Earthcasting: Geomorphic forecasts for society

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Key Points:

- Earthcasts are testable forecasts of Earth surface change with quantified uncertainties, on spatiotemporal scales relevant to planning.
- We discuss a potential avenue for direct involvement of stakeholders, which we argue is essential for an earthcast.
- We provide near-complete examples of earthcasts and suggest a roadmap for developing earthcasts as a part of research in geomorphology.

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1029/2021EF002088.

ABSTRACT

Over the last several decades, the study of Earth surface processes has progressed from a descriptive science to an increasingly quantitative one due to advances in theoretical, experimental, and computational geosciences. The importance of geomorphic forecasts has never been greater, as technological development and global climate change threaten to reshape the landscapes that support human societies and natural ecosystems. Here we explore best practices for developing socially-relevant forecasts of Earth surface change, a goal we are calling "earthcasting". We suggest that earthcasts have the following features: they focus on temporal (~1 to ~100 years) and spatial (~1 m to ~10 km) scales relevant to planning; they are designed with direct involvement of stakeholders and public beneficiaries through the evaluation of the socioeconomic impacts of geomorphic processes; and they generate forecasts that are clearly stated, testable, and include quantitative uncertainties. Earthcasts bridge the gap between Earth surface researchers and decision-makers, stakeholders, researchers from other disciplines, and the general public. We investigate the defining features of earthcasts and evaluate some specific examples. This paper builds on previous studies of prediction in geomorphology by recommending a roadmap for (i) generating earthcasts, especially those based on modeling; (ii) transforming a subset of geomorphic research into earthcasts; and (iii) communicating earthcasts beyond the geomorphology research community. Earthcasting exemplifies the social benefit of geomorphology research, and it calls for renewed research efforts toward further understanding the limits of predictability of Earth surface systems and processes, and the uncertainties associated with modeling geomorphic processes and their impacts.

Plain Language Summary

A major goal of the modern science of geomorphology is to better understand and more accurately predict how Earth surface systems (e.g., the landforms created by deposition of sediment carried by rivers, coastal dunes, hillslopes) respond to natural and human-made forces, and to prepare for and mitigate surface hazards and events that may have major short and long-term impacts (such as debris flows, flooding due to sea level rise, change in river landform, etc). In this paper, we discuss the necessary qualities of practicable Earth surface forecasts, which we call "earthcasts". We suggest that earthcasts are predictions for time-scale ~1 to ~100 years and length-scale of ~1 m to ~10 km; they are developed with direct involvement of stakeholders and public beneficiaries through the evaluation of the socioeconomic impacts of Earth surface events; and they generate forecasts that are clearly stated, are testable, and include quantitative uncertainties. We further discuss challenges and basic and applied scientific developments and investments needed for developing more complete earthcasts. We also provide academic and governmental examples of such earthcasting efforts.

1. Introduction

For many people, a typical day begins by looking at the weather forecast. Based on the predicted rain, wind, or snow, we take the corresponding measures of packing an umbrella, donning a scarf, or lacing up our best pair of boots. State and Federal Governments, land and water management districts, and other public and private-sector stakeholders similarly use meteorological forecasts to plan for year-to-year variability in rainfall, snowpack, or drought [e.g., *U.S. Bureau of Reclamation,* 1922*; U.S. Bureau of Reclamation*, 2016]. In the case of extreme weather, predictions generate warnings that recommend specific courses of action by citizens and government agencies (e.g., NOAA; *Lubchenco and Karl*, 2012). Over longer timescales, societies increasingly look to climate models to plan for predicted changes in sea level, temperature, and storm intensity that might negatively impact their populations or infrastructure [*IPCC*, 2014]. Weather and climate predictions have several consistent characteristics: they use ensembles of model forecasts, which draw from and are tested against ever-growing observational datasets, they state uncertainties and relevant forecast timescales, and they are widely disseminated using mass media.

As is true in the case of weather or climate variability, physical processes occurring at Earth surface have an undeniable and pervasive effect on human populations that inhabit these areas. Discrete events, including landslides and floods [e.g., *Iverson et al.*, 2014; *Gartner et al.*, 2015a; *Staley et al.,* 2017], wildfires and associated landscape erosion [*Sankey et al.*, 2018], or progressive changes including land loss in deltas [*Day et al.,* 2000], fluvial bank erosion, planform shifts [*Lagasse et al.*, 2004], and contaminant transport [*Coulthard and Macklin*, 2003] each have the potential to determine the habitability or societal utility of a particular geographic area. Moving beyond a solely anthropogenic viewpoint, phenomena occurring at Earth surface have the potential to impact biological and geochemical communities and processes across a multitude of spatiotemporal scales. Notable examples include planform and stage-dependent nutrient cycling and ecological community distribution in rivers [*Vannote et al.*, 1980; *Junk et al.*, 1989; *Thorp and DeLong*, 1994; *Thorp et al.*, 2006; *Ensign and Doyle*, 2006], biogeochemical cycling resulting from weathering and erosion of the critical zone [*Chorover et al.*, 2007; *Amundson et al.*, 2007; *Hinckley et al.*, 2017], and the release of sediment and nutrients resulting from accelerated coastal erosion [*Rachold et al.*, 2000; *Rowland et al.*, 2010; *Mars and Houseknecht*, 2007].

The similarities between weather and climate phenomena and Earth surface processes are striking, in that each has significant potential to affect human populations, biological processes and communities, and the flow of material and nutrients across a wide range of timescales, from hours to millennia. Despite their relevance to a diverse array of stakeholder groups and public interests, the major distinction between the two fields is that a suite of robust forecasting tools have been developed, validated, and reliably disseminated to the public in the case of weather and climate, but it remains a major challenge with regard to Earth surface processes. Given the potential for surface processes to affect both life and landscape in profound ways, the lack of reliable and disseminated forecasts of geomorphic change represents one of the more pressing knowledge gaps in effectively linking scientific advances and needs for future research with stakeholder-driven research questions, policy design challenges, and management needs.

To inform practical decision-making in the face of a dynamic Earth surface, geomorphology must move toward generating and disseminating targeted forecasts at a spatiotemporal scale relevant to stakeholders [*Wilcock and Iverson*, 2003; *National Research Council*, 2010]. Any geomorphic forecasts must also track a moving target, as human intervention in the landscape now competes on equal terms with background geologic processes to drive global sediment flux [*Hooke*, 1994; *Haff*, 2003; *Syvitski and Milliman*, 2007]. Additionally, global climate change and other human pressures portend further landscape changes that may manifest in different ways according to local characteristics like soil type and vegetation [*Pelletier et al.*, 2015]. Finally, forecasts become complicated due to the role of stochastic events [*Dietrich et al.*, 2003; *Hasbargen and Paola*, 2003; *Werner*, 2003], the contingency of model predictions with respect to external factors like precipitation [*Wilcock and Iverson*, 2003], and the inherent difficulty in applying first-principles approaches at landscape scale [*Kirkby*, 2003]. A thorough evaluation of the socioeconomic impacts of Earth surface processes is essential for variety of stakeholders, yet it adds another layer of computational demand and complexities to the task. Several of these challenges were first identified in Wilcock and Iverson's [2003] volume *Prediction in Geomorphology*, and while many still persist today, the 18 years since that volume's publication have seen greatly expanded opportunities to both monitor and model surface change [*Larsen et al.*, 2015; *Pelletier et al.*, 2015]. Together, *Wilcock and Iverson* [2003], *Larsen et al.* [2015], and *Pelletier et al.* [2015] have each raised key scientific, technical, and philosophical issues regarding the monitoring and forecasting of Earth surface change. Here, we bring into greater clarity the answers to the following three questions that are key to the design and dissemination of forecast-centered research: (1) What are the essential qualities of a practicable geomorphic forecast? (2) Over what spatial and temporal scales are such forecasts relevant, how are they relevant, and to whom? (3) How should such forecasts be shared within and beyond the Earth science community? Amid a rich and ongoing discussion on the utility of Earth surface forecasts, we currently lack a coherent framework to define the characteristics of effective, forecasting approaches and to guide their design.

In this paper, we build on previous works and recommend a roadmap for (i) generating geomorphic forecasts on human timescales, (ii) evaluating the limits of such forecasts and communicating about them in an accessible manner with stakeholders throughout the process, (iii) encouraging researchers to include geomorphic forecasts in published work and share them beyond the research community, and (iv) promoting practicable forecasts and addressing some of the basic and applied scientific challenges for this work in geomorphology and other fields. We suggest basic criteria for designing Earth surface research which is driven toward forecasting. We define this approach, termed "earthcasting," as the forecasts of Earth surface change on timescales relevant to policymaking, for simplicity defined here as 1-100 years and 100 m to 10 km (Figure 1), while recognizing that considerable variability in these scales may exist depending on individual stakeholder needs and the spatial and temporal extents of the constituent weather and climate models. We also expect that earthcasts include information and quantitative uncertainties that are necessary for future testing (against natural and experimental scenarios) and further evaluations.

The paper is structured as follows: In Section 2, we situate earthcasting in the broader context of geomorphic modeling. In Section 3, we review types of approaches to earthcasting. Section 4 is devoted to the essential qualities of an earthcast, including the inherent forecast timeframes and uncertainties. Section 5 provides examples of earthcasting, and finally, in Section 6 we put forward our vision for the integration of earthcasting into the design and dissemination of Earth surface research, and the simultaneous crafting of science-based policy and management of landscapes, and discuss some of the steps that can be undertaken to facilitate moving in this direction.

