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Predicting, explaining and exploring with computer simulations in fluvial geomorphology

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Abstract
This paper brings a philosophical perspective on computer simulations in the field of geomorphology. The first part of our analysis presents a general framework within which to interpret and evaluate the adequacy of simulations models pursuing three broad epistemic goals (modes): prediction, explanation, and exploration. It also explains the diverse relationships existing between the phenomenon of equifinality and each one of these modes. The second part of the paper applies this framework to a case in fluvial geomorphology. This application enables further specification of the three modeling modes and shows how they can work together in the inquiry of natural phenomena. Finally, our analysis looks briefly at the path-dependent nature of model building, which highlights the importance of historical contingencies in model development and further support the pragmatic stance endorsed in the framework.

Keywords: simulation modeling, adequacy, evaluation, prediction, explanation, exploration, fluvial geomorphology, TELEMAC, path dependence.

1. Introduction

Computer simulations have become an important tool in natural sciences over the last decades, especially in domains investigating complex phenomena that prove difficult to track and control in lab or field experiments. Hitherto, discussions of this type of modelling have raised a number of epistemological and methodological issues. These range from whether simulation modeling is as a special and distinct form of experimentation (Humphreys 1994; 2009; Lenhard 2007; Frigg and Reiss 2009), to questions of (partial) autonomy of simulation models from theory (Morgan and Morisson 1999; Winsberg 2010), to the contribution to scientific understanding by way of representing (Winsberg 2015), predicting (Oreskes et al. 1994; Parker 2010), explaining (Cartwright 1983; Bokulich 2011, 2013) and exploring (Lenhard 2007; Gelfert 2016), and, to name one more, how purposes should play a role in model evaluation (Parker 2011).

The following analysis contributes to this rich and growing literature on the epistemology and methodology of computer simulations by integrating the latter two subjects, i.e., the different ways in which simulation modeling contributes to scientific understanding and the criteria for model evaluation. Parker's (2011) pragmatic position about model evaluation offers a good entry point to explain the relation between understanding and evaluation. She says: "[i]t is the *adequacy-for-purpose* of a model that should be the target of model evaluation and testing: the question is not whether a scientific model is true … but whether it is adequate for the purposes for which it is to be used" (Parker 2011, 1). Our analysis provides a general conceptual framework within which to interpret three well-recognized epistemic purposes: prediction, explanation, and exploration. There is ample literature on these general epistemic purposes, but the different accounts do not always agree on definitions and the delineation of some functions remains difficult and blurry at time. Moreover, besides prediction, these basic forms of inference are rarely specified and integrated in the context of computer simulations. Our framework focuses on general procedural and inferential features of process-based simulation modelling (hereafter simulation modeling) which enables a specific and straightforward conceptual distinction between each mode as well as an elaboration of some of the basic adequacy criteria for each of them.

In Section 2, we present the main distinctive elements and the basic adequacy conditions that characterize predictive, explanatory, and exploratory reasoning. This synthesis is key if we are to understand some of the fundamental potentialities and limitations of computer modelling. Although some examples are provided at this stage of analysis, each mode is treated as a general type of epistemic purpose that can be further specified according to the situation or the researcher's interest. The value of our framework is further demonstrated by explaining how equifinality (defined later) may or may not be an issue, depending on the modeling mode pursued by the researcher.

Developing such a broad synthetic framework means that some issues are discussed at a rather abstract level. To make things more tangible, the third part of the paper applies the framework using an example from fluvial geomorphology. This application permits a more fine-grained explication of all three modes and at the same time exemplifies how they can work together in a series of model-based investigations of a natural phenomenon. The resulting discussion corroborates Bokulich's (2013) thesis that different (families of) models have different affordances, which can lead to a division of cognitive labour in scientific inquiry. Our case analysis focusses on the former aspect and demonstrates that a given model can realize different purposes with different degrees of adequacy. Finally, we look at the broader context of inquiry in the evaluation of computer simulations, emphasizing the role of historical dependencies between models, and how this phenomenon reinforces the adequacy-for-purpose thesis.

2. Three modes of simulation and their general adequacy conditions

Researchers relying on computer simulations to undertake a scientific investigation implicitly adopt one of three modelling modes. These three modes have different inferential methodologies and purposes, thus creating different opportunities and challenges in characterizing and studying target systems.

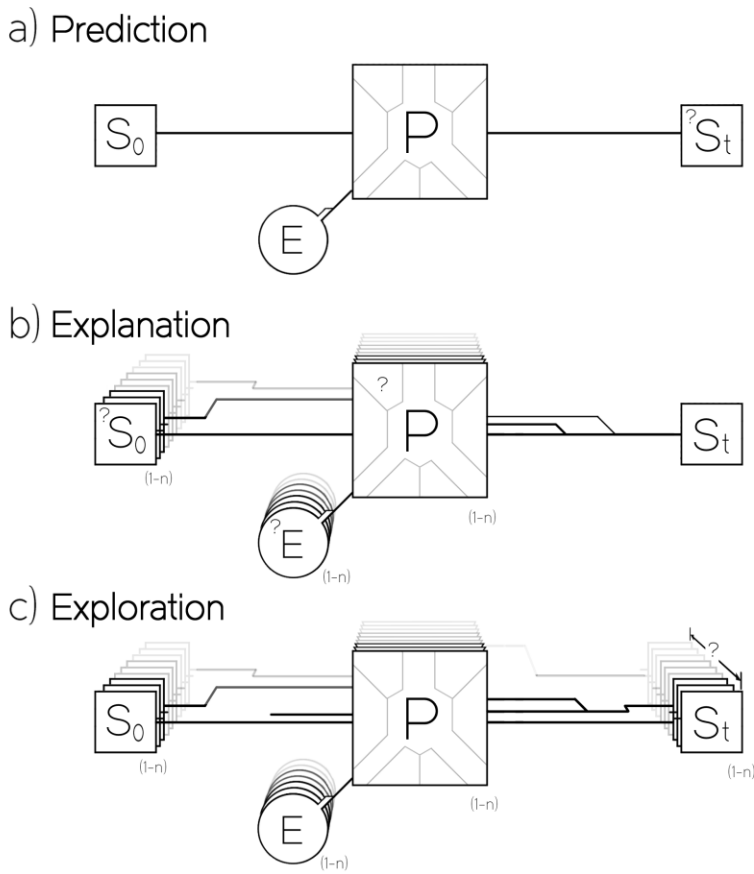

Figure 1. Modeling modes. Each mode involves the implementation and/or manipulation of a few elements: external factors (E)[1] affecting a set of interacting processes (P), and the initial (S_0) and final (S_t) states of the system. The question marks indicate where the uncertainty resides for a given mode. See text for detail. Designed by Nathan Desjardins.

