2015

Transformative Geomorphic Research Using Laboratory Experimentation

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Elsevier Editorial System(tm) for Geomorphology
Manuscript Draft

Manuscript Number:

Title: Transformative Geomorphic Research Using Laboratory Experimentation

Article Type: Special Issue: Laboratory Experiments

Keywords: experimental geomorphology, transformative research, Binghamton Geomorphology Symposium

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Transformative Geomorphic Research Using Laboratory Experimentation

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Abstract

Laboratory experiments in geomorphology is the theme of the 46th annual Binghamton Geomorphology Symposium (BGS). While geomorphic research historically has been dominated by field-based endeavors, laboratory experimentation has emerged as an important methodological approach to study these phenomena, employed primarily to address issues related to scale and the analytical treatment of the geomorphic processes. It is contended here that geomorphic laboratory experiments have resulted in transformative research. Several examples drawn from the fluvial and aeolian research communities are offered as testament to this belief, and these select transformative endeavors often share very similar attributes. The 46th BGS will focus on eight broad themes within laboratory experimentation, and a strong and diverse group of scientists have been assembled to speak authoritatively on these topics, featuring several high-profile projects worldwide. This special issue of the journal *Geomorphology* represents a collection of the papers written in support of this symposium.

Introduction

The study of geomorphic systems—the analysis of the processes that shape the Earth's surface and their associated landforms—has been dominated by field research endeavors. This field tradition of geomorphic research can be traced back to the world's early explorers, which provided the impetus for physiographic mapping and the necessary context to consider landscape origin and evolution (Church, 2013). The focus on field geomorphic research also is logical because geomorphologists can conduct research activities at the exact locations where processes operate and landforms are created (McKenna Neuman et al., 2013). Both Butler (2013) and Harden (2013) recognize the invaluable insight and broader context gained by field experiences, which potentially can lead to epiphanies in the understanding of geomorphic systems as well as serendipitous and salutary observations and discoveries simply by being in the right place at the right time.

Yet field research is not the only methodological approach available to the geomorphic research community. A second approach is numerical modeling. Here, modeling is broadly defined to include empirical and statistical approaches to quantify geomorphic phenomena, analytical approaches to define or extend governing equations, and numerical models of varying complexity to simulate geomorphic systems. At present, there is a wide array of geomorphic models available in the literature, some of which are summarized in Wilcock and Iverson (2003) and Pelletier (2008). A third methodological approach available to the geomorphic research community is physical modeling and the use of laboratory experimental facilities. Here, physical modeling is broadly defined to include scaled models based on similarity principles, analogue models based on similarity in form and/or composition, and single-purpose facilities designed to explore a specific geomorphic phenomenon. Experimental investigation has been part of geomorphology for many decades although there are few treatises or seminal papers reporting on the design and use of laboratory experiments and facilities in geomorphology. Some representative examples include Hjulström and Sundborg (1962), Mosely and Zimpfer (1978), Schumm et al. (1987, and references therein), Peakall et al. (1996), Paola et al. (2009), and McKenna Neuman et al. (2013).

The annual Binghamton Geomorphology Symposium (BGS) is one of the most recognizable geoscience meetings worldwide. For nearly 50 years, the symposium series has addressed a wide range of scientific and socially-relevant topics in geomorphology, engaging a multitude of geoscientists (Sawyer et al., 2014). The continued success of the symposium is due, in part, to the dedication and commitment of the BGS Steering Committee comprised of both long-term and rotating members. These individuals work closely with the geomorphology community to identify emerging topics of scientific importance, they facilitate greatly in the organization and success of each symposium, and they ensure that the products for the symposium are disseminated to the global community in a timely fashion. The titles of previous symposia illustrate the timeliness and relevance of the selected topic (Sawyer et al., 2014). But the BGS has not yet organized a formal discussion of laboratory experiments in geomorphology, one of the methodological approaches embraced by the research community. The 46th Binghamton Geomorphology Symposium, entitled "Laboratory Experiments in Geomorphology," seeks to bring together leading experts and emerging scientists actively engaged in experimental geomorphic research. This special issue introduces those invited papers to be presented at the symposium. The objectives of this paper are as follows: (1) to define the motivations of the geomorphic laboratory experimentalist, (2) to illustrate through select case studies the transformative nature of geomorphic experimental research, and (3) to provide the rationale for the 46th BGS on laboratory experiments in geomorphology. It is contended here that geomorphic research has been greatly enhanced and transformed by laboratory experiments, and the future of geomorphic research depends on the continued successful melding of the three approaches to geomorphic research: field work, numerical modeling, and laboratory experimentation.