2. What is an earthcast? Weather and climate models as blueprints for geomorphic forecasts

Ideally, earthcasts identify processes driving the evolution of a particular natural system and quantify sensitivity to changes in external forcing, internal conditions, and boundary conditions. Models used to develop earthcasts can quantitatively forecast the response of a particular geomorphic system to hypothetical, future scenarios. This framework uses weather and climate models as a blueprint for defining a forecasting model in Earth surface sciences, in the same sense that weather and climate models forecast the evolution of atmospheric conditions over time by numerically simulating the dynamics of the atmosphere and ocean and their interactions with ice and land surface [*Cess et al., 1990*]. In weather and climate models, meteorological processes that are very complex or that occur at scales smaller than the model grid are often parameterized, including surface solar radiation, topographic drag, cloud micro-dynamics, and the effects of soil moisture and vegetation [*Rennó et al.,* 1994a*; Rennó et al.,* 1994b*; Emanuel and Pierrehumbert,* 1996]. In addition, the forecasting power of a weather or climate model depends on the quality and spatiotemporal density of data used to initialize the model, the accuracy of parameterization, and deficiencies in the model's ability to model the relevant physical processes. Weather models are also limited by the chaotic nature of atmosphere dynamics, which only permits accurate forecasting for at most 14 days. Furthermore, weather and climate modelers quantify uncertainty in their predictions through the use of ensemble forecasts, which aggregate the outputs of multiple simulations performed with a single model or multiple numerical models using a range of parameterizations or initial conditions. Weather models are validated by comparing their predictions against field-measured and satellite observations, and by evaluating the accuracy of forecasts from various models against one another. Similarly, climate models are evaluated by comparing model simulations against the observed behavior of current and historical climate in order to quantify their predictive power.

Guided by the example of the weather and climate modeling community, we believe that earthcasting models should generally have the following characteristics:

1. Earthcasts are bounded by spatiotemporal limits of scales relevant to planning, as well as the spatial and temporal extents of the weather and climate (and other forcing) models.
2. Earthcasts make testable forecasts that are compared against known outcomes when possible.
3. Earthcasts quantify the uncertainties in their constituent data and models.
4. Earthcasts are obtained with direct involvement of relevant stakeholders and public beneficiaries, for the information needs of the stakeholders, and for developing an understanding for quantities or observables of interest for stakeholders (such as in the form of evaluation of the impacts of a geomorphic response).

We note that earthcasting does not necessarily require the development of a new genre of models; rather, many of the models' requisite for developing earthcasts already exist, and we call instead for enhancing the forecasting capabilities of future and existing models throughout the geomorphic community. In some cases, these models could be used to make earthcasts in their present state [e.g., *Rathburn and Wohl*, 2003; *Lai and Capart*, 2009; *Liang et al.*, 2016] or with minor modification to increase computational power, including, for example, three-dimensional coupled morphodynamic models [e.g. *Bates et al.*, 2005] and high-resolution models of debris flow and mass failure [e.g. *Kean et al.*, 2013]. Thus, earthcasting in Earth surface research may in many cases be in the form of the specific usages of existing models, such as the capabilities developed over the past decade at the Community Surface Dynamics Modeling System (CSDMS) at the University of Colorado at Boulder. When using existing models, we encourage complete transparency in model operation and workflow, particularly as it relates to the uncertainties associated with the model inputs, outputs, and boundary conditions and forcing, and making every effort to understand and quantify the limits of the predictability of the model.

In some cases, a nonlinear dynamics study may also be necessary to better understand the limit of predictability; this analysis has been well-established for atmospheric processes over the last few decades, starting from the work of *Lorentz* (1963). However, exploring such limits is perhaps in its early stages in geomorphic forecasts. Earthcasts are particularly useful if the magnitude of the forecasted phenomena exceeds that of the potential error or uncertainty in prediction or observation (sensu *Jerolmack and Paola*, [2010]; *Wheaton et al.*, [2010]; *Grams et al.*, [2015]).

The purpose of an earthcast is to provide necessary information for stakeholders and public beneficiaries so that they can make responsible and informed decisions. To achieve that goal, part of the earthcast work must be focused on modeling or estimating the impacts (social, economic, etc.) which may result from a geomorphic response, knowing again that this work ultimately serves a heuristic purpose for most surface process systems (which are open systems for modeling purposes [*Oreskes et al.*, 1994]). In Figure 2, we further expand this idea by considering a forcing scenario *F* for an earthcast site, that is the outcome of a probabilistic study, and/or direct input from other scientists or practitioners. Different forcing scenarios will have a range of probabilities as well, termed *P(F)*. Earth scientists can obtain forcing probabilities from weather and climate scientists, forecasters of wildfires, seismologists, glaciologists, volcanologists, etc., or from governmental, local, or state agencies. If we assume that the earthcast model produces a geomorphic response to a forcing *F*, termed *R(F)*, we can call the impact of the geomorphic response *I(R)* (Fig. 2A). This impact can have different sources, from economic and social to others types relevant to stakeholders or the public. The probability of a given impact is then *P(I)*. For an earthcast, the impacts of a geomorphic response under a forcing scenario *P(I)* can be obtained with a simple probabilistic analysis. At this point, we also emphasize that the geomorphic response as a function of forcing *R(F)* is itself a topic that deserves detailed investigation, where much research for advancing our predictive abilities of geomorphology processes has been performed in the past few decades, and where the idea of the earthcast and practicable earth surface forecasts may open new research fronts and questions. We envision here that *R(F)* is a response function at the system scale, where the “system” is the earthcast model with the desired spatiotemporal scales. Such a system will very likely produce a non-linear (e.g., with a stress, or strain threshold) geomorphic response function (Fig. 2A), that may also vary on spatial scales. The spatiotemporal scale of the earthcast model can also have a potentially significant influence on the geomorphic response function and therefore on the estimates of impacts. The relationship between the geomorphic response function and the impacts can also depend on the types of impact that we need to consider for a given earthcast [*Pelletier* et al., 2015]. This further highlights the importance of collaboration and involvement of stakeholders from the early stage of developing an earthcast to determine and fully evaluate the information (independent and dependent variables, observables, outputs) that stakeholders need, to define impacts and to decide about methods for calculating the geomorphic response, estimating the impact functions and the uncertainties associated with both the geomorphic response and the impacts.

For a sophisticated model that may have a probabilistic forcing scenario, a full realization of the impact probabilities will require a detailed computational analysis, such as Monte Carlo method simulations, as well as consultation or collaboration with other specialists in the area of uncertainty quantification, probability analysis, and other fields. This may further necessitate that an earthcast be developed in collaboration with other scientists, such as mathematicians, statisticians, computational physicists, and social and behavioral scientists. We propose that part of an earthcast task is to either provide the impact function and its associated probability, namely $I(F)$ and $P(I)$, or to otherwise provide all the necessary information that the stakeholders or public beneficiaries may need to develop a probabilistic evaluation of impacts.

Figure 3 shows our proposed vision for the essential interactions between Earth surface process specialists and stakeholders. In the same figure, we also consider other beneficial interactions between Earth surface specialists, climatologists and weather forecasters, statisticians and computational scientists, and stakeholders that may also contribute to developing an earthcast. These fields are only some examples and are not inclusive of all branches of science and engineering that may be involved in a sophisticated earthcast.

We note that at the time of this manuscript's submission, the National Academies of Science, Engineering, and Medicine have been tasked by the US federal government to develop a framework for, and to make recommendations about, “Earth System Predictability Research and

Development". NASEM recently organized a workshop for this purpose in which scientists from various disciplines discussed, among other topics, the styles of interaction of scientists in public and private science agencies with stakeholders and beneficiaries of Earth system predictions. The brief of this workshop provides a few examples for such interactions from different fields of Earth sciences [*National Academies of Sciences, Engineering, and Medicine*, 2020]. Although the examples are not specifically drawn from Earth surface processes, we believe they are useful suggestions. In applying those recommendations toward earthcasts, we acknowledge that the official forms of involvement of stakeholders in earthcasts could vary based on the individual information needs of stakeholders. The interactions could include, as some examples, approaches in which stakeholder(s) participate as co-investigator(s) and/or collaborator(s) in basic and applied science proposals for the national/federal and local funding agencies, and settings in which stakeholders and scientists collaborate in form of consultancies. They could also include settings in which public and private research and academic institutions form partnerships and cooperative agreements with stakeholders to address the stakeholder's earthcasting needs, and/or to monitor particular impact or variables/observables of interest for the stakeholder.

3. Approaches to earthcasting

We envision seven main modeling approaches for forecasting the behavior of an Earth surface system. It is worth noting these systems are almost always open systems for modeling purposes, because of reasons including, but not limited to [*Oreskes et al.*, 1994]: (1) the model input parameters being incompletely known; (2) the model at the earthcast spatiotemporal scale requiring the scaling-up of the model parameters or of the model non-additive properties; (3) observations and measurements for both dependent and independent variables, which are needed for calibration and confirmation of the model behavior in a setting, being obtained through inference, and therefore requiring assumptions in the data acquisition and comparison steps. As a result, the earthcast and the modeling work involved in it ultimately serve a heuristic purpose [*Oreskes et al.*, 1994]. We will expand more on this idea in Section 4.2 of the paper. Furthermore, since a geomorphic forecast may involve many different components, an earthcast may also be developed by a combination of approaches (hybrid), i.e., different modeling methods are used for different components of the model.

Physics-based or theoretical approach A geomorphic forecast that is developed using the governing equations (of transport and deformation phenomena) that are deterministic and derived from basic laws of physics (e.g., conservation of mass, momentum, and energy, depending on the phenomenon), or dimensional analysis based on empirical observations at the fundamental scales of materials and phenomenon at work [*Ackers and White,* 1973; *Parker*, 1979; *Andrews*, 1984; *Parker and Toro-Escobar*, 2002; *Parker et al.*, 2003]. For example, a series of studies showed that gravel-bed rivers undergo bankfull width and depth adjustment resulting in a shear stress that is above the threshold for bed load transport, but not so high as to cause bank erosion [e.g., *Parker*, 1979]. This theory is expressed in terms of the dimensionless shear stress and is the result of dimensional analysis on a set of hydraulic flume experiments. This result is an important advancement in our understanding of the link between channel geometry and bedload transport. The laws obtained from such studies can be used to model the response of a river channel to a given forcing condition. We consider this example physics-based since it is the result of a dimensional analysis, but it is also empirical. We do not wish to distinguish here between a purely-physics based approach, or an empirical physics-based approach, since the majority of laws of transport in Earth surface processes are at some scale still empirical. Figure 2B shows schematically the idea that macroscopic behavior of the geomorphic processes, such as bedload sediment transport, can be described mathematically in terms of physical properties of material, or using approximate formulation developed based on empirical data. Such formulations and obtaining input parameters would require assumptions, data inference, and scaling methods, so it is impossible to truly verify them for the natural world, or for a given prediction of the natural world in the future, but they are what is available and deemed suitable approximations by scientists in a field.