2.1. Predictive mode

In predictive modelling (Figure 1a), the researcher seeks to ascertain the future state of the target system captured by the model. The researcher thus sets the values of S_0, E and P, to predict a single future state (S_t) of the relevant metric(s). What counts as a relevant metric depends on the target system and the goal of the researcher. Some studies will aim for a precise value, whereas

[1] The concept of "external" is linked to the studied system, but also to the way in which components are represented in the model. Fluvial models, for example, represent rivers as channels transporting water and sediment due to gravitational force, but impose factors such as water discharge and riparian vegetation. The integration of new algorithms in existing modelling packages can result in internalizing factors by extending the set of recognized processes and metrics.

other will only attempt to predict qualitative trends.

In predictive mode, the adequacy of a model is determined through accuracy, i.e. by the model's ability to correctly predict the future value of relevant metrics within a reasonable degree of error. It is possible however that a prediction cannot be tested (e.g., if the target system is difficult of access, or if the predictions are for a very distant future, or if the conditions S_0 or E never arise in the world). Finally, to be predictively adequate, it is not necessary that the variables and processes implemented in the model capture the causal structure of the target system. A model that produces the right results for the wrong reasons can still be predictively adequate, as long as it can reliably inform the user about the future value of key metrics. However, the relevance of causal structure is key for the adequacy of the next modeling mode.

2.2. Explanatory mode

In explanatory modelling (Figure 1b), the researcher is interested in understanding why or how a target system gets to be *in a known state*. For example, a researcher might observe patterns in sediment size distribution in a given river type and seek to discover the origins and causes of these patterns. In the context of a meandering river, particles tend to be finer on point bars (Anderson and Anderson 2010) than in riffles (Church and Jones 1982). To explain this situation, the researcher could use a computer code and vary the model configurations (set of S_0, P, E) until the successful simulation of the observed distribution. In morphodynamic modelling, it is quite common to vary P, along with associated parameter values, while keeping S_0 and E constant. Given data on a system's state at two points in time and on the external influences on the system during the period of interest, but a lack of information regarding the processes that are responsible for the change in system state, a modeller can run a series of numerical simulations, enabling, disabling or adding processes, changing parameter values and tweaking the nature of process interactions, to find a subset of processes and interactions that can possibly yield the observed final state. For instance, although sedimentological properties can be obtained through surveying and discharge measurements obtained from the nearest gauging station, the sediment transport formulae needs to be adjusted to fit the observed dynamics of the target system's bed. In terms of the framework proposed, the values for S_0 and E might be relatively well known, but due to uncertainty about the active processes and their interaction, the explanation would be stated in terms of processes. The inference, then, is that the successful formulation of P, given S_0 and E, is representative of how the target system *might* work internally. In other words, explanatory computer modelling provides how-possibly explanations.[2]

Note however that our framework does not limit explanation to inferences about processes. Various versions of explanation can be obtained by manipulating different aspects of the model. When the uncertainty lies principally within external conditions E or past states S_0, as might be the case for example in paleo-environmental reconstructions, then the explanation is an inference about the production of a given outcome from selected initial conditions or external factors—a problem also known as postdiction.

A basic and minimal requirement for adequacy under the explanatory mode is the faithfulness of the model i.e., whether it has the capacity to agree with the observed phenomenon (e.g. system state or dynamics). In this context, it is important not to confound faithfulness with precision. The nature of the explanation will at least depend on the research question and on the algorithms

[2] For a good analysis of the difference between how-possibly and how-actually explanation in the context of computer models, see Bokulich (2014).

comprised in the modelling solution. For instance, the outcome of a modelling exercise could be a qualitative description of a system, e.g. increase or decrease in river bank stability as a function of key external forces, timing of bank retreat in respect to a flood hydrograph, or channel enlargement or narrowing due to colonization by riparian vegetation. Alternatively, a greater precision may be preferred in other circumstances, e.g. stream temperature at low flow during summer, biodiversity index of the macroinvertebrates community, grain size distribution on a stream bed, or patterns in landscape topography. In all cases, the model could be equally adequate. A model could be perfectly faithful to a phenomenon, e.g. river channel migration, without necessarily being able to simulate precisely the recorded bank retreat rate of a given river. Explanatory adequacy thus depends on the level of description sought rather than on the amount of details provided (see Bokulich (2014, 334) for a similar view).

The capacity to simulate an observed phenomenon is a necessary condition for explanatory adequacy, but it is a minimal and sometimes insufficient requirement. To achieve a greater degree of explanatory adequacy, the model should not only be faithful but also include the key constituents, processes and interactions that are hypothesized to govern the target system. This second requirement, here called *representativity*, can be further specified in two ways. First, the processes admitted into the model should be present (or at least believed to be possibly present) in the target system. Second, the way and extent to which each process affects model variables should reflect the hypothesized interactions amongst components in the target system. For example, if a researcher wants to explain sedimentological changes on a river bed over a decade, it would generally be adequate to use a model that includes features and processes related to hydrological regimes, sedimentology, and riparian vegetation. However, if the river is also affected by additional anthropogenic processes, e.g., gravel mining, then the researcher would provide a more adequate explanation if the model also included this human-driven process.