Motivations of the Geomorphic Laboratory Experimentalist

There may be several ways to define the term experimental geomorphology. Mosley and Zimpfer (1978) stated that it is the study of a physical representation or model of a selected geomorphic feature under laboratory conditions. Schumm et al. (1987) provided a brief historical context for experimental geomorphology, including some very early case studies.

There are several advantages afforded the geomorphic laboratory experimentalist, but the motivations to employ such facilities, and to invest so heavily into methods, procedures, and infrastructure, can be reduced to two issues: scale and prediction. The temporal and spatial scales over which geomorphic processes operate often are very large. In general, spatial scales for geomorphic systems can span from 10^{-8} to 10^{7} km^2, and the time scales of persistence can span from 10^2 to 10^9 yr (Bloom, 1998). Although technological advances and numerical models have facilitated the study of such systems in the field (Church, 2013), these large time and space scales potentially could pose insurmountable challenges to the geomorphologist. Consequently, geomorphologists have employed experimental facilities and physical analogues to compress time and shrink scale, while exerting experimental control, to examine the dynamics of these systems. In general, laboratory experiments have spatial scales that range from 10^{-2} to 10^{2} m^2 (or 10^{-8} to 10^{-4} km^2), and time scales of persistence for such processes that range from 10^0 to 10^6 s (or 10^{-7} to 10^{-2} yr), or potentially even shorter in length (ms).

This large discrepancy in scale between natural geomorphic systems and many laboratory facilities remains the primary challenge to the experimentalist. Dimensional analysis and the use of similarity principles have long been employed successfully in the design and execution of laboratory experiments and their application to natural settings (Yalin, 1971; Peakall et al., 1996; Julien, 2002; Gallisdorfer et al., 2014). Unfortunately, application of similarity principles to experimental apparatuses typically employed for geomorphic research invariably requires some relaxation of these scaling requirements, as well as some distortion of select ratios and dimensions. In general, distortions often are accepted for the depth of the geophysical flow and the size and density of the sediment on the boundary or in transport. Paola et al. (2009) further loosened these rigorous requirements by arguing that even poorly-scaled experiments seem to capture the primary characteristics of the geomorphic system under investigation, presenting several examples in support of this belief. They employed the phrase "unreasonable effectiveness" to refer to the consistency of observations made between these poorly-scaled experimental systems and their field prototypes. Even with much analytical evidence presented and the "unreasonable effectiveness" of experimental systems, skeptism remains within the broader geomorphic community when laboratory experiments of geomorphic systems are compared to their natural analogues (Paola et al., 2009).

The second motivation for the geomorphic experimentalist is the focus on prediction. As noted by Paola et al. (2009), geomorphologists are moving away from reasoning by analogy toward reasoning by analysis. It is often difficult to describe in analytic terms the equations governing geomorphic processes due to the large number of degrees of freedom that can occur in natural settings. This is particularly challenging in field-based research where temporal and spatial scales are large or where the processes themselves may not be observed or measured directly. It is this quest to define these fundamental relationships and their governing equations that drives the geomorphologist into the laboratory. Through controlled experimentation, functional relationships and robust theory for geomorphic phenomena emerge, so that these analytic arguments then can be tested against both experimental and field data and further refined (see also Schumm et al., 1987; Paola et al., 2009). It is this iterative process between reasoning (see Kleinhans et al., 2010), experimentation, and field application that leads to generalized theory, geomorphic transport laws, and predictive explanations of landforms (Dietrich et al., 2003).