Stochastic approach A geomorphic forecast that is developed using partial differential equations that are stochastic (for example, derived from the Langevin equation) and fulfill physics-based criteria across a range of scales of materials and phenomenon [*Dodd and Rothman*, 2000]. A recent example for such effort is the case of turbulence, where combining universal concepts from statistical physics with fluid mechanics has proven necessary to predict and describe different states of the system across all scales [*Kadanoff*, 1990; *Passalacqua*, 2006; *Goldenfeld and Shih*, 2016; *Pomeau*, 2016]. Some more examples of advances in Earth surface processes that provide a stochastic view of processes include laminar and turbulent sediment transport formulations [*Einstein*, 1937; *Ancey*, 2010; *Lajeunesse et al.*, 2010; *Houssais and Lajeunesse*, 2012; *Furbish and Schmeeckle*, 2013], channelization and stream network evolution [*Abrams et al.*, 2009; *Devauchelle et al.*, 2012; *Seizilles et al.*, 2013, 2014], surface erosion dynamics, and hillslope evolution and topographical features [*Kardar et al.*, 1986; *Sornette and Zhang*, 1993; *Pastor-Satorras and Rothman*, 1998; *Sweeney et al.*, 2015].

Reduced-complexity approach A geomorphic forecast that is developed using a model which is parametrized with macro-scale descriptions, often derived from stochastic or physics-based laws at the model element scale (they are called macro descriptors because the model element is often much larger than, for example, the sediment size in the model or field data). The combination of parameters typically results in an emergent phenomenon that in turn dictates the evolution of the system [*Murray*, 2007; *Paola and Leeder*, 2011, *Liang et al.*, 2015]. The macro-scale descriptors can be used at the appropriate level to summarize fine-scale behavior that is suited to a given purpose [*Dietrich et al.*, 2003]. The elements of a reduced complexity model include a set of geological and topographical features, and only those constitutive relations that are truly essential for a phenomenon of interest. It is noteworthy that complexity is generally ordered and hierarchical, and that its influences are typically non-additive. In other words, simple features and interactions at small scale can have significant effects on producing a complex behavior at larger scales [*Paola and Leeder*, 2011]. In many cases, understanding the limits of reducing complexity for a given geological or geomorphological phenomenon may itself require additional basic research in experimental or computational facilities.

Semi-empirical approach This approach involves a geomorphic forecast that is developed using empirical or semi-empirical results. It is common in geomorphology that for some of the processes involved in an earthcast, there is not yet a physics-based law or stochastic partial differential equation (PDE) that can accurately and sufficiently describe the process, and the alternative choices are empirical or semi-empirical laws obtained from extensive laboratory or field-based studies, without a rigorous dimensional analysis. Some examples include the soil production function [*Heimsath et al.*, 1997], which is important for hillslope evolution models on longer range of timescales, and the temporal variations in the threshold of motion for polydisperse sediment beds [*Johnson*, 2016], which is important for calculating sediment flux in a river. In these situations, at least those aspects of the earthcast will have an empirical basis, and the earthcast will be semi-empirical (It is also a form of hybrid approach).

Mathematical or analytical approach This earthcasting approach involves a geomorphic forecast that is developed by analytically solving boundary value problems. The boundary value problems are obtained from the equations of conservation of mass and momentum, and the boundary and initial conditions of a geomorphic model. In this case, the laws governing the transport phenomenon can be physics-based, stochastic, or semi-empirical. The analytic approach can be applied as long as the boundary value problem (the differential equations) has an analytical solution (which is usually limited in spatiotemporal scales and system complexity, but it is still a useful tool for exploring behavior of the system and for verifying numerical models in the domain that analytical solutions exist). In the absence of an analytical solution, an earthcast can be still obtained by solving the differential equations using computational or numerical methods.

Ensemble approach This is a geomorphic forecast that is developed using an ensemble of modeling approaches. We call for an ensemble approach when there is no best model available that can capture all significant processes involved in a geomorphic phenomenon. Alternatively, ensemble approaches can be used in situations where scientists and stakeholders are interested in quantifying the variability and uncertainty due to different modeling approaches, or due to the variations in the model inputs (design, initial and boundary conditions, forcing, etc.). The ensemble approach can be especially useful for earthcasts that their outcomes may have significant impacts on society, the economy, or policy making.

Statistical approach These earthcasts involve a geomorphic forecast where the main observable phenomenon is predicted using a statistical approach and based on existing data of some other control variables. This type of forecasting is useful when a mechanistic understanding of (all or main components of) geomorphic processes involved in an earthcast is not yet available, hence modeling based on first principles is not possible.

4. Considerations regarding spatio-temporal scales and the role of stochasticity in earthcasting

4.1. Earthcasts are bounded by spatiotemporal scales relevant to planning

The spatiotemporal scale of an earthcast is designed collaboratively with stakeholders to obtain an adequate (with desired uncertainty) estimate of impacts due to likely geomorphic events. We also generally expect that the scales would vary for different types of forecasts. For example, whether we aim to forecast the response of a river delta to subsidence [*Liang et al.*, 2016], a drainage basin to climatic variabilities [*Tucker and Slingerland*, 1997; *Dettinger et al.*, 2004; *Merritt et al.*, 2006], or a river or estuary to development [*Surian and Rinaldi*, 2003], significantly controls the bounds of the model. In addition, while the spatiotemporal scales can be clearly defined, the scales at which the system actually evolves might be unclear: landscapes respond to a variety of physical and chemical phenomena at hierarchical scales, including channelization, hillslope processes, and weathering, among others [*Phillips*, 2004; *von Blanckenburg*, 2005; *Turnbull et al.,* 2008; *Lamoureux et al.,* 2014; *McGuire et al.,* 2016]. Furthermore, stochastic events such as floods or avulsions may be infrequent overall, but nonetheless occur within the timescale of interest [e.g., *Beven*, 2014]. The fundamental (impact-related) scale of change can therefore vary depending on the dominant forms and types of Earth materials and the nature of forcing in each setting. In addition, whether a geomorphic system responds to a perturbation (e.g. a rain event, an earthquake) in a catastrophic threshold manner [e.g. *Schumm and Lichty*, 1965; *Phillips*, 2006] or through a continuous evolution, depends on its geological constituents, initial dynamical state, and the thermodynamic nature of the process and the system [*Pomeau*, 1986]. In cases where change happens slowly and continuously, the average rate of system change can be used to estimate the maximum earthcasting timescale over which models can predict system evolution, up to the point of a state change. This estimate allows a compromise between prediction uncertainty and computational efficiency for a desired forecasting timescale, as in the case of reduced-complexity models for fluvial morphodynamics [*Murray and Paola*, 1994; *Williams et al.,* 2016].

An *a priori* set of spatial and temporal scales are always relevant to an earthcast, as depicted schematically in Figure 1. These scales are the approximate range at which the dominant processes for a given geomorphic setting take place from fine-scales to geologic (macro-) scales.

As an example, for estimating the probability of landsliding for a region [e.g., *Staley et al.*, 2017], we can identify the type of features of interest (deep or shallow-seated events), the processes that can be further influencing the magnitude, timing, and rate of landslide (precipitation, snow melt, soil properties and recent perturbations), and the feedbacks between these processes and factors like topography and vegetation. These connections define corresponding spatial scales from fine grain-scale processes to geologic scales over which forecasts can be made. Factors including landscape history and weathering regime further set the stage for the fine- to larger-scale processes and should inform an earthcast. Further understanding the nature of these interactions requires basic research in Earth surface processes, mechanical and chemical properties of Earth material, flow and deformation of Earh materials, among other topics. We therefore believe that advances in basic research in Earth surface processes broadly could benefit the mission and purpose of earthcasting.

4.2. Earthcasts make testable forecasts, and are compared against known outcomes when possible

It is part of the work of the group who make an earthcast to demonstrate the degree of the correspondence between the model and the natural phenomena and the geological setting they seek to represent and model. The criteria discussed in the article “Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences” by *Oreskes et al.* [1994] are our roadmap for evaluating an earthcast in this respect. Since earthcast is modeling of an open system, confirmation of the numerical model results (for the geomorphic earthcast) with other kind of scientific observations, including in-situ and field-scale data as well as laboratory observations, is the a viable path to demonstrate the degree of correspondence between the model and the natural world. The inherent uncertainty of the model independent and dependent variables, and the fact that the scales of an earthcast are usually out of the domain of the laboratory and in-situ verifications, will preclude verifying an earthcast in the true sense. In other words, earthcasts can only be confirmed against existing data in the domain of the data. Some of the possible ways to confirm and support earthcasts with in-situ, field-scale, or laboratory data include, but are not limited to:

1. Using the stratigraphic record as an archive of past geomorphic responses to change [*Knox*, 2000; *Allen*, 2008; *Armitage et al.*, 2011; *Macklin et al.*, 2012]. It is, however, arguable that few cases exist where stratigraphic record provides ways of testing predictions in the 1- to 100-year time frame.
2. Using "natural experiments" to isolate a specific variable that differs between two otherwise similar landscapes, and thus exploring the effects that variable has on geomorphic processes [e.g., *Salter et al., 2019*; *Whipple et al., 1998*]. The modeling works involved in an earthcast can also be a heuristic tool, and they can further help us to identify topics and parameter domains in need of further study, and to find areas where more empirical data might be helpful to better understand the system response.
3. Trading space for time to examine longer-than-human timescales of geomorphic response to a perturbation [e.g., *Hilley and Arrowsmith*, 2008; *Ferrier et al.*, 2013].
4. Scaling down landscapes to physical experiments to control for and simplify initial and boundary conditions, while allowing for the emergence of self-organization and autogenic dynamics [e.g., *Tal and Paola*, 2007; *Braudrick et al.*, 2009; *Reinhardt and Ellis*, 2015; *Singh et al.*, 2015; *Sweeney et al.*, 2015; *Métivier et al.*, 2016].
5. Using specific and well documented landscape changes, such as restoration projects, floods, externally-induced abrupt natural changes, infrastructure construction, to observe geomorphic responses [e.g., *Cook et al.*, 2013; *East et al.*, 2015; *Gartner et al.*, 2015ab], and to use them to verify the earthcast in the domain of such data.
6. Separately testing specific aspects of a complex landscape to build a better picture of the whole landscape [*Nittrouer et al.*, 2011; *Murphy et al.*, 2016].
7. Assembling datasets of forecasts versus observations for specific models, to facilitate ongoing model testing.

