natural or representative anymore. Such deterioration can also take place during the course of experiments, and hence organism conditions do not necessarily remain constant for the entire test duration despite a similar appearance. The planned duration of experiments, including setup and time between experiments, in conjunction with the facility's capability to cater for organism needs, will therefore determine if living organisms can be used or if physical surrogates are necessary.

2.4 Do you have time to let organisms acclimatise in the flume set up?

When live organisms are used, they require time to acclimatise to the new conditions that they encounter in the experimental facility prior to the experiments. Behaviour and growth rates can be negatively affected if insufficient acclimatisation time is allowed for. For instance, mobile animals will show increased activity when introduced to a new environment, which cannot be considered representative of behaviour in their natural environment (Johnson et al., 2014a). In some cases, acclimatisation can take weeks, for instance when a living mussel bed needs to establish a stable configuration (van Duren et al., 2006) or when plants need to grow roots between soil sections. Experimental planning may not be able to account for such long acclimatisation times due to facility availability or because organisms would not survive long enough due to husbandry issues outlined above. In that case, the use of physical surrogates is a valuable alternative.

2.5 Do you need to scale your organisms?

It is best scientific practise to choose a laboratory facility based on the requirements of the study at hand, including a working area of suitable size to accommodate fully grown specimens of the organism. However, this is not always possible due to time or cost limitations. If the available facility does not allow for full scale tests, it will be necessary to adjust the size of study objects to fit in the scaled down version of the setting. In some cases, biological surrogates can be used to study larger scale vegetation dynamics (e.g. alfalfa as representation of floodplain forests; Tal and Paola, 2010). But most often, artificial surrogates made of inert materials will be required for scaled eco-hydraulic experiments. For example, polyethylene dowels have been used to represent trees across a sloping coastline in a 1:40 wave run-up model (Noarayanan et al., 2012) and Sánchez-González et al. (2011) produced a 1:10 model of the seagrass *Posidonia oceanica* from polyethylene and polypropylene to achieve similarity in stiffness according to Froude similitude.

2.6 Is there an appropriate biological surrogate?

As mentioned above, it can be possible to use other biota to substitute the organism of interest. Biological surrogates are best used when the research focus is on processes over large spatial and temporal scales and studies that require biophysical feedbacks, such as floodplain and channel development. In those cases, development of vegetation cover and soil stabilisation by roots can be reproduced using small, fast growing species with a similar morphology as the prototype (Tal and Paola, 2010). If biological surrogates are appropriate, it should be evaluated if the surrogate is fast growing enough to achieve the planned results within the given time frame. Additionally, the same questions and conditions apply with regards to husbandry (i.e. maintaining the health of organisms; Johnson et al., 2014a) for biological surrogates as for prototype organisms.

3 How to use and produce surrogates?

If it is not possible to use a living organism to achieve the research aims, a surrogate may provide a successful alternative. However, care needs to be taken in their design so as to achieve high-quality results and suitably answer the research questions. The decision tree in Figure 2 is designed to guide researchers in the process of finding a suitable surrogate material and produce surrogates that serve the purpose of their study.

3.1 What is your prototype and how variable is it?

A key aspect of surrogate design is the choice of an adequate prototype. While organisms within a population will exhibit features characteristic of the whole population, no two specimens will be identical. Perhaps the simplest way of choosing a prototype is to pick a single specimen and reproduce its characteristics in the surrogate. However, this approach raises the question, how representative the chosen prototype is for the whole population. It may therefore be adequate to establish mean values or a probability density function for the parameters of interest and base surrogates on these values, even though the resulting surrogate may not entirely resemble any one specimen within the population.

Prototype selection needs to consider seasonal variation both at the individual organism and patch scale. It is possible to model riparian woody vegetation with simple single stem elements, but the results may not be applicable to the summer state when trees and shrubs are covered with leaves. Equally, aquatic vegetation (e.g. seagrass) sheds leaves in autumn which can result in differences in shoot density of an order of magnitude (Paul and Amos, 2011). A similar seasonal variation can be found in physiological and vitality parameters, which are likely to affect results. Detailed ecological knowledge of the species under investigation is therefore required to identify the natural range of parameters of interest and to judge which state is the most appropriate for surrogate design. Such knowledge may also be relevant with respect to colonisation by epiflora and -fauna. Epibiota can vary spatially and seasonally and can affect a host's vitality and mechanical behaviour. Depending on the required level of detail, this may be incorporated in the surrogate design, but particularly when particle capture is of interest, epibiota may have to be considered individually.