There are additional benefits afforded to the geomorphic experimentalist. Experimental geomorphologists seek control, precision, and reproducibility in their work (Mosley and Zimpfer, 1978; Paola et al., 2009; McKenna Neuman et al., 2013). Control is derived from knowing exactly when and where a geomorphic event or process will occur so that all data collection activities can be planned in advance. Precision is derived from the use of technology and appurtenant devices that measure with great resolution and accuracy all parameters deemed important. Experimental uncertainties in measured parameters rarely exceed a few percent, even though the phenomenon under investigation can be highly dynamic. Reproducibility is derived from knowing that the experiments can be executed again and again, either by the initial scientist or by others, and that the results will (or should) be statistically invariant. Such opportunities for comprehensive study of geomorphic phenomena often are rarely possible in field research (Schumm et al., 1987; Paola et al., 2009). For these reasons, experimental geomorphologists also are expected to be meticulous scientists.

Major disadvantages to geomorphic experimental research, however, also have been identified. These disadvantages include (1) problems with the boundary conditions of the physical model, (2) materials used and processes observed in laboratory experiments may be dissimilar when compared to those in nature, and (3) the study of a restricted number of processes or phenomena may mask more complex interactions observed in nature (Mosley and Zimpfer, 1978). Experimental geomorphologists likely are well aware of such potential problems.

Select Examples of Transformative Experimental Geomorphic Research

A common phrase used in academia today is transformative research. A definition for transformative research can be found in a report prepared by National Science Foundation (NSF, 2007):

> *Transformative research is defined as research driven by ideas that have the potential to radically change our understanding of an important existing scientific or engineering concept or leading to the creation of a new paradigm or field of science or engineering. Such*

research also is characterized by its challenge to current understanding or its pathway to new frontiers (p. 10).

While this definition appears to be self-explanatory, identifying examples of transformative experimental geomorphic research remains highly subjective. Below a few examples are provided of studies that are considered to be transformative, with the knowledge that these examples represent the obvious bias of the authors and that many more examples could have been presented.

Rill networks and landscape evolution

In the late 1960s, faculty in the Civil Engineering Department at Colorado State University created a research initiative to investigate the hydrology of small watersheds (Dickinson et al., 1967). A specific research focus was the creation of an experimental research facility to examine watershed response to rainfall. The primary objective for this facility was quite modest: it should be large enough to respond as a prototype watershed, but small enough to permit controlled variation of watershed and rainfall characteristics. The outdoor facility built was a rectangular box 9.1 m wide, 15.2 m long, and 1.8 m deep, and it was fitted with upward-directed vertical sprinklers that could simulate rainfall at up to four intensities.

Shortly after its construction, Parker (1977) used this facility to examine the evolution of drainage basins and the growth and development of rill networks. To do this, he filled the basin with a sandy loam sediment mixture, fashioned the topography into an initially flat, gently sloping surface, and then subjected the system to continuous rainfall and episodic baselevel lowering. Although Parker (1977) reported on only two experiments, these results were very enlightening. Parker documented the time- and space-evolution of rill networks forced by rainfall and baselevel lowering, and he could link network extension and sediment efflux to each wave of degradation imposed on the system. Parker then used these data to assess current models of network initiation, extension, and abstraction, to document the role of knickpoints in communicating exogenically-forced perturbations through the network, and to address sediment budgets, sediment delivery ratios, and sequestration of sediments along evolving channel networks. The results from this experimental campaign can be found in Parker (1977), Parker and Schumm (1982), and most prominently in Schumm et al. (1987).