In the process of developing and testing earthcasting models, we should emphasize work targeted at forecasting the evolution of natural experiments, especially those where the long-term behavior is well constrained and a limited number of elements are perturbed [*Tucker*, 2009]. When modeling the response of specific sites to perturbations, the variation of the response to the initial and boundary conditions must also be carefully explored, before attempting to predict the spatial patterns of change.

4.3. Earthcasts quantify the uncertainties from data and models

Dunwoody [2009] argues that "science is one of the few disciplines that have standardized ways of communicating what they don't know." Characterizing the unknowns is by no means straightforward in any natural system, including landscapes [*Jerolmack and Paola*, 2010; *Wheaton et al.*, 2010; *Grams et al.*, 2015]. We argue that earthcasts should strive to incorporate and communicate quantitative uncertainties. These uncertainties may depend on variability in both external forcing and system responses. As an example, erosional variability in natural landscapes could result from both stochastic external forces (e.g., climatic condition that would result in precipitation and discharge time-series) and intrinsic self-organized response variability (e.g., those resulting from interaction of different macro-scale elements of a catchment basins, rivers, hillslopes, and the micro-scale elements within each of them). *Hasbargen and Paola* [2003] studied the predictability of erosion rates in landscapes using a set of hillslope experiments. They found two sources of stochasticity, namely intrinsic and externally forced stochasticity. The former is induced by the stochastic nature of the interactions within the system, and the latter results from stochastic external conditions applied to the system. A geomorphic system could also respond to a combination of these two stochastic elements. The dynamic and equilibrium states in geomorphic systems are influenced by these sources of stochasticity as well. Steady-state refers to a system that is balancing inputs to, and outputs from, the system with (i) static steady-state implying uniform flux divergence at any scale (spatial and temporal), and with no deviation from average divergence; and (ii) dynamic steady-state, implying ongoing dynamics and/or non-zero forcing at the boundaries of the system, with a balance of global fluxes into and out of the system. The local fluxes, however, generally exhibit deviations from the global average. There are further evidences from experiments and field observations that eroding landscapes are inherently dynamic [*Dietrich et al.*, 2003; *Hasbargen and Paola*, 2003; *Lague et al.*, 2003; *Tejedor et al*., 2017]. This statement holds even if an average balance between uplift and erosion rate has been attained for a given drainage basin [*Willenbring and Jerolmack*, 2016].

Given the aforementioned sources of stochasticity and the degree to which they are driven both externally and internally and are interconnected across scales, it is highly recommended for any earthcast to explore the statistical and nonlinear dynamical properties of the system, rather than constraining the forecast to the exact sequence of events. We envision that this approach to earthcasting can benefit from the methods used in seasonal and short-term weather predictions to take into account uncertainties. For this advance to happen, we also would need an improved understanding of the sources and consequences of stochasticity, in addition to the limits of predictability of a geomorphic process across the spatial and temporal scales of the geomorphic system. The complexities and their influences are difficult to separate in natural settings because most types of forcings are highly variable. However, carefully crafted experiments can provide a means of separating internal and external effects. Until such fundamental knowledge of the stochasticity and uncertainty is obtained, we can benefit from practical approaches developed in weather forecasting, for example, by using the ensemble modeling approach. Meteorologists treat and report uncertainty in the weather forecast by using multiple models and deciding either to favor one model over another, or using ensemble averages. To make a similar approach feasible in geomorphic models, Earth scientists must feel more comfortable with documenting and developing multiple models for similar phenomena and working toward understanding the biases and uncertainties inherent in each model or modeling approach (e.g., by verifying them with existing and new observational and experimental data).

Uncertainty in an earthcast model can also stem from sources owing to the open system nature of earth surface processes. Some of the most common sources among these include initial and boundary conditions of the system, model input data (e.g. topographic uncertainty [*Wheaton et al.*, 2010; *Bangen et al.*, 2015], scaling up and inferring model parameters from existing observational data that may not be completely relevant to the space and timescales of the natural world [*Orekese et al.*, 1994]), and model simplification due to abstraction from controlled experiments [*Wilcock et al.*, 2003]. To be most useful, the predictive uncertainty involved in any earthcast must be translated into the degree of confidence that practitioners or decision-makers can have in the prediction [*Helmer and Rescher*, 1959]. As mentioned before, we envision that earthcasts are designed and produced with direct involvement of stakeholders who may not necessarily have a formal background in scientific experimentation and model building. We suggest the recommendations of *Oreskes et al.* [1994] for earthcast modeling, and encourage the scientists and engineers involved in this effort to think about and to find answers to questions such as, how much of the model is based on observational and measurement of accessible phenomena, how much of it is based on informed judgement, and how much of it is based on convenience. We further argue that earthcasts use *commonplace* methods for communicating the answers to those questions and the degree of uncertainty and the partial confirmation of the model results and parameters with observation data. Some of the standard methods and tools for uncertainty estimation that can be employed in earthcast studies include uncertainty propagation analysis and Monte Carlo method for uncertainty analysis [*Refsgaard et al.*, 2007; *Sebastine et al.*, 2015]. In developing a theoretical or phenomenological model based on experimental or field observational data and as part of an earthcast, repeating in-situ and experimental measurements can also inform uncertainty estimates [e.g., *Wheaton et al.*, 2009]. Accurate identification and quantification of the individual sources of uncertainty, their interactions and accumulations to an overall value in many scenarios and problems may also require further basic research in Earth surface processes and other research areas. As a result, we believe close collaboration between academic institutions, local and national laboratories, and the stakeholders is beneficial for advancing research efforts related to earthcasting.

The defining features and spatiotemporal considerations of an earthcast discussed here can also be sources of scientific challenge, and these challenges may be more prevalent in certain fields. Here, we name a few of them:

- Identifying the sources of uncertainty in modeling approaches (governing laws and assumptions used in the model, constitutive relations used for the behavior of earth materials, etc.), the degree to which they depend on the spatiotemporal scale of the problem, and quantifying them as they propagate in different part of the earthcast elements. For example, in the case of constitutive laws, many of the empirical relations for flow, deformation, and fracture of earth materials, are derived from small-scale laboratory experiments on simple material samples. The responses needed for modeling the behavior at the scale of an earthcasts can be substantially different from the scale of small-scale lab experiments, or they can be substantially influenced by heterogeneities at the earthcast's spatiotemporal scale. If it is desired to model the evolution of a landscape on timescales of one to several centuries, we currently have no way of ensuring that the constitutive relations we measure in the lab remain accurate or relevant on such timescales.

- Sensitivity of our models of many geological processes (especially those for which we use stochastic approaches) to the choice of initial boundary conditions. The spatiotemporal resolution at which we know the initial conditions can also limit the accuracy and uncertainties of the earthcast. This challenge is especially apparent in processes where initial boundary conditions are in subterranean (particularly, deeper than the shallow crust where our current capabilities for high resolution subsurface imaging are still limited) or subglacial environments.
- Modeling events or processes for which we would need to account for several interconnected or coupled geological processes, or for which the loading or initial boundary conditions are the result of another geological process with uncertain outcomes at the scale of an earthcast. For example, if we are interested in modeling tsunamis induced by earthquakes in a certain locality, there are significant challenges and uncertainties associated with how an earthquake with an unknown magnitude (that will take place at some time in the future) would unfold and what the ultimate slip profile and ground motion of that future earthquake would look like.

5. Earthcasting examples

In this section, we turn to existing studies to evaluate how the earthcasting approach can be incorporated for specific Earth surface processes. Many studies partially meet the criteria described in the previous section but may not emphasize the forecasting nature of the research for planning purposes, may not include an evaluation of the impacts of a geomorphic scenario, or may not fully estimate uncertainty. Most of these earthcast examples were not generated with full interaction or collaboration involving stakeholders, and would benefit from this additional criteria in their development. However, it can be argued that for the examples of earthcasts by the U.S. Geological Survey below, the work is formally designed and performed for public information and decision making in collaboration with partners at local, state, and federal government levels. The following examples draw from coastal and fluvial geomorphology, volcanic-related and earthquake-triggered hazards in surface processes, but highlight opportunities for forecasting that apply more broadly to Earth surface science.

5.1. Forecasting of post-wildfire debris flow hazards

Wildfires in steep landscapes destroy existing vegetation and inhibit infiltration of precipitation, rendering burned areas more susceptible to mass failure and debris flows [*Moody et al.*, 2013]. Forecasting of this post-fire erosion is important due to the deleterious effects on downstream ecosystems, communities, and infrastructure, including water storage reservoirs [*Sankey et al.*, 2017]. The work of *Staley et al.* [2016] provides an example of how earthcasting can be applied to estimate post-wildfire debris flow hazards and provide stakeholders with information that can mitigate risk to life and property. A similar modeling framework has been developed by *Murphy et al.* [2019] to estimate the occurrence of post-wildfire debris flows. Both frameworks use rainfall-runoff relationships to estimate the likelihood of post-fire debris flows, while the model of *Murphy et al.* [2019] also computes the depositional location (e.g., on hillslopes, in valleys, in river networks) of mobilized sediment. Both of these approaches bound forecasts with future estimates of precipitation, and compute hazards at a scale relevant to planning, in these cases individual spatially-discrete watersheds and stream networks. The frameworks compute the occurrence probability of an event, specifically post-fire debris flows, and compare model results against actual occurrences of these events to aid in quantifying uncertainty and refining the models' input parameters for debris flow generation. In the case of the U.S. Geological Survey post-fire debris flow modeling approach (see *Staley et al.*, 2016 and https://landslides.usgs.gov/hazards/postfire_debrisflow/), predictions of post-fire debris flow probability and debris flow volume following wildfire are released as interactive GIS maps at the scale of individual drainage basins for public communication and stakeholder dissemination.