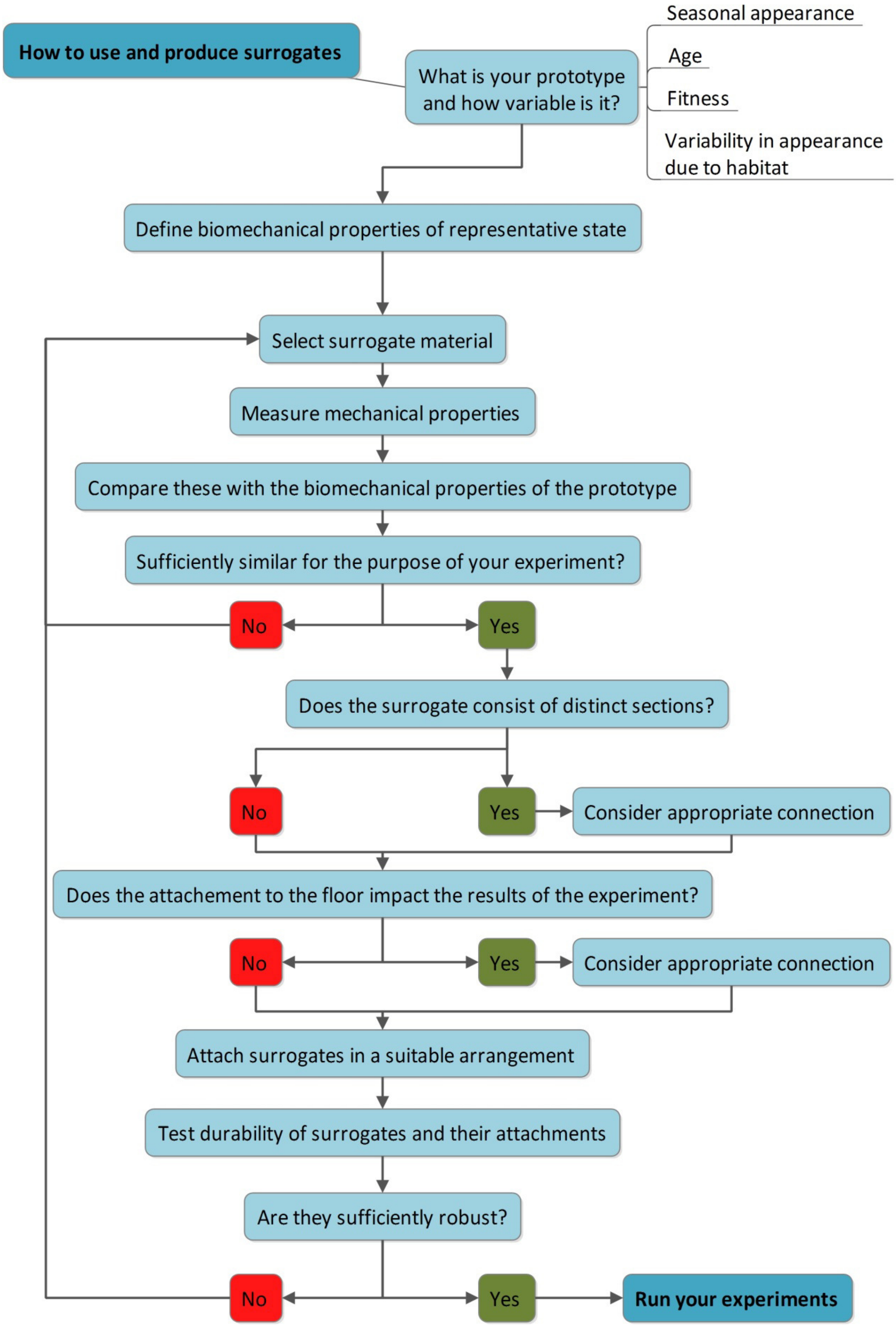

Figure 2: Flow chart to aid in deciding how to produce surrogates.

The same applies for phenotypical differences between populations that live under different abiotic conditions, e.g. the adaptation of aquatic plants to prevailing hydrodynamic forces. A reduction in size and redistribution of biomass is generally the most common adaptation to increasing hydrodynamic energy (Gaylord et al., 1994; Idestam-Almquist and Kautsky, 1995; Coops and van der Velde, 1996; Blanchette, 1997). However, increases in shoot lengths with increasing flow velocities have also been observed (Puijalon et al., 2005). It is therefore important to consider which hydrodynamic conditions will be tested when choosing a suitable prototype for eco-hydraulic experiments.