One of the interesting, and perhaps surprising, consequences of defining explanation in terms of relevance and representativity is that calibration constitutes a form of explanation. Calibration is the optimization of model parameters, which typically influence the strength and interaction of simulated processes, to "best explain" an observed state S_t of the system. In practice this is achieved by adjusting the model's parameters, and hence the model's process representation *P*, to minimize the discrepancies between simulated and observed metrics at the final state of the system, which results in a localized explanation, i.e. one that applies to the specific case being examined. So, calibration matches the structure depicted in Figure 1b. However, modellers don't typically call this an explanation. In fact, calibration can be relevant for other modes and it does not constitute a goal of modelling in and of itself. Moreover, calibration does not necessarily lead to the identification of causalities. Indeed, different calibrated models can fit the same target system, and it is possible that multiple distinct model configurations (set of processes *P* and parameters) result in the same system state S_t (a condition known as equifinality; see Section 2.4). Nevertheless, the successful calibration of a model involves at least one possible, and hopefully plausible, set of parameter values that explains an observed phenomenon.

2.3. Exploratory mode

The third and final mode, exploratory modelling (Figure 1c), is arguably the most experimental of all three.[3] Here, the researcher is not interested in finding or explaining a particular final state

[3] Several philosophers of science conceive of computer simulations as a form of inquiry that resembles experimental investigations (e.g., Dowling 1999; Hugues 1999; Norton and Suppes 2001; Winsberg 2003, 2009; Parker 2009). We are sympathetic to this viewpoint, but engaging with this debate would distract us from our main objective.

S_t, but instead, is seeking to gain knowledge of the affordances of a model without immediate concern for representativity or fit. This typically involves exploring a set of model configurations to discover sensitivities, divergences, plausible ranges, existence of spatial and temporal patterns or trends, existence of thresholds, etc. As it was the case with the explanatory mode, it is possible to explore a system's behaviour by fluctuating initial states, external factors, and processes. The key aspect that distinguishes the two modes, however, is the fact that an explanation involves matching known components from a target system, whereas exploration evaluates multiple simulated future states S_t of a system, based on different S_0, P and E values, which are not necessarily associated with a target system. The exploration mode is thus essentially analyzing the simulation outputs collectively in search of overarching properties that might emerge from all the simulated S_t. Although exploration using a calibrated model allows to evaluate the impacts of hypothetical perturbations on a known target system, it is important to note that exploring, in our framework, does not involve an assessment of the goodness of fit between simulated datasets and a measured state in a target system. As such, this mode is perhaps the most susceptible to be seen as mere frivolity; a numerical computation of hypothetical idealization. However, this would be an oversimplification.

Research engaging into exploratory simulations is often guided by information obtained from empirical observations. Moreover, exploration can be an important step toward a better understanding of unexpected features of natural phenomena (Gelfert 2016; Lenhard 2007; Winsberg 2009; Larsen et al. 2014). As highlighted by Larsen et al. (2014), the capacity to manipulate model components makes computer-based exploration similar to experiments that seek for causality. It enables the examination of a system with initial or environmental conditions different than those commonly observed in nature, thereby exploring counterfactuals that can enable the formulation of hypotheses and improve our understanding of causal mechanisms responsible for the emergence of systemic properties. However, unlike Larsen et al. (2014), our framework does not limit exploratory modelling to that role. Nor does it imply that exploration requires oversimplification or omission of salient physical details. Furthermore, certain activities involving exploratory modelling have a clear practical value and are much less in danger of becoming mere computational curiosities. For example, sensitivity analysis, i.e. the process of assessing variability in outputs with respect to changes in parameter values, is a form of exploratory modelling that can identify the key factors affecting a system's behaviour. This information can play a crucial role in reducing uncertainty of the modelling exercise as a whole (e.g. orienting field work efforts towards the most sensitive variables) and in guiding policy making (e.g. identifying key processes as intervention targets to reduce flood risk).

Due to the diversity of exploration possibilities and contexts, it is rather difficult to provide a complete list of adequacy conditions for the exploratory mode. Gelfert (2016, Ch.4) identifies four purposes of exploratory modelling: 1) starting point for future inquiry, 2) proof-of-principle demonstration, i.e., a proof that a target can be represented or that a certain kind of behavior could be produced, 3) generation of potential explanations, and 4) assessment of suitability of target, i.e., adjusting one's conception of a target phenomenon by modifying various parameters or the range of initial conditions. Our framework presents exploration under a different light than Gelfert does, and thus, not all of these purposes count as exploration for us. For instance, the "proof-of-principle demonstration" corresponds to what we call "faithfulness" under the explanatory mode in our framework. Gelfert suggests that model-based explanations are potential, and thus exploratory, when there is no theory under which the model can be subsumed. Our framework is independent of such top-down/bottom up considerations. Since all simulation-based explanations are merely potential (i.e. how-possible) in our framework, the kind of distinction used by Gelfert loses its meaning in our framework. Under the criteria established in Section 2.2., modeling remains explanatory as long as there is a step in the process where the modeller engages in a selection process for a model (or model configuration) that can produce an outcome that matches a known dataset. This said, exploration can be an initial step that many modellers take before engaging in an explanatory mode (as exemplified in Section 3.1).

Despite the diversity of exploratory purposes, two general and universal adequacy criteria remain: *manipulability* and *tractability*. In the context of this paper, manipulability simply means the capacity to configure a computer model in such a way as to gain some understanding of the model's limits and capabilities, and ultimately of the target system's behaviour. The second adequacy criterion, tractability, refers to the ability to trace the origins of interesting dynamics or patterns in the simulated system, such that they can be attributed to specific S_0, P or E. Thus, a model that enables different kinds of changes (e.g. qualitative, quantitative, and incremental) or a model in which researchers can integrate heterogeneity while maintaining tractability and analysability of outputs will have a greater exploratory potential. As implied by Larsen et al.'s (2014) analysis, simpler models may fair better at this task, but it does not mean that exploration cannot be performed with complex models as well.