5.2. How do changes in sea level affect the geometry of the shoreface?

Using an energetics-based sediment transport formulation, *Ortiz and Ashton* [2016] derived a mathematical framework to describe shoreface bed evolution and found the relevant timescales over which the bed evolves diffusively. They found a time-dependent morphodynamic depth of closure (MDOC), or a depth beyond which the rate of morphologic bed evolution in response to shoreface change becomes asymptotically slow (i.e., timescales for change > 1000 years). They applied this theory to six sites (Fig. 4a) around the United States by computing equilibrium bed profiles and comparing them to field-measured shoreface profiles. Finding a reasonable comparison between the profiles, they also noted that the 1000-year MDOC corresponds with a break in slope of the actual profiles. Moreover, *Ortiz and Ashton* [2016] predicted that increasing sea level oversteepens the shoreface and would increase offshore sediment transport based on their theory (Fig. 8 Ortiz and Ashton [2016]). Their work fits as partial earthcasting because it provides a metric for management of beach restoration or coastal engineering projects that need the MDOC, the depth that is relevant for long-term response and evolution. Given predictions of 1.0 m to almost 2 m sea level rise over the next two centuries [*Kopp et al.*, 2014], we adapted *Ortiz and Ashton* [2016] work to calculate a response of the theoretical shoreface (Fig. 4b-4c) for different sea level rise scenarios (Figure 3, *Kopp et al.* [2014]).

Ortiz and Ashton [2016] did not compute the predicted profile or MDOC with 1-meter eustatic global sea level rise (the worst-case scenario predicted to occur over the next century) for specific sites. As a result, this study could be improved as an earthcast if *Ortiz and Ashton* [2016] specifically forecasted the response of each of the sites to changes in regional sea level or wave climate given predicted climate change impacts over the next century. Nevertheless, they did test their earthcast by using local validation when comparing theoretical predicted equilibrium profiles to actual profiles and comparing predicted MDOC to the slopes of the beach profile. While not a full earthcast, by predicting the response of the suspended sediment components and total flux (Fig. 4b-4c), *Ortiz and Ashton* [2016] provide a range of uncertainty associated with their forecasts. This example illustrates the relative ease of incorporating earthcasting into existing research frameworks, as it requires simply placing the work in a particular context while providing predictions.

5.3. How does dam removal affect sediment transport dynamics and riparian sediment connectivity?

Here we consider an example that focuses on forecasting the magnitude and response of geomorphic systems to dam removal. This is an important topic as the U.S. is now entering an era of increasing dam removal or repair as the majority of its large and medium sized dams reach the end of their design lifespan. The example by *Gartner et al.* [2015b] uses a dam removal on the Ashuelot River in southern New Hampshire (Fig. 5a) to test how a sudden, spatially non-uniform increase in river slope alters sediment transport dynamics and riparian sediment connectivity. They characterized site conditions by detailed pre- and post-removal field surveys and high-resolution aerial lidar data to forecast locations of erosion and deposition through one-dimensional hydrodynamic modeling. Furthermore, they tested their forecasts with post-removal observations at up to a year and beyond following the removal and showed that spatial gradients in sediment transport can be used to predict locations of erosion and deposition on the stream bed (Fig. 5 b-d). *Gartner et al.* [2015b] found the stream bed response was consistent with the hypothesized predictions in ~73% of the reaches. Some of this uncertainty stems from model uncertainty, especially the ability of HEC-RAS program (a computer program that models the hydraulics of water flow through natural rivers and other channels, using physics-based and empirical equations of transport; https://www.hec.usace.army.mil/software/hec-ras/) to simulate stream hydraulics and the ability of sediment transport equations to predict sediment loads. Other uncertainty stems from input data uncertainty, especially the inherent smoothing generated from the spacing of cross sections.

This study could be improved as an earthcast with a more detailed analysis of the uncertainty and stochasticity of the system. There are many additional elements that generally need to be considered (though it might not have been deemed necessary for this particular study) in a full evaluation of the geomorphic response of dam removal. Some frequent consequences include destruction of pools and riffles, burial of coarse-grained riffles by finer-grained sediment, and modification of bedforms and armor [*Pizzuto*, 2002], most of which are still under development to understand their physical phenomenology (e.g., *MacKenzie et al.*, 2018; *Masteller and Finnegan*, 2017) and require new experimental, field-scale, and theoretical research.

A more generalizable earthcast in regard to dam removal is provided by *Cui and Wilcox* [2008]. They use a first-principle model to develop a two-phase forecast (coarse gravel transport and fine sand transport) for the fate of sediments. Their gravel-transport model is based on *Parker's* [1990] surface-based bed load equation, while the sand transport model is based on *Brownlie's* [1982] bed-material equation. Using a numerical model, they explore alternative scenarios following the dam removal with respect to (i) amount of bed aggradation, (ii) increase in suspended sediment concentration, (iii) influence of transport distance on suspended sediment concentration and coarse and fine sediment accumulation, (iv) influence of dredging of varying amount of sediment prior to dam removal on the sediment transport dynamics after removal, and (v) influence of discharge conditions during and following the dam removal on sediment transport and deposition characteristics. The model uses input data on channel gradients, channel widths, water discharge at each section of the river for the duration of the simulation, grain-size distribution of the sediment deposit in the reservoir and in the downstream channel, and the sediment supply with associated grain-size distribution upstream of the dam reservoir. They further performed sensitivity analysis to characterize the potential uncertainties in model results as a result of uncertainties either in model input data or in basic assumptions. The model results are additionally compared against observed data and the procedure is current standard for predicting downstream evolution of sediment following dam removals.

The advantages of the *Cui and Wilcox* [2008]'s study are that different first-principle models are developed for alternative scenarios, each model is provided with actual input data from the upstream river, and reservoir characteristics along with their uncertainties are tested and quantified against field observations. As noted by the authors, despite the rigor of this work, the use of separate sand and gravel transport models will produce uncertainties and potential errors in this earthcast. This limitation is a reminder that a comprehensive, physics-based transport model that includes the interaction of sand and gravel and their influences on transport rate and pattern formation on one another (e.g., gravel bars, armor) is still not available, but is a necessity for more reliable earthcasts. This challenge also emphasizes the importance of basic and fundamental research for solving practical and socially relevant problems.

5.4. Postglacial topographic evolution of glaciated valleys

Forecasting the evolution of landscape and surface processes in parts of the world that are experiencing a transition from glacial to fluvial processes represents a major challenge under current and future climate change scenarios. To better understand how glaciated valleys respond to those changes, *Dadson and Church* [2005] developed a model incorporating three elements: a stochastic landscape evolution model that incorporated a stochastic process to represent deep-seated landsliding, a non-linear diffusion model to represent shallow landsliding, and the Bagnold relation to represent sediment transport processes. They calibrated several components of the model using field data from British Columbia, Canada, although their study was not focused on a specific site location and used a generic idealized topography. The stochastic nature of their model allowed generating an ensemble averaged behavior for a given initial topography and a confidence interval around that ensemble average. They compared their model behavior, including the adjustments of the upper valley side slopes by bedrock-based landsliding, against empirical data from the Coast Mountains of British Columbia (BC). Those regions of BC also experienced a significant retreat of Neoglacial alpine glaciers within the past century. They showed that their model results broadly correspond to the empirical data in several critical aspects. They then used the model to better constrain the estimated magnitude and duration of the paraglacial sediment pulse in future glacier retreat. As a part of this study, *Dadson and Church* [2005] also explored the sensitivity of the model predictions to the changes of the rate of fluvial and hillslope transport, which were among the input parameters of their model.

5.5. Volcanic hazard forecasts and communication

The U.S. Geological Survey operates a network of five volcano observatories that provide near-real-time information to the public on the hazards posed by 169 active volcanoes within the United States. Through a combination of remote sensing (e.g., thermal imaging, ash hotspot delineation, synthetic aperture radar), in-situ and airborne gas monitoring, topographic deformation measurements, and in-situ earthquake and lahar sensors, information regarding ongoing and potential volcanic activity is collected continuously. These data are translated to a readily-communicable hazard scale depicting five levels of concern from 'normal' to 'warning' states (see https://www.usgs.gov/natural-hazards/volcano-hazards/). Because these forecasts of hazards are derived from real-time monitoring, these earthcasts are intrinsically coupled to timescales relevant to stakeholders. Individual volcano-specific information is also provided to stakeholders and the public. There is relatively little information on uncertainty in forecasting provided to the public, although the certainty of a volcanic hazard is assumed to increase with the hazard scale steps. In addition, accompanying software is available that allows stakeholders to predict and visualize related hazards, including ash plumes [*Schwager et al.,* 2012].

5.6. Long-term landscape evolution in a postglacial erosion setting

Forecasting landscape evolution on long-term or geologic timescale is a significantly challenging problem, because of the large number of uncertainties associated with describing the properties of geological materials on such timescale, as well as the uncertainties about first principle or mechanistic relations for describing geomorphic processes (again on such timescale), the initial and boundary conditions of the problem, and the climate and hydrological forcing or the records of these forces. Despite the challenges, certain infrastructure and environmental plans would considerably benefit or necessitate long-term geologic change forecasts. To address this problem, Barnhart and colleagues develop a framework and provide an exemplary study on how to forecast landscape evolution on long timescales. This is presented in form of a three-part (companion) papers, which include performing sensitivity analysis, calibration, and multi-model analysis for long-term landscape evolution [*Barnhart et al.* 2020a, *Barnhart et al.* 2020b, *Barnhart et al.* 2020c]. They also present a workflow for estimating uncertainties associated with the model input and outputs, for determining the initial and boundary conditions of the model, and for implementing and comparing a variety of constitutive relations that govern geological processes. Barnhart et al.'s studies are focused on modeling the evolution of a postglacial landscape located in western New York state, USA. The study site is used for hazardous waste storage, where management decisions necessitate knowledge of long-term geological behavior of the Earth's near-surface, and the magnitude and spatial pattern of erosion for the site. Barnhart et al. first obtain the modern topography of the site, and then compare the predictions of their landscape evolution model with plausible model parameters and known past environmental conditions against the modern topography. This step allows them to evaluate the success of their model, and to make the best decision for the choice of model parameters, the level of complexity for geologic processes, and the initial and boundary conditions of the model. They then use this information to develop an ensemble-based prediction for the site well into the future. Although the studies do not include an assessment of the impact scenarios for their Earth surface predictions, they provide all the tools and information needed (in forms of accessible datasets, and open-source computational and landscape evolution modeling tools) for a full evaluation of impacts of the Earth surface change by the stakeholders.

5.7. Earthquake hazards and influences of earthquakes on surface processes

Earthquakes produce ground motion, ground shaking, and static and dynamic stresses that directly or indirectly result in earth surface change, trigger earth surface hazards or events, and affect both nearby and distant communities depending on the nature of the processes involved.