3.2 Define relevant properties of prototype and surrogate material

For physical surrogates of plants a set of attributes has been established (Frostick et al., 2011) of which some are equally relevant for animals. Similarity between these variables for both prototype and surrogate will enhance accurate reproduction of morphology and response to the flow: (i) Buoyancy/mass density; (ii) Flexibility/elasticity; (iii) Stem and leaf diameter, size and shape; (iv) Stem areal concentration (i.e. stems per unit area); (v) Breaking strength; and (vi) Surface texture. These parameters can be integrated using two non-dimensional similarity numbers (Luhar and Nepf, 2011) for better comparison between model and prototype: the Cauchy number, which is the ratio of drag and the stiffness restoring force, and the buoyancy parameter, which is the ratio of the restoring forces due to buoyancy and the stiffness. Moreover, similarity in these non-dimensional numbers may be used to produce scaled surrogates of plant species that are too big for full scale modelling (e.g. mangroves, flood plain trees).
A specific feature limited to animals only is hydrodynamic activity which describes the effect of active animal motion on hydrodynamics. It will be addressed at the end of this section.

Buoyancy/mass density

Mass density is one property of aquatic vegetation that helps to maintain an upright posture and hence partially controls plant motion under hydrodynamic forcing. It is therefore important to model it correctly, if plant reconfiguration is of interest. Mass density of potential surrogate materials is usually known, but may change once the material is submerged in water if the surface is not fully sealed (Paul and Henry, 2013). This is particularly relevant if a material with sealed surface but porous core (e.g. artificial leather) is used to cut surrogate shapes, leaving the edges open for water penetration. In that case, the surrogate's mass density will change slowly and irregularly and full soaking may need to be established before the start of experiments.

Flexibility/elasticity

Flexibility is the other property that determines plant posture and motion. Values for flexibility or elasticity are therefore important, but are often not available for inert materials. Even if values are given by the manufacturer, it may not be possible to compare them to values obtained for the prototype. For instance, absolute values of bending modulus differ for a single material depending on the method used to obtain the value (Bower, 2010). It will therefore be necessary to measure flexibility of possible surrogate materials using the same method that has been employed to establish values for the prototype.

In material sciences, standard procedures such as the three or four point bending test exist to obtain bending moduli for materials. Modifications of these have been applied to different types of vegetation (Gaylord and Denny, 1997; Stewart, 2004; Harder et al., 2006; Miler et al., 2012; Paul et al., 2014). For these tests, a sample is placed horizontally on support structures on either side and the force required to push the sample's centre down by a defined distance is recorded. Consequently, a certain rigidity of the sample is required which stops it from bending under gravity alone. Many aquatic plant species (or parts of them) are not that rigid, which limits the correct implementation of such tests to purely qualitative estimates (Paul and Henry, 2014). For those very flexible materials, Henry (2014) suggests a different method based on Peirce's cantilever test and applied it successfully to blade tissue of the brown macroalgae *Laminaria digitata*.

Stem and leaf diameter, size and shape

Stem and leaf dimensions can be reproduced with relative ease by cutting surrogate material to shape and repeating the process until the required stem areal concentration is achieved. When designing the surrogate shape, the required level of complexity needs to be considered. In order to interpret general trends in the flow field around obstacles the use of standardised shapes such as hemispheres and tubes may be sufficient, as have been employed in studies of animals and their constructions (e.g. Eckman and Nowell, 1984; Davidson et al., 1995; Friedrichs et al., 2009). However, if small-scale hydrodynamics are of interest, species specific features, such as sharp edges in mussel shells, may be particularly relevant. Similar criteria apply for the vegetation domain where a simple strip-like surrogate may not be sufficient to replicate vegetation that has more biomass closer to the ground than in the upper part of the canopy (e.g. the seagrass *Posidonia oceanica*; Stratigaki et al., 2011). The required complexity of surrogate shape also depends on vegetation stiffness. Flexible vegetation streamlines under hydrodynamic forcing and the resulting shape will determine the plant's effect on the flow field rather than the original shape. It may therefore be sufficient to produce simple shaped surrogates, given they reach the same posture after streamlining than the more complex shaped prototype (Paul and Henry, 2013).

Breaking strength

Hydrodynamic forces can also break and damage plants. The effect of breakage can be indirectly simulated by removing surrogate material between experiments. If these processes are to be modelled directly, e.g. to address survival thresholds, detailed knowledge of the maximum tension before breaking for all plant parts and joints is required. Adequate reproduction of this parameter in a surrogate may make its design too complex to be feasible and it has hence not yet been undertaken.