This experimental work is considered transformative for two reasons. First, Parker (1977) and his advisor, Stanley Schumm, noted that due to the short time available to the geomorphologist, theories and models of landscape evolution depended quite heavily on inferences based on limited field data. Moreover, they also noted that simulation models for hillslope and landscape evolution available during this time period made a number of simplifying assumptions, and they could not necessarily be tested against empirical data. As such, Parker and Schumm recognized that experimentation could be used to fill this obvious gap between field observations and numerical and simulation models, and it could provide the necessary empirical data to test hypotheses and to explore parameter space. Geomorphologists now routinely conduct experimental campaigns in direct support of analytic and numerical models (e.g., Hancock and Willgoose, 2001; Paola et al., 2009). Second, while Parker and Schumm (1982; Schumm et al., 1987) focused their attention on landscape evolution, the experimental facility they employed also could be used to address hillslope processes directly responsible for soil degradation, which was especially important to soil scientists, agricultural engineers, and the farming community. Thus, the same facility and experimental methods could be used by a wide range of researchers straddling different disciplines and having different perspectives and complementary objectives, yet servicing completely different clientele. Many examples now exist of using similar apparatuses with different disciplinary foci (Brunton and Bryan, 2000; Pelletier, 2003; Rieke-Zapp and Nearing, 2005; Douglass and Schmeeckle, 2007; Gordon et al., 2012).

Flow and sediment transport in sand-bedded channels

The most notable flume experiments ever conducted on sediment transport were those summarized by Gilbert (1914). Gilbert, a charter member of the U.S. Geological Survey (USGS) began this work a few years earlier while stationed in California. He observed that some rivers, including the Sacramento River, were experiencing overloading of sediment (aggradation) due to the waste from hydraulic mines. Gilbert sought to study bedload transport, and how the quantity of load was related to river channel slope and flow.

To this end, Gilbert (1914) and his colleagues constructed a flume at the University of California-Berkeley. The flume was 9.6 m long, 0.60 m wide, and 0.30 to 0.55 m deep, it could recirculate water, and sediment could be fed into the flow at the upstream end (see Parker and Wilcock, 1993). For a given flow rate, Gilbert and his colleagues would feed different sediment mixtures (unisize and mixed-size sand and fine gravel) into the flume at various rates using a wide range of flow discharges. A number of important observations and results were reported in this work, which included the following: (1) empirical formulae for the prediction of bedload transport, (2) the various modes of bedload transport, (3) the formation and movement of dunes, the transition of dunes to upper-stage plane beds, and the transition of upper-stage plane beds to upstream migrating antidunes, and (4) the enhanced mobility of coarser-grained sediment in the presence of finer-grained sediment.

The work of Gilbert (1914) is transformative for a number of reasons. First, it is one of the first empirical studies of flow and sediment transport using an experimental channel. Second, the data collected are still being used today, primarily to test and verify bedload transport equations (e.g., Wiberg and Smith, 1989; Bridge and Bennett, 1992). Third, Gilbert and his USGS and university colleagues used experimental facilities to address a societal problem. Gilbert's work is considered to be highly influential for these reasons, being cited more than 750 times using *Harzing's Publish or Perish* citation search tool.

In September of 1956, several decades after Gilbert's (1914) work, the Water Resources Division of the U.S. Geological Survey initiated a project focused on water and sediment movement in alluvial rivers, in general, and flow resistance and sediment transport rates, in particular (Guy et al., 1966). Luna Leopold was the Chief Hydrologist at that time, and his own research on river dynamics, water and land conservation, and floods embodied this new initiative. Given the large quantity of data required to address this problem, it was decided by Leopold and his colleagues that recirculating flumes would be employed since these were comparable to flow and sediment processes observed in most streams of interest (Guy et al., 1966).

The primary outcome of this project was the publication of a U.S. Geological Survey Professional Paper by Guy et al. (1966), which was a compilation of 339 experiments conducted over a period of five years and employing a number of graduate students and agency personnel. In this report, two tilting recirculating flumes (one was 2.44 m wide, 0.61 m deep, and 45.72 m long, the other was 0.61 m wide, 0.76 m deep, and 18.29 m long; both located at Colorado State University) were filled with 10 different sands (median sizes ranging from very fine to coarse sand) and systematically subjected to a wide range of flow conditions (Froude numbers *Fr* ranging from 0.14 to 1.70, where $Fr = u/\sqrt{gd}$, *u* is mean downstream flow velocity, *g* is gravitational acceleration, and *d* is mean flow depth). The data collected in these experiments was exhaustive, and included water surface slope, mean flow depth and rate, vertical profiles of downstream flow velocity and suspended sediment concentration, bedload transport rate, and bed configuration. Interestingly, the report provides little to no analysis, discussion, or interpretation of the data.