2.4 Equifinality and adequacy

Equifinality, i.e. the situation where a given simulation output S_t is compatible with multiple model configurations (i.e. multiple combinations of S_0, E and P) (Beven 2006), is commonly seen as a problematic phenomenon in modeling. However, this verdict is in fact too simplistic. Whether or not equifinality is a problem depends largely on the modelling mode (Table 1).

Table 1. Adequacy criteria for the predictive, explanatory and exploratory modes and the relevance of equifinality for each criterion.

Mode	**Adequacy criteria**	**Relevance of equifinality**
Predictive	Accuracy: capacity to correctly predict the value or trend of a metric.	Not applicable to single prediction. Possible indicator of robustness for multiple predictions.
Explanatory	Faithfulness: capacity to produce a model output that fits observation.	Not an issue.
	Representativity: ability of a model to capture the (hypothesized) relevant processes of a phenomenon.	Makes explanations "how possibly" rather than "how actually". Needed to simulate multiple realizability.
Exploratory	Manipulability: capacity to intervene on a computer model to produce diverse analyzable model outputs.	Precondition for equifinality.
	Tractability: capacity to relate the model output to a parameter value(s) and/or modelling options.	Established causalities may not be bidirectional. Possible indicator of robustness in sensitivity analysis.

Under the predictive mode, the consequences of equifinality are not very serious for two reasons. First, a model is predictively adequate if it reliably informs the user about the future value of key metrics, but since the details of the exact mechanisms that produced a final state are of secondary importance, equifinality becomes less relevant. Second, and arguably more fundamentally, predictive modelling involves running *a single simulation*, whereby a specific combination of S_0, P and E are given and a single prediction for S_t is obtained. Hence, equifinality is not even arising in predictive mode. It is, of course, possible to run multiple individual predictive models (e.g., scenario planning, where different S_0 or E are considered), at which point convergent predictions basically indicate an insensitivity to the variation in scenarios. Alternatively, one could run multiple predictive simulations using the same S_0 and E with different models (i.e. different P), at which point identical predictions indicate a robustness of the models and help establishing trust in the assessments of various scenarios. This is not commonly done in geomorphology, but in the context of climate change, for example, most models included in the fifth IPCC report agree that "human activities caused more than half of the observed increase in global mean surface temperature from 1951 to 2010" (Bindoff et al. 2013, p.869)[4]. The high degree of confidence in this claim is in part due to multiple independent models (i.e. different representations of implementations P) supporting such attribution. In this case, equifinality between the models helps building trust in a potential future system state.

In the case of explanatory modeling, equifinality is certainly likely to be perceived as a more important issue. The problem is analogous to what philosophers of science call "underdetermination", namely the fact that a given observation does not dictate which hypothesis to endorse, either because researchers can adjust auxiliary hypotheses in the face of counter-evidence (holistic underdetermination), or simply because alternative hypotheses happen to be empirically equivalent and thus imply identical observation statements (contrastive underdetermination).[5] So, equifinality and underdetermination are issues under the explanation mode not because of faithfulness (i.e., the model can produce the desired outcome), but because

[4] Note that the agreement here is about the claim that anthropogenic forcing is responsible for more than 50% of the observed increase since the last 60 years. This does not mean that all models agree about how many degrees are attributed to human activities.

[5] The problem of underdetermination is widely discussed in philosophy of science. Two classic analyses are by Duhem (1954) and Quine (1976). For a comprehensive and clear introduction to the topic, we recommend Stanford (2017).

of the uncertainty it raises with regard to representativity. Recall the fictive situation mentioned earlier where a researcher wants to explain the transformation of a river's morphology in a complex urban environment, and can do so by adopting either of two strategies/hypotheses: by including only natural processes, or by also including human-induced processes such as gravel mining. It might well be that both of these process configurations (*P*) would lead to acceptable realization of the simulated final state S_t, albeit likely with different parameter values for the selected processes. This situation is likely to occur when modelling complex phenomena, and the ubiquity of equifinality is essentially what renders simulation-based explanations how-possibly explanations rather than how-actually explanations.

Procedures have been devised to deal with equifinality (Beven and Freer 2000). A modeller can compare model configurations that lead to a unique outcome, and decide which one(s) provide(s) plausible explanations, given the knowledge and data available for the target system. This can involve taking additional measurements on the target system to eliminate implausible solutions, i.e. parameter sets (or values) that do not contribute to the observed change in state of a given system, thereby increasing representativity and trustworthiness (Morton 1993). In situations where relevant metrics are inaccessible, modelers must rely on theoretical knowledge, common sense, or reliable proxies, thereby reducing trust in representativity of the model. Yet, in many cases, tracking the source of equifinality can provide insights into the mechanisms forming the target system, as well as into its attributes. Ideally, the retained model configuration must include the most relevant processes and interactions, but also the fewest *ad hoc* parameters.

Note, however, that despite the epistemic problem arising because of explanatory equifinality, being able to produce the same outcome from multiple model configurations can be an asset when the target system is itself subject to multiple realizability. For instance, it is possible for two very similar landscapes to occur at two different locations, without having been affected by the same types of forces (Chorley 1962; Schumm 1991; Cruslock et al. 2010). In this case, equifinality is needed to provide two adequate explanations. However, different combinations of parameter values leading to equifinality may not exist in the target system.

In exploratory modelling, the occurrence of equifinality is only an issue for one of the adequacy conditions. Manipulability can be a precondition for the discovery of equifinality, but it is not reduced or enhanced by equifinality. In fact, interventions on the model can reveal some equifinality, which can in turn be very informative for the researcher, e.g., the convergence on similar (or identical) outcomes can indicate the emergence of a pattern or trend in the system dynamics. Alternatively, during a sensitivity analysis, equifinality could unveil the insensitivity of certain parameters, or it could indicate the existence of self-regulatory mechanisms, forcing a large number of model configurations to converge to well-defined potential outcomes. In both situations, the model user or researcher benefits from this information.