Some major effects of earthquakes on shallow earth structure and earth surface include the liquefaction of shallow earth surface (in certain soil types and environmental conditions) due to earthquake ground shaking [*Quigley et al.*, 2013; *Holzer et al.*, 1989], triggering of landslides and earthflows following earthquakes [*Meunier et al.*, 2007; *Scheingross et al.*, 2013], changes in permeability of earth's near surface structure caused by the passage of seismic waves (this in turn may result in streamflow and groundwater level changes) [*Manga et al.*, 2003; *Manga et al.*, 2012; *Ingebritsen & Manga*, 2019] , and the production of tsunamis in coastal regions [*Melgar & Bock*, 2015; *Melgar et al.*, 2016; *Lee et al.*, 2020]. Each of these processes that are influenced by earthquakes are also cases of earthcasting, if the focus of understanding of the process and modeling or prediction efforts is within the spatiotemporal scales of interest for communities that may be affected by those processes.

As an example of earthquake-related hazard prediction that can be in the form of an earthcast, we briefly review the study of *Melgar & Bock* [2015] for a case of tsunami runup prediction. In that work, the authors use a combination of strong motion data and high-rate GPS observations to develop a kinematic source model of the Mw 9.0 Tohoku-Oki earthquake that occurred in Japan in 2011. The kinematic model serves as the initial condition for tsunami runup modeling as the next step of their study. For simulating tsunami wave propagation, they solve the two-dimensional shallow water equations using available regional bathymetry and topographic information and a numerical technique known as the finite volume method [*LeVeque*, 2002], implemented within the open-source code GeoClaw (http://clawpack.org). They further compare the model prediction against actual tsunami runup observations in the region and find a good agreement between the model and field observations, that is only limited in scale by the resolution of available topography and bathymetry data for their study.

6. The value of earthcasting: ways forward

Scientists view their work and its social relevance across a range of perspectives. Some see their work in fundamental or mathematical terms that capture the essence of a natural phenomenon, while some others see it in answering or exploring new questions in basic sciences. Some other scientists prioritize direct practical applications, while others choose research topics that involve both basic scientific advances and social use and relevance. We believe that earthcasting, as a whole and as defined here, exemplifies a research endeavor that belongs to this last category, with both basic and applied interests and social relevance and use. We emphasize that an earthcast study can be performed by individual scientists, by collaborative efforts between different groups, or by advances made at discontinuous points of time by different research groups. In other words, it is for the scientists to organize the research and its basic and applied components in a way that an earthcast can be made. Interactions with stakeholders are necessary at least for the prediction and modeling (both the Earth surface processes and the impacts) components of an earthcast, however, other aspects of the study can also benefit from such interactions. As in other fields of science and engineering, the interaction with stakeholders can also introduce new exciting scientific questions and challenges at all levels of science and engineering.

In introducing the concept of earthcasting, we also acknowledge the work that has been done in the field of geomorphic hazard assessment, both as outlined in several of the example earthcasts above and through review papers published previously (e.g. *Gartner et al.,* 2015; *Rougier et al.*, 2013; *Ortiz and Ashton*, 2016; *Leahy*, 2017). At the same time, we believe that earthcasting differs appreciably from traditional hazard assessment in three main ways. First, earthcasting necessarily incorporates and communicates the uncertainty inherent in predictions, through ensemble modeling and collaboration with mathematicians and statisticians in model development, implementation, and the communication of model outputs to the public. Second, earthcasts define a societal impact (i.e., costs to infrastructure, impacts to social or economic characteristics of an area) of geomorphic processes as opposed to simply making predictions of the likelihood of that process occurring (see Section 2). Finally, earthcasts are developed with direct involvement of stakeholders in the community, who guide the choice of timescales, meaningful event magnitudes, and effective communication of uncertainty at all stages of earthcast development (see Figures 3, 6).

We observe that many studies in Earth surface processes and adjacent fields have both direct and indirect relevance to near-future forecasts of Earth surface changes, but we believe more work is needed to fully realize an earthcast as defined here. We think this need is more pronounced for the involvement of stakeholders in the design and production of an earthcast, the near-future focus of an earthcast, and the evaluations of uncertainty or the limit of predictability of the Earth surface change (and its coupled processes) within the context of the spatiotemporal scales of an earthcast. Organizing research toward earthcasting, as a part of the Earth surface processes research and more broadly geoscience research, can further energize efforts for building an effective community response for an actionable science framework. This idea is also summarized in Figure 6. In this paper, we advocate that performing basic research on geomorphic processes across scales and environments is the core work of Earth surface scientists. However, to realize the full potential for this research to answer emerging and important societal needs, geomorphic research must be more fully connected to the climate and social sciences. The research products must also be more clearly and readily communicated to a broader scientific audience (from different adjacent fields), stakeholders and the public. *Nisbet* [2009] argues that "…if scientists have a duty to figure out what is approximately true about the world, they also have a responsibility to communicate this truth effectively." The way that research (and implications for public preparedness) is *framed* is crucial, and in this regard *Nisbet* [2009] advocates that scientists "should work with communications researchers to…identify effective messages and media platforms" for disseminating their work. This emphasis on communications strategy is also important for earthcasting, as public benefit for local communities is maximized through effective, frequent, and bidirectional communication between scientists, engineers, policy makers, and the public. Educational institutions can play a role in this dialogue by encouraging a multidisciplinary view of geosciences, so that the new generations of scientists, engineers, and policy makers can be better equipped to communicate and collaborate to address new and emerging challenges. Figure 6 places geoscience and Earth surface research science in a context as one part of a broader alliance for informed policy making that will also rely on government officials, engineers, and the public.

Generally, as academic researchers, we are motivated to focus on the bridge buttress in Figure 6, labeled "understanding of geomorphic processes". With this paper, we argue that it is also our responsibility, in collaboration with stakeholders and public beneficiaries, to translate basic research into a forecasting framework. Communicating the science and tools that we develop along the way is another important element for further growth. It allows us to put together a scientific framework that can also be understood by the diverse communities that work on preparedness for Earth surface change (the right side of the bridge; Fig. 6). A bridge that only reaches halfway to its destination, or that does not connect with the other half, does not meet its full potential nor does it serve the needs of its community. Similarly, developing a deeper understanding of the geomorphic process alone does not improve society's ability to predict and adapt to change in our geomorphic systems driven by a changing climate and other human-induced and natural pressures. Instead, we need to develop earthcasts that can be accessed and understood by other communities.

Many in our community are already finding influential ways to communicate their research. These tools and approaches model the types of outreach needed to bring earthcasts to society's most pressing challenges:

- Writing books and monographs focused on this multi- and interdisciplinary area of research inquiry, filling the knowledge gaps between modeling and understanding of near-surface processes over socially relevant spatiotemporal scales, assessing impacts of earth surface processes and the uncertainty of the impacts, among other topics.
- Disseminating peer-reviewed earthcast results through social media (e.g., Twitter, Facebook, Instagram), blog posts and fact sheets targeted at a broad audience (both scientific and public audiences).
- Open sharing of data, data analysis, numerical and analytical codes and algorithms, using platforms such as GitHub, SEAD, EarthCube repositories, projects such as the SEN-Knowledge Base, the NCED data repository.
- Developing and disseminating knowledge in the area of Earth surface processes broadly, using publicly accessible teaching platforms, such as SERC teaching vignettes hosted at Carleton College.
- Attendance at meetings geared toward a broad spectrum of stakeholders, including local, state, tribal, and federal governments, NGOs, and applied scientists.
- Promoting the development of transparent, accessible, and scalable open-source modeling frameworks for Earth surface process research and development, as well as for related and connected areas of geoscience research and applications.

Additional ways to encourage and advance earthcasting may include:

- Including earthcasting plans in funding proposals, for example in broader impacts sections.
- Writing review papers that distill and integrate cutting edge research into the “big picture” of earthcasting.
- Funding of continuing education for professors at institutions where the focus is on teaching the next generation of applied geomorphologists and geoscientists.
- Contributing to open-access journals, which disseminate knowledge beyond the research community.
- Soliciting and incorporating the perspective of geomorphologists who work farther out towards the right side of the bridge (Fig. 6), including teachers, regulators, technicians, consultants, and applied geomorphologists.
- Surveying the engineering, design, policy and management communities to determine current sources and future needs for Earth surface data.
- Encouraging Ph.D. students to broaden exposure to applied fields in addition to fundamental research.

As a community, we are at the forefront of understanding the geomorphic challenges that are arguably some of the greatest challenges of our time because of their role in our response to climate change, sea level rise, environmental pollution, and the effects of other human-induced perturbations to the environment. To apply Earth surface science to this great challenge, we as a community must develop ways to take our work to the next step towards earthcasts. We should encourage and support this mission as a more formal part of our teaching, publications, and broader approaches to science.

As a final note, while we decided to use the verb “earthcast” for the research efforts described in this paper, we think our idea can also be called “practicable Earth surface forecasts”. We are open and fully embracing of any noun, verb, or phrase that the community prefers to call this effort, to most effectively communicate their research and science.