The experimental techniques employed and the empirical data presented would appear pedestrian by modern standards, yet the publication by Guy et al. (1966) is considered transformative for the following reasons. First, its premise was based on a recognized scientific and societal need—improving the current understanding of mass transport and floods in rivers and streams, and that a federal agency would assume the responsibility to do this. Second, it represented the first systematic data collection program of flow and sediment transport processes in sand-bedded channels. As such, the data collected and the observations made would become the foundations for nearly all theories related to bedform stability and transition, sediment transport, analysis of fine-scale sedimentary deposits, and hydraulic resistance in rivers (e.g., Rubin and Hunter, 1982; van Rijn, 1984; Southard, 1991; Bridge and Bennett, 1992; Leclair and Bridge, 2001) as well as other geophysical flows of interest (e.g., Miller and Komar, 1980; Mulder and Alexander, 2001). Third, this work forged a new paradigm in experimental research, one that was focused on instrumentation and infrastructure (Williams, 1971). It is no surprise that Guy et al. (1966) has been highly cited (>525 times using *Harzing's Publish or Perish* citation search tool).

Birth of aeolian geomorphology

Wind erosion processes are notoriously difficult to study in the field. Unlike rivers, for example, which represent confined flows that are unidirectional and more or less continuous through time, boundary layer flows in the atmosphere are unconfined, omni-directional, ephemeral, and extend over entire regions. Aeolian transport is initiated at wind speeds that often are an order of magnitude greater than in water, so that the ensuing particle motion is not only rapid but also short-lived during wind gusts. Aeolian geomorphologists are well acquainted with the disappointment of spending many days to weeks in the field waiting for suitable winds to trigger a transport event, only to have their instruments set up in the 'wrong' location and/or orientation relative to the prevailing conditions. Early seminal work in the 1930s through the 1950s, which laid the foundation for studying the physics of particle transport by wind in laboratory and portable wind tunnels, was borne out of both curiosity and crisis, and perhaps also, a good deal of frustration. The convenience of being able to create a unidirectional airflow at the desired wind speed whenever required provided early engineers and soil scientists with an invaluable tool and transformative insights that amounted to the birth of aeolian 'process' geomorphology.

Without question the founder of modern aeolian geomorphology was Brigadier Ralph A. Bagnold, a pioneer of desert exploration, who as an engineer and first commander of the British Army's Long Range Desert Group made the earliest recorded crossing of the Libyan Desert (Bagnold, 1990). Upon his subsequent retirement from the army in 1935, Bagnold constructed the first wind tunnel designed for the sole purpose of studying the inception and transport of sedimentary particles in airflows. Housed in the hydraulics laboratory at Imperial College, University of London, the plywood tunnel had an open-loop, suction-type configuration with a small cross-section (0.3 m x 0.3 m) but a comparatively long fetch (9 m). Laboratory wind tunnels must be highly customized for studying particle motion, and indeed it is an art that depends strongly on the experience of the researcher and the resources available. Even to this day, particles are generally not permitted in wind tunnel facilities used for research on the physics of fluids, owing to problems with sediment abrasion and recirculation. Bagnold borrowed heavily from his engineering studies in fluid dynamics, however, to adapt instruments for obtaining measurements in particle-laden flows.