Tractability, on the other hand, is affected by equifinality because it implies there may not always be a one-to-one causal relation between predicted features and input parameters. However, the implications of this are tightly related to the objectives of the modelling exercise. For instance, if a modeller seeks to define causal relationships, then the conceptual model(s) emerging from an exploratory modelling exercise may be complicated by the existence of many-to-one relations. Alternatively, if a modeler seeks to identify sensitivities to processes or initial conditions, equifinality might be an indicator of robustness or insensitivities of the model (and a potentially the target system as well), which could be traced to specific P, S_0 or E.

2.5 Summary

The typology presented above provides a general and abstract account of some of the most basic types of scientific understanding as pursued in simulation modeling. Specifically, it shows that computer simulations can, in their own way, be involved in the general epistemic objectives of predicting, explaining and exploring. Although we do not claim to exhaust all goals, many specific modelling objectives would, nevertheless, fall under one of these three simulation modes (or epistemic purposes). More importantly, looking at computer simulations as experiments undertaken under different investigative modes permits a more practice-oriented and fine-grained analysis of their purposes and adequacy.

3. Applying the framework to fluvial geomorphology

Using an example from fluvial geomorphology, we will now apply the framework developed in the previous section. Our analysis demonstrates how a given model can have different adequacy for different purposes and that developing a model to achieve a certain type of understanding can affect its ability to be employed for other purposes. These findings are in line with Bokulich's (2013) division of cognitive labour thesis. Depending on the nature of a modelling investigation, a user may not necessarily engage with all modes of modelling or may encounter them in a different order than presented in the preceding section. In sections 3.2-3.4 we present them in the order in which they were chronologically encountered in a specific modelling investigation.

3.1. <u>Origin and purpose of numerical modelling in fluvial geomorphology</u>

Knowledge on river dynamics in geomorphology has traditionally been obtained from field observations (Rhoads and Thorn 1996), and more recently, from controlled experiments within downscaled physical models (e.g. Pyrce and Ashmore 2005; Tal and Paola 2010). Gaining knowledge about rivers from field observations presents numerous challenges. Owing to centuries of evolution through hydrologic, geological, and biological processes acting at different spatiotemporal scales, a diverse array of river channels and floodplains have developed. Heterogeneity in biophysical conditions, combined with the anthropogenic activities that have altered river channels and drainage networks, added multiple confounding variables and blurred the examined fluvial phenomena (Güneralp et al. 2012). Earth scientists also face additional difficulties such as the presence of feedback loops and nonlinearities dissimulating causal relations, and evidence being wiped out with time (Cox 2007; Phillips 2006).

Due to these constraints, geomorphologists increasingly employ computer models to create virtual abstractions of the components and processes affecting channel dynamics (Coulthard and Van de Wiel 2012; Van de Wiel et al. 2016). Several modelling strategies have been envisioned and implemented to address a range of research questions pertaining to a diversity of river phenomena and contexts. In this section, the focus will be on the use of numerical morphodynamics models[6] comprising mathematical algorithms to simulate 1) water motion in an open channel, 2) sediment transport along its bed, and 3) bank retreat due to mass wasting. River meandering processes can be examined using this family of models (e.g. Duan et al. 2001; Shimizu et al. 2009; Lai et al. 2012). The discussion is oriented toward the epistemic aspects related to a recent adaptation of the open TELEMAC-MASCARET suite of solvers that sought to include a physics-based description of river bank retreat processes while considering the mechanical properties of bank material and riparian vegetation (Rousseau et al. 2017) (Figure 2).

[6] This family of models rely on the shallow-water equations for fluid motion, i.e., a two-dimensional simplification of Navier-Stokes equations, combined with formula for sediment transport.

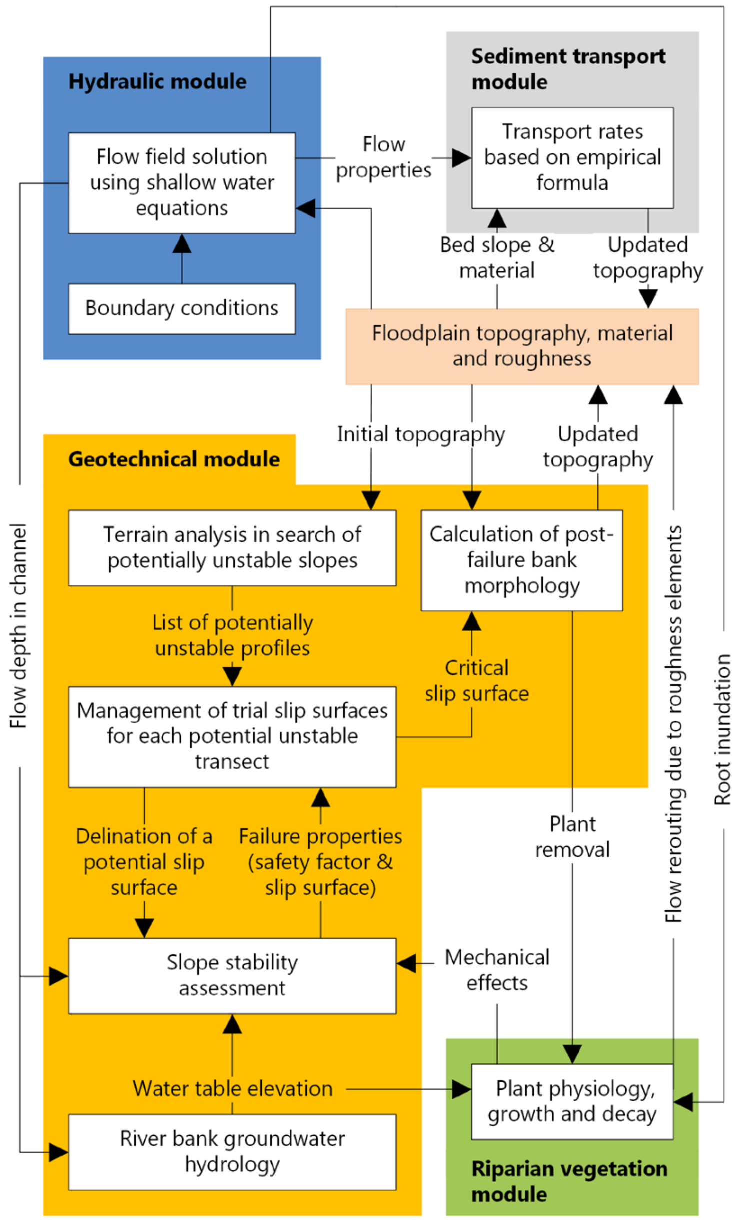

Figure 2. Modules and sequence of steps involved at each iteration of the altered morphodynamic model. Based on Rousseau et al. (2014).