ACKNOWLEDGEMENTS

We thank Mike Ellis, Gordon Grant, Liam Rienhardt, Joel Sankey, and an anonymous reviewer for their reviews and suggestions that helped us to improve the structure and clarity of this manuscript. We also thank Chris Paola for insightful suggestions and comments during the process of writing and revising the manuscript. We thank Mariela Perignon and Ajay Limaye for their contributions to an earlier version of the manuscript. All authors acknowledge support from the National Center for Earth surface Dynamics-2 Postdoctoral Synthesis Fellowship through grant NCED2 NSF EAR-1246761. BF has been partially supported by the US Army Research Office, Division of Earth Materials and Processes grant 64455EV, US National Science Foundation (NSF) grant EAR-1224943. JG has been partially supported by the North Atlantic Landscape Conservation Cooperative and the U.S. Fish and Wildlife Service. AK was supported in part by funding from the US Bureau of Reclamation's Glen Canyon Dam Adaptive Management Program and the Mendenhall Postdoctoral Fellowship Program of the U.S. Geological Survey. KM has been partially supported by NSF EarthCube RCN Award 1324760. ACO was partially supported by NSF grants 1426997 and 1135427. AT has been partially supported by the Water Sustainability and Climate Program (NSF grant EAR-1209402) and the International BF-DELTAS project on "Catalyzing action towards sustainability of deltaic systems" funded by the Belmont Forum (NSF grant EAR-1342944). The data sources used in Figures 4 and 5 are cited in the corresponding figure captions. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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FIGURES

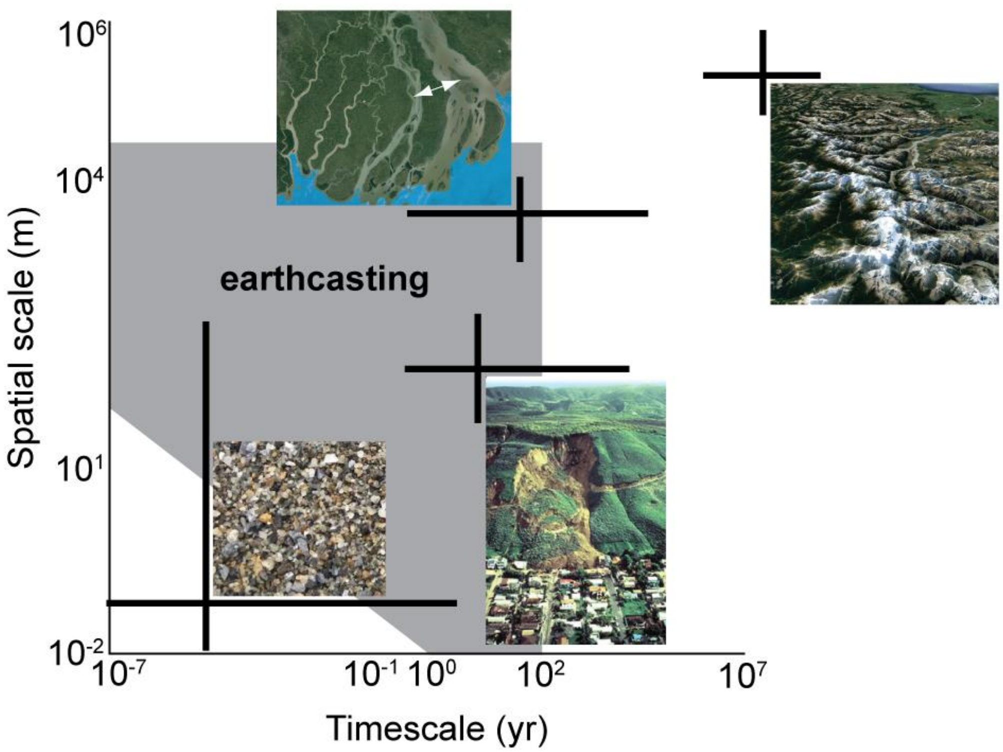

Figure 1. Ranges of spatial and temporal scales in Earth surface processes in general, and the restricted range for earthcasting in particular (gray). Each image represents a geomorphic process, including fluvial sediment transport, mass movements, delta avulsions, and orogen evolution. The cross adjacent to each image represents the approximate spatiotemporal scale range for each process. Image sources: Landsat/Google Earth (Ganges-Brahmaputra-Meghana delta, Bangladesh; Southern Alps, New Zealand), US Geological Survey (La Conchita landslide, California, USA).

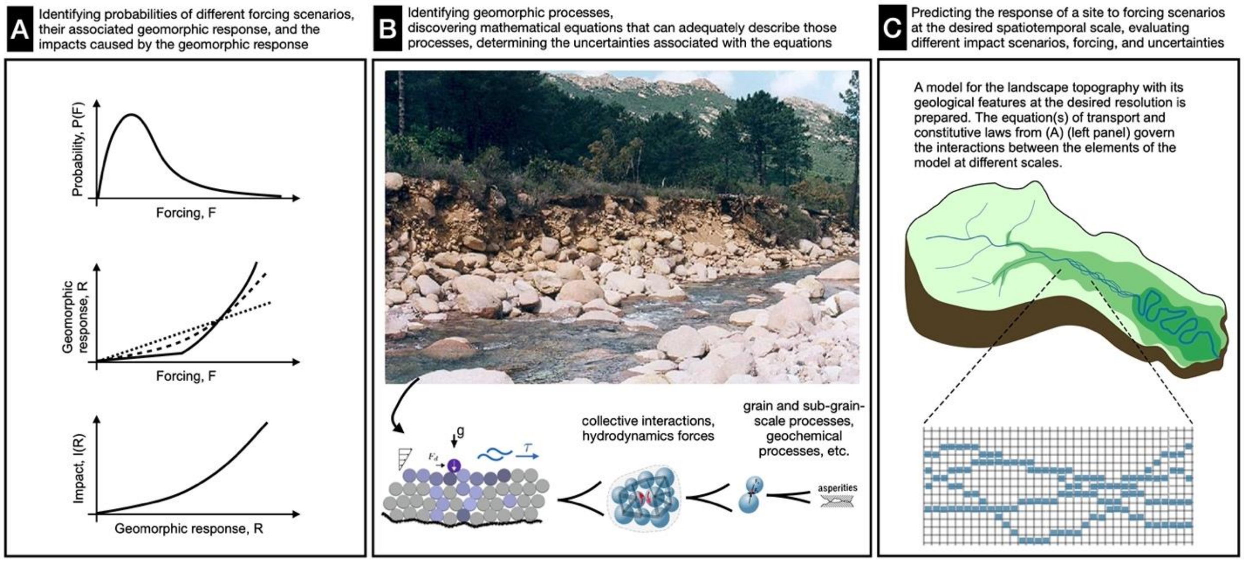

Figure 2. Elements of an earthcast. (A) the links between climatic, hydrological and other forcings, the geomorphic response of an earthcast model (in panel C) associated with those forcing, and the impact of a given geomorphic response at the scale of the earthcast model; (B) Underlying physical processes at scales from sub-grain to landscapes and their associated uncertainties are identified. A number of approaches (including physics-based, stochastic, reduced-complexity, semi-empirical, etc.) can be used to develop the mathematical equations that describe these processes and form the earthcast model. (C) Findings and decisions from steps A and B inform the development of the model at the human-relevant spatiotemporal scales. Key elements include geological and topographical features, constitutive relations, and forcings. The model yields a forecast for Earth surface change (e.g., for the evolution of a river longitudinal profile) at the spatial and temporal scales of an earthcast. This forecast is then evaluated for its impact (returns to panel A).

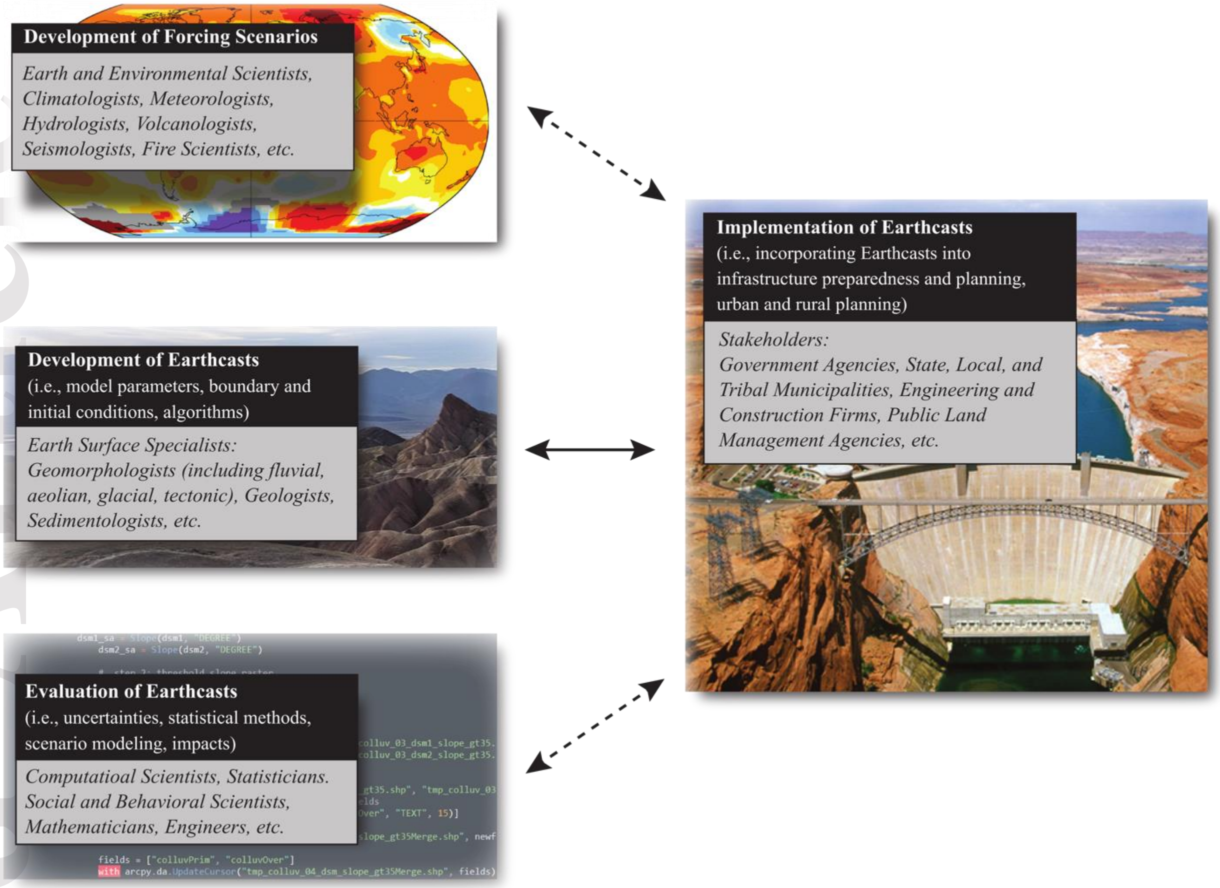

Figure 3. Interactions between the Earth surface process specialists and other Earth science specialists (to develop an earthcast model), mathematicians, statisticians and engineers (to calculate the impact of earth surface change scenarios), climate scientists, fire and weather forecasters, meteorologists, seismologists, volcanologists, glaciologist (to develop forcing scenarios), and the stakeholders and public beneficiaries. The solid arrows suggest an essential interaction (between Earth surface scientists and stakeholders), and the dashed arrows show other interactions that might be also important to earthcasts that have broader implications or those that involve significant complexity (of forces, modeling approach, impact calculations, etc.).