Surface texture

If small-scale hydrodynamics are of interest, the surface roughness of an organism should be considered in the surrogate design as it may have an impact on turbulence. However, this requirement depends strongly on the measurement resolution and how close to the surrogate measurements are to be obtained. The latter may be a limiting factor for actively (e.g. mobile animals) or passively (e.g. swaying plants) moving organisms or their surrogates as their motion makes the identification of a single measurement location difficult (Frostick et al., 2011). Once the need for detailed surface roughness modelling is established, resin casts (O'Donnell, 2008) or dead animal shells (Folkard and Gascoigne, 2009) can provide the required surface texture for animal surrogates. For vegetation, especially flexible species, the importance of surface texture also depends on flow velocities and plant flexibility. Especially at low Reynolds numbers the effect of streamlining may be dominant compared to the effect of surface roughness. Thus, the effort required to model surface roughness on a flexible surrogate may not justify the resulting effect on data accuracy (Albayrak et al., 2012).

Hydrodynamic activity

In some cases it may be relevant to incorporate locomotion or hydrodynamic activity in the design of an animal surrogate. Particularly in shellfish biology, so called hydrodynamic surrogates are used regularly to either sample the inhalant or to mimic the exhalent currents (Ertman and Jumars, 1988; Crimaldi et al., 2007; Petersen et al., 2013). If such features are relevant for the given study and the experiments cannot be conducted with live specimens, detailed information on nozzle size, jet strength and frequency and resulting flow rate is required. Otherwise it can be questionable that siphoning will be included in the surrogate in a meaningful manner.

3.3 Find suitable surrogate material

When the decision is made to use surrogates and the relevant parameters of the prototype are established, the search for surrogate material requires creativity. DIY stores and craft shops can be useful sources of inspiration and it helps to talk to people from other disciplines or outside academia. When working closely with an organism, people tend to concentrate on details like colour or exact shape and loose the focus on parameters that are truly relevant for the science question at hand. The crown of a mangrove tree, for example, can be modelled with a bundle of palm fibres if only its volume and porosity are of importance (Husrin and Oumeraci, 2010). Talking to people not involved in the project can help to sharpen the understanding of the key properties of an organism and broaden the search for possible materials.

3.4 Connect distinct sections of surrogates

Vegetation stiffness and buoyancy will determine if it is possible to produce surrogates from a single material, or if different plant parts need to be modelled with different materials. For strip like vegetation (e.g. grasses) or woody structures (e.g. mangrove roots) the property difference between plant parts may be small enough to be negligible, but if stems and leaves of a plant (e.g. kelp, trees) need to be modelled, a significant difference between those parts may require the use of multiple materials (Paul et al., 2014). Similar considerations are necessary for animal surrogates. The overall shape can often be modelled with solid casts or tubes (e.g. mussels, barnacles), but feeding organs that protrude into the flow may require a more flexible surrogate material (Pullen and LaBarbera, 1991).

If different materials are used within a single surrogate, the attachment point between those materials needs to be carefully designed, especially if they are directly exposed to the flow. In composite vegetation that consists of stems and leaves, the joint between those two plant parts may play a central role in streamlining (Schoneboom et al., 2010). If that is the case, a rigid connection would be inadequate. Equally, some surrogates may require a rigid connection between two different parts. For instance, the brown macroalgae *Laminaria digitata* exhibits a significant difference in stiffness between stem and blade which requires its surrogate to consist of two different materials (Paul et al., 2014). However, streamlining leads to continuous bending throughout the length of the algae and a sharp bend at a flexible joint in the surrogate would not result in correct posture.

3.5 Attach surrogates to the floor

Once a surrogate for the above ground part of an organism is developed, a method of attaching it to the base of a flume or basin needs to be determined. Surrogates rarely mimic the attachment strategies of organisms even though these may be significant to some studies. Surrogate plants are usually rootless and are firmly attached to a base. Consequently, they are more difficult to uproot and entrain than their prototypes, which has implications for the type of study that can be conducted with these surrogates. Similarly, the attachment mechanism of mussels is not solid and acts as a shock absorber under hydrodynamic forcing (Waite et al., 2002). A firm attachment of surrogates may therefore not replicate the wave mitigation of natural mussel assemblages correctly.

If large quantities of surrogates need to be installed, e.g. to replicate a vegetation meadow, it is common to first produce the surrogate stand which is then firmly attached to the flume/basin floor with glue, weights or screws. Surrogate stands have successfully been produced by gluing surrogates into predrilled holes in wood or metal sheets (Folkard, 2005; Stratigaki et al., 2011) or by tying them onto a mesh (Lee et al., 2001; Paul et al., 2012). Depending on the scale and measurement resolution, the base can introduce undesired roughness elements into the experiments. However, this can be mitigated by covering the base with sediment that resembles the natural substrate.