The Open TELEMAC-MASCARET package comprises several modules, including TELEMAC-2D (a fluid dynamics solver) (Riadh et al. 2014) and SISYPHE (algorithms describing sediment entrainment and transport caused by moving fluid) (Tassi and Villaret 2014). Code availability allows the integration of additional processes. These processes are described in terms of the fundamental laws of physics, such as conservation of mass and momentum (for flow) and balance of forces (for river bank stability) (e.g. Bishop 1955). In a few instances, however, they are based on empirical relations developed in natural and artificial river channels. Sediment transport formulae are empirically-based, and the physiological properties of riparian vegetation are based on measurements taken from a very small sample of species and individuals (Tubbs 1977; Kenefic and Nyland 1999).

As with all mathematical simulation models, idealizations were introduced. For example, despite physics-based slope stability assessment and conservation of mass during bank transformation (following the collapse of an unstable bank), the model represents post-failure bank surface geometry as a planar surface oriented from the horizontal at an angle that is related to the bank material; this greatly simplifies the natural phenomenon, especially in the case of a rotational failure, which usually results in the accumulation of soil material at bank toe in a natural context. In addition, the model is difficult to use with large-shallow channels due to algorithmic limitations.

Finally, note that the decision of adding new modules into an existing modelling package, i.e. TELEMAC-MASCARET, was motivated by financial, time, and strategic constraints. It significantly affected algorithmic choices of the developed modules, but most importantly, imposed restrictions on model applicability – as indicated below.

3.2. Exploratory mode

The expansion of the morphodynamic model was initially developed to *explore* the contribution of key biophysical factors (especially those related to soil composition) and hydrological regimes on the morphological evolution of an alluvial at the spatial scale of a few kilometers and at the temporal scale of a few months. Note, however, that this exploration was preceded by a proof of explanatory faithfulness—prior to exploration the researcher made sure that the augmented model could produce the right type of outcome, i.e. morphological evolution of a meandering river. Once demonstrated that the model is capable of producing the relevant type of outcome, the researcher proceeded to a sensitivity analysis. Recall that this type of analysis can provide insights into model behaviour (Legleiter et al. 2011), while enabling the formulation of hypotheses regarding natural analogues (Loheide and Booth 2011; Nassar 2011). Furthermore, this exercise can help planning and prioritizing field data collection activities by identifying the factors that deserve a greater level of attention (Newham et al. 2003; Kuta et al. 2010). In the case of the coupled model analyzed here, i.e. TELEMAC-MASCARET combined with the geotechnical and riparian vegetation modules, multiple simulations were launched, and their results analyzed, to evaluate the modelling software and functionalities, to define thresholds in parameter values, and to identify the most sensitive parameters. For instance, the model was found to be very sensitive to geotechnical properties of the bank material, in particular to soil cohesion, friction angle, and species assemblage (Rousseau et al. 2014, 2018).

The fact that manipulating model parameters required to undertake a sensitivity analysis was possible demonstrates a good degree of manipulability. Tractability was also sufficient to enable the researcher in the elaboration of new hypotheses on river morphodynamics that could not be formulated and tested using other morphodynamic models. For example, hypotheses emerging from the relationship between established plant types/species (defined in terms of measurable physiological traits) and channel planform and morphology, or the possibility to define plant cover in detail, renders the model adequate for use in a large range of studies.

Other qualities make the augmented model adequate for exploration. First, its universal (or non-context specific) character means that it can be applied to a wide range of alluvial river types, although it is most relevant to those evolving in at least partially cohesive soils (Rousseau et al. 2017). More generally, context-specificity does not preclude exploration, but it can limit the range of processes considered by the researchers. Second, model manipulability is also enhanced by the use of formulae and algorithms that make computation more efficient. For example, integrating a genetic algorithm (e.g. Li et al. 2010) to solve slope stability equations efficiently enabled the researchers to consider a larger set of parameters and configurations. Third, strategic decisions taken during software planning and development stages, which influenced the computer code's structure, added flexibility by permitting incremental spatial variations for a large number of biophysical parameters, thereby enabling the simulation of irregular patterns found in nature.

3.3. Explanatory mode

Let us now consider the same model serving an explanatory role. Recall that explanation requires faithfulness and representativity, which we described earlier as finding values and configuration for S_0, E and P that 1) yield a simulated state S_t in agreement with an observed state S_t in the target system and that 2) are representative of the S_0, E, P that are hypothesized to govern the target system. The model described in Figure 2 meets both requirements. It can be broken down into key biophysical components and mechanisms, and it is also possible to find at least one combination of biophysical mechanisms and parameter values leading to an agreement between observed and simulated state S_t. Moreover, the attributes in the model are associated with measurable physical quantities. Hitherto, the model has been calibrated and validated against datasets from flume configurations (artificial laboratory channels) (Rousseau et al., 2016) and from two natural rivers (Rousseau et al., 2018). For instance, the locations of retreated river banks along Medway Creek, Ontario, a 20-meter wide reach of a semi-alluvial stream, were reasonably well predicted after calibrating the model against field observations made over a period of 3.5 years (Figure 3). The model output does not perfectly match observations (e.g., false negatives at transects 760-762 and 798-807; Figure 3a). This mismatch could be attributed to limited representativity, because the real system has some heterogeneity not accounted for in the model (related to soil and riparian vegetation), as noted by Güneralp et al. (2012) and Bertoldi et al. (2014). However, despite its limited adequacy to simulate bank erosion along a vegetated river reach, the model correctly identifies most of the unstable bank locations (e.g., the three unstable zones along the second monitored river bank were detected (Figure 3b)).