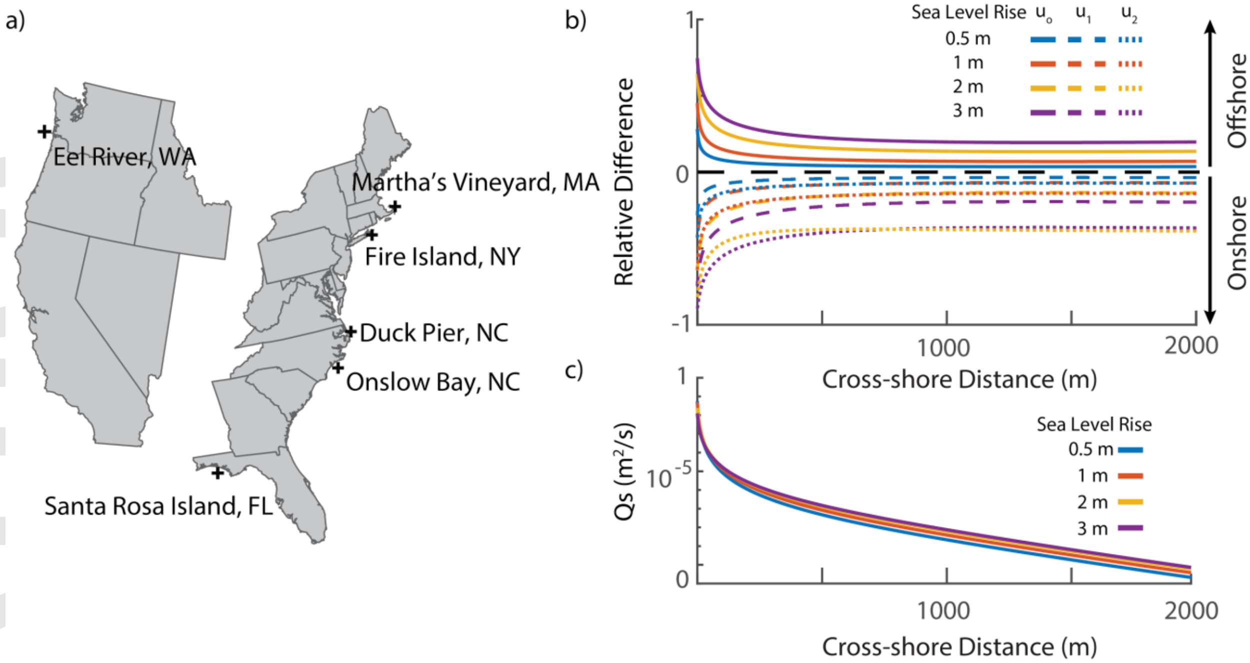

Figure 4. Model forecasts for shoreface bed evolution, modified from *Ortiz and Ashton* [2016]. (a) Locations of bathymetric data, topographic data, extracted shelf profiles around the United States that the earthcast is applied to. Computed effect of an increase of sea level rise (0.5 to 3 m) on an equilibrium profile using linear Airy wave theory on (b) components of cross-shore sediment transport and (c) total cross-shore sediment transport (positive direction is offshore). Here, w_s = 0.033 m/s is the sediment fall velocity, H_0 = 3 m is deep water wave height, and T = 10 s is the wave period.

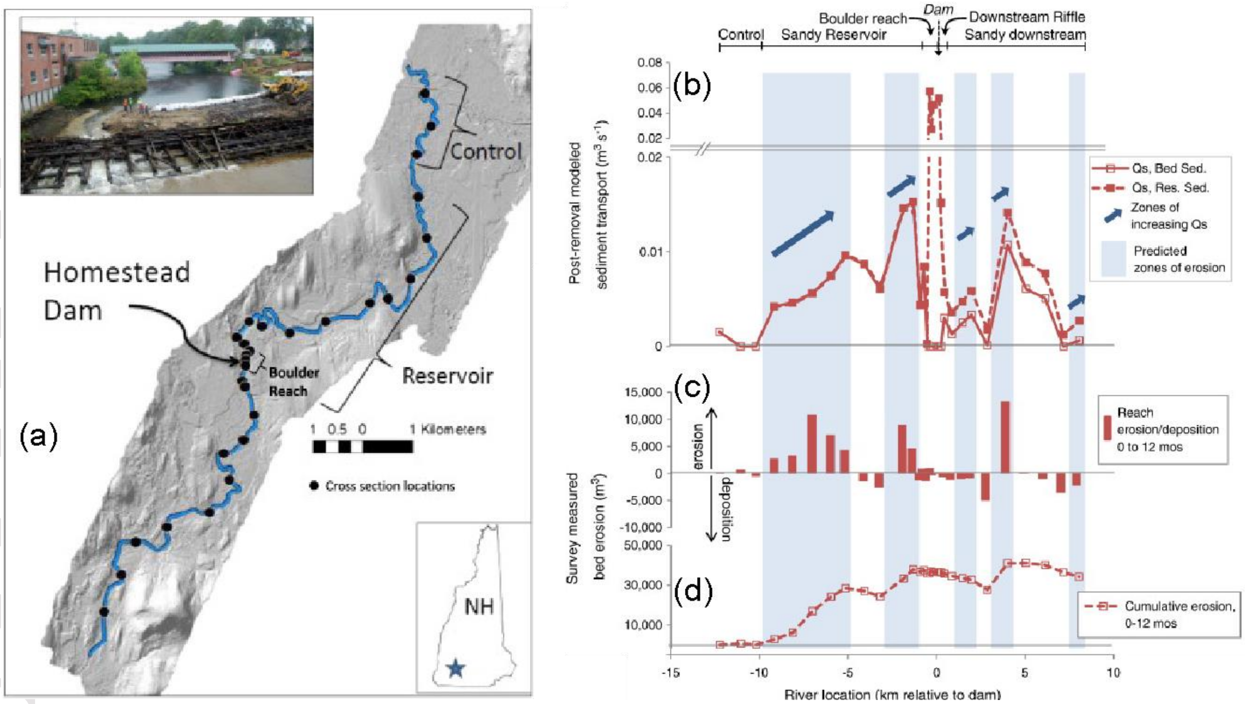

Figure 5. Geomorphic response to dam removal on the Ashuelot River in southern New Hampshire, modified from *Gartner et al.* [2015b]. (a) Locations of cross sections, Homestead Dam, reservoir reach, and upstream control reach. Inset shows the breaching of the Homestead Dam. (b) For the time period immediately after dam removal, modeled sediment discharge of 2-year recurrence interval storm using bed sediment grain size (solid line: Q_s, volumetric sediment discharge across the entire river width using bed sediment grain size, and sandy reservoir grain size (dashed line: Q_s, reservoir sediment). Arrows indicate zones of increasing Q_s, with respect to distance downstream. Shading corresponds to the arrows and indicates predicted zones of erosion. c) Surveyed erosion and deposition of bed material at cross section intervals from 0 to 12 months after dam removal, with positive values for erosion and negative values for deposition. d) Cumulative bed erosion, where a positive slope of the line indicates a zone of net erosion and a negative slope indicates a zone of net deposition.

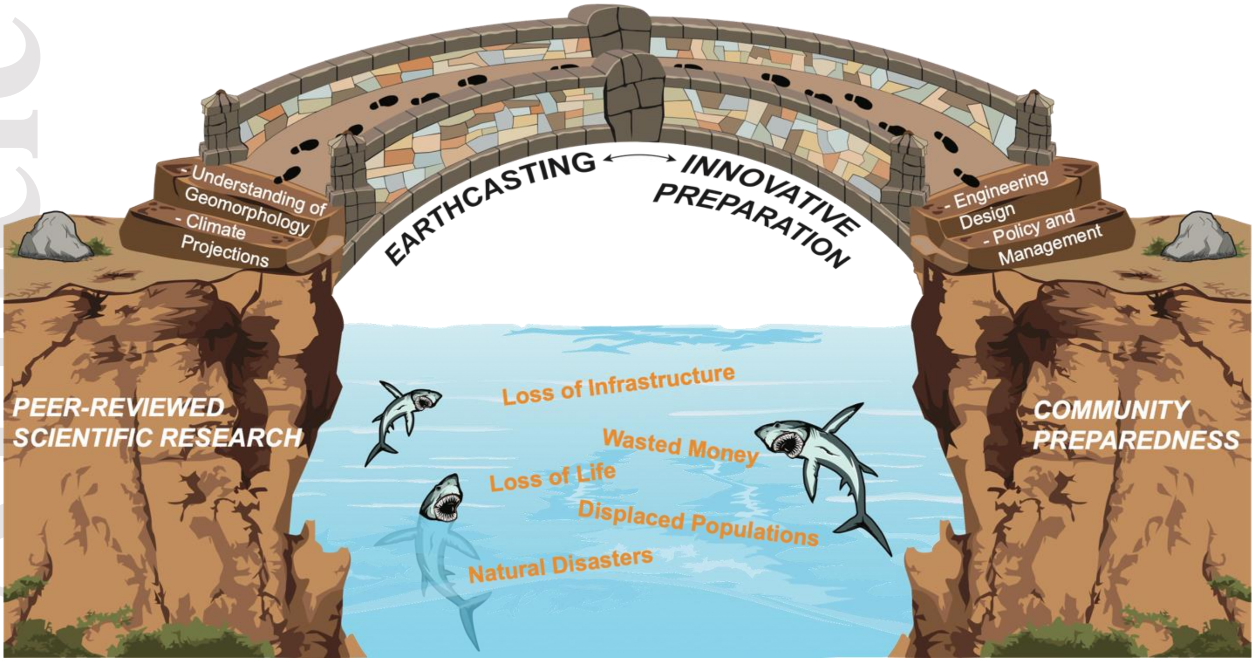

Figure 6. Conceptual diagram of earthcasting, which uses peer-reviewed scientific research to improve preparedness for Earth surface change (through direct involvement of stakeholders of earth surface forecasts, engineering design, policy, and management). Strengthening this connection between basic research and its applications to community preparedness can mitigate the negative consequences of Earth surface change, including loss of infrastructure and loss of life through natural disasters, wasted money, and displacement of populations.