Substrate and substrate composition will also play an important role if the effect of organisms on sediment stabilisation is a focus of research, which may also require the modelling of below-ground organism parts such as roots. Also, if uprooting and entrainment of individuals is of relevance, individual attachment of surrogates may be necessary. However, the processes involved in biota-sediment interaction are still poorly understood and no attempts have yet been made to model them with the use of surrogates.

For organism aggregations such as vegetation meadows, mussel or barnacle colonies, the arrangement within the aggregation can have an impact on measurement results. Even though it does not represent a natural distribution, the simplest way of placing surrogates is in a regular pattern and this may be sufficient for particular research aims. However, even a regular pattern needs to be designed carefully, as in-line and staggered distributions will have different impacts on wake evolution, flow diversion and turbulence profiles

(Schoneboom, 2011). In many cases, the most natural representation would be a truly random distribution, which can be achieved with surrogates that do not need to be attached to the ground and can therefore be sprinkled across the respective area (e.g. alfalfa seeds; Tal and Paola, 2010). For surrogate vegetation meadows, a semi-random approach has been used in the past, where the area has been divided into small squares and a surrogate was placed haphazardly within each square (Folkard, 2005; Paul et al., 2012). Alternatively, a random distribution can be generated with software tools, such as Matlab®.

3.6 Durability of surrogates

Durability, or lack of durability, is generally not reported in the literature. Nevertheless, it is a crucial part of successful surrogate design. If a surrogate is not able to withstand the experimental conditions for the test duration, it cannot be considered suitable and needs to be redesigned. Consequently, surrogates and their attachment points should be tested prior to the actual experiments and possible issues and failures should be addressed. Some problems can be easily solved by using different materials. Silicone, for instance, will lose its bonding properties when exposed to salt water for several hours, but other sealants exist that can serve the purpose in salt water conditions without time limitation. Other material failures (e.g. many plastics get brittle under long UV exposure) potentially cannot be avoided because other materials do not exhibit the required mechanical properties. In this case, surrogates can be replaced on a regular basis to guarantee surrogate functioning for the duration of experiments. Moreover, some changes or degradation in material property can be mitigated by regular maintenance. For example, porous material (e.g. geotextile) may accumulate fine particles suspended in the surrounding water, resulting in changes to mass density and, in turn, changing surrogate posture and motion under hydrodynamic forcing. However, this effect can be reduced or even avoided by regular cleaning of surrogates. Regular maintenance is generally recommended for the duration of the experiments irrespective of known potential durability issues as it helps to identify faults and failures due to normal wear and tear and enables detection of non-anticipated durability issues.

3.7 Confirm similarity between surrogates and prototype

As with other models, the similarity of relevant parameters between the surrogate and prototype is key to successful surrogate development. For inert materials, this includes morphological parameters (e.g. shape and size) as well as mechanical parameters (e.g. buoyancy and flexibility). However, it can be difficult to find a material that reproduces all required parameters equally well. In those cases the non-dimensional Cauchy number and buoyancy parameter can be used for comparison between surrogate and prototype (Luhar and Nepf, 2011). They combine different biomechanical parameters and hence enable the evaluation of a possible trade off between them in surrogate design.

A complete understanding of the similarity between surrogate and prototype will, however, only be achieved through direct comparison under test conditions (Paul and Thomas, 2014). Full scale tests would make surrogate design obsolete and may not be feasible due to the reasons given in this guideline. Nevertheless, small scale comparisons may be possible and will significantly enhance confidence in the surrogate design. Marine vegetation that does not fare well in fresh water, for instance, may still survive long enough to observe and record reconfiguration under hydrodynamic forcing (Johnson et al., 2014b). Here modern video technology can help to quantify streamlining and motion of organisms.

4 Concluding remarks

Overall, surrogates are extremely useful tools for studying organism-environment interactions. They can be beneficial because they avoid the challenges and costs associated with using living organisms. However, surrogates are best used (i) to limit or avoid the inherent variability in organism response to abiotic environmental factors, (ii) to limit or avoid morphological diversity between living organisms and (iii) when quantifying particular organism properties or morphological behaviours in the absence of other confounding factors, which is not possible when using living organisms.

Nevertheless, the successful application of a surrogate is dependent on the research aims and careful design and construction of organism mimics is required to achieve high quality results that are transferrable to the living prototypes and their natural environment. This guideline provides an introduction to surrogate design and implementation but is not exhaustive. Details, including mathematical equations, in many of the aspects mentioned here can be found in the "Users Guide to Ecohydraulic Modelling and Experimentation" (Frostick et al., 2014) and other references provided here.

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