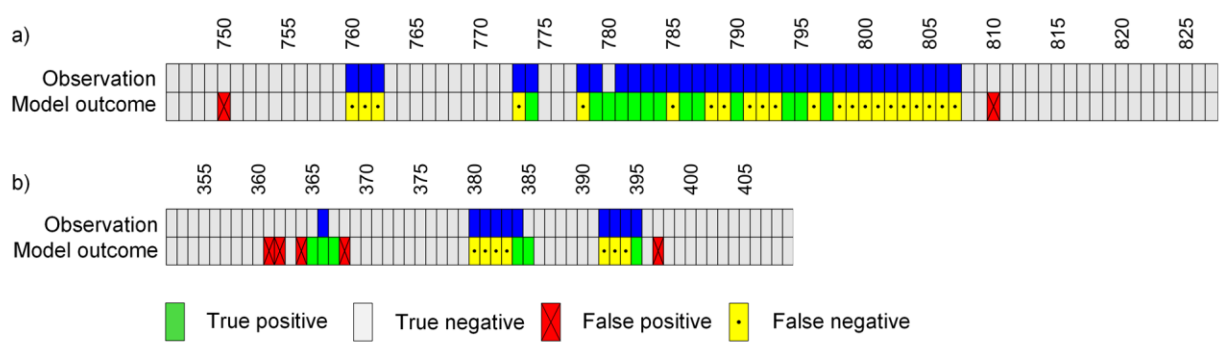

Figure 3. Comparison of simulated and observed (indicated in blue) bank failures along two river banks of Medway Creek, London, Ontario between January 2012 and June 2015. The labels along the x-axis correspond to locations along each river bank. The distance between adjacent locations is 3.3 meters. A bank failure prediction was considered correct if it occurred within a distance of one location from the location associated with an observed prediction. This is the case for transects 365, 367, 385, and 780.

Although the model presented in this section contains several assumptions and idealizations, it nevertheless contains the two key processes deemed essential for producing the right type of irregularity. The added modules allow spatial variations in plant cover and does not impose any geometrical restriction on planform migration. Not only has this strategy proven appropriate after the successful calibration of the coupled model against morphological datasets from river reaches (Rousseau et al. 2017; 2018), but it also favors the development of irregular morphologies typically found in natural channels. Broadly speaking, the model produces the right kind of resemblance with the target system, which is an important indicator of representation adequacy (Mäki 2011, 57).

Trust in the model's adequacy to explain channel evolution is affected by several external factors. TELEMAC has been employed, improved, and evaluated in a range of contexts over an extended time period (Bates et al. 1997; Corti and Pennati 2000; Sun et al. 2010; Langendoen et al. 2016), which enhances the level of trust in its general adequacy to explain fluvial processes. However, the level of confidence in the software presented in Figure 2 might be lowered by the fact that the added algorithms are not as well tested. This could be improved after calibration and validation against datasets from a diversity of alluvial river types and spatial scales, where cohesion plays a key role in bank evolution due to the occurrence of a fine-textured soil or of a riparian vegetation cover. However, very few comprehensive morphological datasets exist at the moment to achieve this ambitious objective (but see Rousseau et al. 2018). This situation can introduce uncertainty in parameter estimation, and thus decrease model reliability (Samadi et al. 2009). The large number of factors and parameters comprised in the model, combined with context-dependent data requirements and scarce datasets that can take a diversity of forms, further increases this challenge. For instance, records on physiological traits, hydrological and mechanical properties of riparian plants are rather thin and are not always available for the context of interest.[7] Therefore, trust in river morphodynamics model seems to be affected by a variety of circumstances external to the modelling exercise, including technology, time, and financial constraints.

3.4. Predictive mode

The augmented model has not yet been used in predictive mode. Given the current state of technology and computational capacity, the primary consequence of integrating geotechnical and vegetation processes into a river morphodynamics modelling package that relies, to a large extent, on physics-based algorithms, is that simulations are limited to short spatiotemporal scales. Even with substantial improvements in computational power, the model presented in this section may not produce realistic landscapes during long-term simulations due to propagation of errors (Kleinhans et al. 2005). Some researchers were able to study long-term river evolution using variants of this model type, but only by making choices that significantly limit the representativity and explanatory potential of their model. For example, they must represent river environments as rather homogeneous channels with simplified transportation and sedimentological properties, describe physical processes in fewer than three dimensions (Lane et al. 1999; Wu et al. 2004), lump erosion processes into an erodibility coefficient (Camporeale et al. 2005), ignore the floodplain or assume that it is lacking elements such as topography, secondary channels (Abad and Garcia 2006), or hydraulic and mechanical effects of riparian vegetation on the flow and geomorphic processes (Bertoldi et al. 2014). This suggest that there might be a threshold between representative completeness and predictive abilities of a model.

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[7] For examples of studies that provide plant properties for riparian species see Abernethy and Rutherfurd (2001), Simon and Collison (2002), Pollen (2007), or Adhikari et al. (2013).

The fact that simulations involve idealizations is known territory (Weisberg 2007), but it does not mean that all value is lost. As discussions about exploration often highlight, model value is often heuristic in that the simplification of a system can still provide insights into future research and field data requirements (Oreskes et al. 1994; Gelfert 2016). Furthermore, one must recognize that, under special circumstances, e.g. forecasting the impacts of the anthropogenic climate change on a river network's form and organisms, the predictive mode may be the only means available to foresee the future state of a system and to inform the decisions made by competent management authorities (Verhaar et al. 2011).