In 1941, Bagnold published a seminal book entitled "The Physics of Blown Sand and Desert Dunes" in which he summarizes, compares and integrates findings from his laboratory experiments with observations made in the field. To this day, this monograph remains the most frequently cited work in aeolian geomorphology (>4000 citations using *Harzing's Publish or Perish*). Bagnold's accomplishments include describing and quantifying the inception of motion and transport of particles in atmospheric boundary layer flows, identifying saltation (sand particles moving in a ballistic trajectory) as the primary mode of aeolian transport, and distinguishing between the impact and fluid thresholds for particle entrainment. Bagnold attempted, for the first time, to understand and describe the linkages between the physics of the transport phenomena and aeolian bedform development (e.g., ripples and dunes). Although many of his perceptions concerning such linkages have been superseded and refined with ongoing technological developments (as reviewed by Shao, 2010), the core concepts, terminologies, and methodologies introduced by Bagnold (1941) remain soundly imprinted upon present-day aeolian geomorphology. His laboratory experiments and theoretical developments were transformative in that they provided a new foundation to build upon, one based on the laws of physics and engineering practice, as opposed to earlier subjective approaches involving qualitative description and classification. In subsequent initiatives, Bagnold expanded his experimental interests to the physics of sediment transport by water in alluvial channels (see Bagnold, 1966), participating in flume experiments with Leopold of the USGS (see above) and his co-workers.

Responding to the Dust Bowl Era

The largest environmental disaster to affect North America was the drought and associated wind erosion that occurred in the 1930s, a period known as the Great Dust Bowl. In response to the devastation, amounting to an estimated loss of 480 tons of soil per acre by 1938 (Hansen and Libecap, 2004), the High Plains Wind Erosion Laboratory of the U.S. Department of Agriculture (later named the Wind Erosion Research Unit or WERU) was established in 1947 on the campus of Kansas State Agricultural College in Manhattan, KS. William S. Chepil joined the unit in 1948 and beginning in 1953, led it for a decade. Chepil was widely recognized as a pioneer of wind erosion research in North America, a career that was launched from his doctoral thesis research at the University of Minnesota (Chepil, 1940) and his early work as a soil scientist with the Canada Department of Agriculture. The WERU 'laboratory' hosted a large collection of custom designed research equipment, inclusive of several wind tunnels of varied scale and configuration. A particularly novel initiative was the deployment of a portable field wind tunnel that could be placed over undisturbed natural surfaces of wide-ranging texture and roughness.

Similar to Bagnold, Chepil carried out basic research into the dynamics of soil erosion by wind (e.g., Chepil, 1945a, b, c), but in accordance with the mission-driven nature of WERU, emphasis was placed upon examining the key factors governing wind erosion, and upon developing methods to reduce or eliminate soil loss by wind (e.g., Chepil and Woodruff, 1963). The overarching goal was to develop a Wind Erosion Equation (WEQ) that would parallel the Universal Soil Loss Equation (USLE) used for predicting water erosion. The transformative work carried out under Chepil's direction substantially extended the highly idealized experimental conditions (e.g. dry quartz particles) examined by Bagnold, and firmly established the role of both laboratory and portable field wind tunnels in the development and validation of semi-empirical predictive models describing the erosion of natural soils by wind. On the whole, the large body of journal publications produced by the unit (over 50 by Chepil alone) provided the seminal foundation for understanding the effects of soil texture, structure, and aggregation, surface roughness, and cohesion (e.g., water and organic matter content) in aeolian systems. This work also established a number of measurement techniques that are still used to quantify these governing factors.

Morphology of alluvial channels

For over a century, many concepts and insights about fluvial landforms, processes, and responses have been derived from laboratory experiments and models (e.g., Schumm et al., 1987) based in experimental programs established in laboratories around the world. In many cases the laboratory work contains essential insights, tests, and measurements that are not possible from field observations and also provide ideas that can be transferred to analysis of problems in the field or provide some verification of inferences from field observations. One thinks, for example, of Friedkin's (1945) descriptions of meander morphology and dynamics, which has many successors (and some predecessors), or the observations of Leopold and Wolman (1957) of the formation of braids under equilibrium conditions, which contained the essential insight that braiding is an equilibrium state that "does not necessarily indicate excess of total load" and which is the antecedent of several experimental programs on morphology and bedload in braiding rivers in particular (Schumm et al., 1987; Warburton, 1996). In this sense, the development of experimental programs in fluvial geomorphology is transformative as a whole, bringing both exploratory and formal experimental (including theory testing) and predictive-analytical programs to the discipline.