Note, however, that models that are only adequate for short-term predictions can nonetheless be relevant to examine practical questions of fluvial channel designs and management. The previous generation of morphodynamic models, which only included basic fluvial processes, have been employed to evaluate the technical effectiveness of instream hydraulic structures, i.e. artificial structures put in place as a mitigation measure against bank erosion (Matsuura and Townsend 2004; Minor et al. 2007), to improve navigation (Jia et al. 2009; Huang and Ng 2007), and to enhance fish habitat (Boavida et al. 2011). Predictions were based solely on flow hydraulics (Haltigin et al. 2007) or were able to simulate sediment dynamics (Minor et al. 2007). Due to a recent shift in the type of river management/restoration interventions toward the use of less invasive procedures, it is expected that the augmented model studied in this section, as well as a variety of similar morphodynamic models, will soon serve in scenario planning involving riparian vegetation.

4. Looking more broadly at the context of inquiry

It is tempting, while developing adequacy criteria for different modelling modes, to think of models in isolation from the broader context of inquiry. However, like any other theory-building activity in science, computer modelling involves several decisions over multiple stages and takes place in a complex network of interacting agents and institutions engaged in research. These interactions, combined with many contextual factors (e.g., technical abilities and knowledge of model users, level of documentation, hardware, financial and time constraints), can affect the product developed, the way states and processes are described, and the researchers' judgement about model's suitability. In other words, deciding whether a given model is the right tool for the job is not only an internal affair based on epistemic adequacy criteria. The social and historical background, i.e., research and modeling inquiries that happen elsewhere and those that took place in the past, can also shape the decision landscape. In this section, we discuss one type of model-to-model interaction that can influence researchers' judgement while deciding whether a tool is adequate or not.

A model is typically the result of an historical process involving incremental developments that are constrained by a pre-established structural framework.[8] The fluvial modeling example we used in Section 3 illustrates this situation. The TELEMAC modeling software was introduced in the early 1990s (Galland et al. 1991) and has become increasingly popular in the modeling community following the release of its code to the public domain. Developers gradually introduced new modules and coupled them to existing code to improve representativity. Many modellers and industries have adopted TELEMAC-MASCARET, not only based on its

[8] See Winsberg (2009, pp.109-110) for a discussion of the historical nature of climate models.

trustworthiness, but also due to the much greater costs involved in learning, implementing, or developing an alternative model. Rather than reinventing the wheel, model users typically tinker and sometimes add functionalities to an established set of algorithms. So, existing models are not as independent of previous models as they may appear.

The integration of additional processes and features in an existing model impose constraints on subsequent algorithmic developments. For instance, the way in which a TELEMAC-compatible mesh holds biophysical quantities, i.e. within vertices using a finite element discretization scheme, is different from the way in which the same information is organized in a cellular automata model type, i.e. in a grid with rectangular, orthogonal cells (Van de Wiel et al. 2007; Coulthard et al. 2013). Therefore, the implementation of the same process in both models, based on a common theoretical understanding of a natural phenomenon, could take different forms. Similarly, simulating river bank retreat within the former model type can be quite cumbersome. The implementation in TELEMAC-MASCARET of a universal algorithm of bank retreat by Rousseau et al. (2014) was accomplished by only permitting vertical adjustments. Conversely, Langendoen et al. (2016) integrated an adaptive grid algorithm to improve resolution near water boundaries (i.e. nodes can relocate horizontally as well), but limited the applicability of the resulting model to single-threaded channels. Both implementations relied on different strategies to deal with TELEMAC's legacy, which resulted in distinct sets of experimental limitations. These examples show that the decisions adopted by a group of experts depends on a series of past contingencies. The same theoretical understanding and the same modeling starting point can lead to divergent modeling strategies.

This phenomenon of path dependence has received a lot of attention in the economical (e.g.

Arthur 1994; David 1985, 2007), political (e.g. Pierson 2004), and biological realms (e.g. Jacob 1977; Gould 1989; Beatty and Desjardins 2009; Desjardins 2011). In the latter contexts, path dependence has often been used to explain why certain social institutions and evolutionary strategies are suboptimal. Cultural and biological evolutions do not proceed by selection of what is best, but by piling up and tinkering with strategies that work, i.e., strategies that are merely adequate. This viewpoint applies to modelling as well. Completely rewriting and streamlining a code requires a massive time-investment with minimal immediate pay-off. On the short-term, it is more effective to tinker with an existing model, even though the result is an ever-monstrous code and an ever-greater impediment to doing the overhaul. This type of sub-optimality and historical constraints are further reasons for approaching model evaluation in terms of adequacy and reliability instead of focusing (exclusively) on the semantic category of truth.

5. Conclusion

Computer models are useful idealizations that can serve various purposes. The most commonly recognized roles are forecasting future states (prediction) and identifying key influences in a target system (explanation). This paper provided a framework within which to explicate these two important modeling purposes/modes and it integrated a third one, exploration. It also identified some of the main adequacy conditions for each mode. In brief, a model is adequate under the *predictive mode* if there is (or would be) a fit between simulated data set and yet-to-be-measured metric on target system. Under the *explanation mode*, adequacy has two dimensions. First, a model is minimally adequate when it is at least faithful, i.e., capable to yield some known specified outcome. Second, a greater degree of explanatory adequacy is achieved if a model is also representative, i.e., the ways in which the processes/initial conditions/external factors are implemented in the model capture features of the target system. Finally, a model is adequate to *explore* if a user can integrate and manipulate parameters to perform various types of analyses that provide understanding of model capabilities, thresholds, and limitations. Such improved understanding will typically require tractability as well.

As shown using an example from fluvial geomorphology, these three modelling modes are not completely independent. In practice, many modelling projects involve each of the different modes of modelling at different stages of inquiry. We saw that exploration is often a precursor to explanation, and the confidence one has in the ability of a model to produce relevant information through exploration could be boasted by the verification of a somewhat surprising prediction. Moreover, these modes can work together at different stages of inquiries. A common, although not necessary, progression could be: explore model dynamics, then explain observed measurements in various conditions, and finally predict future state(s) of a system for a given scenario. Finally, our analysis of the broader context of inquiry reveals the path-dependent nature of model building, and thus provides another reason to believe that models can only be adequate rather than truthful. If model building is a path-dependent process, where decisions of the past impose some constraints on what and how models are built today, then looking at the history of a given modelling tradition can help us to understand the direction of modelling practices by different communities of modelers.

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