Experimentation on cross-section morphology and dimensions has been prominent in establishing principles, observations, and predictive relations for this fundamental aspect of fluvial systems. Leopold et al. (1960) and Wolman and Brush (1961) used experiments to derive insights into the determination of flow resistance from irregular channel boundaries, the factors controlling river channel dimensions, and application of channel mechanics for fluvial morphology. This complemented the early hydraulic geometry and regime analyses from field data and provided experimental observations and formal tests of theory to stimulate and support these analyses, helping to establishing formal analytical and experimental work as an essential part of geomorphology.

The focus on channel morphology and pattern motivated another study important to the geomorphic community. The Hydraulics Research Station, Wallingford, UK, was established in the early 1950s partly to study 'loose boundary' problems primarily for civil engineering. The experimental work of Ackers (1964) is an early example of the use of small-scale rivers to generate new observations and measurements of morphological characteristics and processes of development, and also to explicitly derive and test empirical and theoretical relations for predicting, in this case, alluvial channel dimensions and compare results with full-scale channels. His experiments used a simple sand box about 100 m long and 30 m wide divided into 10 m wide strips each with a different grade of sand. Initial conditions were straight channels with trapezoidal cross-section and erodible boundary and channel development was observed until a stable state (no measurable change over extended period of time) was reached at constant (channel-forming) discharge. Sediment flux was determined by the conditions in the channel by using a sediment recirculation system to give conditions equivalent to an infinitely long channel. Channels were 1 to 3 m wide and up to 0.2 m deep with discharges up to 30 l/s. Adjustment to a stable state included a tendency to meander in some cases. In part, the study was aimed at comparing predictions from physical theory derived from fundamental equations of river mechanics with empirical formulae developed in the regime approach.

The results of the experiments of Ackers (1964) showed that empirical relations for dimensions of small channels were consistent with physical theory. They also established the hydraulic basis for the importance of width-depth ratio in channel mechanics and its relation to differences in bed and bank material, consistent with the contemporary field observations of Schumm (1960). The analysis also established the possibility of a regime sediment concentration. The rational formulations gave reasonable agreement with the experimental results, showed the crucial role of bedform resistance in channel morphology, and established the principle that both a resistance law and a transport law were essential for rational prediction of channel dimensions (consistent also with Henderson, 1961). The experiments also helped to establish connections between river engineering and geomorphology, which have proved extremely fruitful in fluvial geomorphology. The debate about empirical versus 'rational' formulae for predicting and explaining river channel dimensions has been a central concern in fluvial geomorphology ever since and continues to some extent today (Eaton, 2013). Ackers' (1964) work was followed by similar experiments on meander geometry (Ackers and Charlton, 1970). Experimental work on river channel geometry has become almost commonplace since the 1960s, both in single and multi-thread channels both for empirical investigation and explicit theory testing (e.g., Warburton et al., 1996; Eaton and Church, 2007).

Bar development in alluvial channels

Experimental observations of bar development in rivers have provided crucial insights into the formation, morphology, and dynamics of these features, stimulating theoretical developments and insights applicable to field conditions in which observations are much more difficult to make, initial conditions unknown, and fundamental relations may be obscured by local contingencies. Insights into the role of bars in development of river channel patterns, and associated theoretical explanations, come primarily from experimental studies that can be traced back to several laboratories in Japan where river morphology and engineering were prominent issues in landscape processes and society. Rooted in the observations from rivers, these experimental studies were intended to reproduce the morphological characteristics of a variety of rivers and analyze the conditions controlling the occurrence of particular morphologies. Studies of this type began in the 1950s (e.g., Kinoshita, 1957) based on principles of morphological similarity in small-scale rivers. Many subsequent analyses of alternate bars and more complex bar patterns in rivers can be traced back to this initial work, and the resulting data from experiments such as Ikeda (1973, 1975) are still used in tests of theoretical models of bar morphology and dimensions. As a group, these studies used experimental flumes in several laboratories with a variety of dimensions and sediment types, which could be manipulated to set up a range of initial conditions (e.g. channel width/depth ratio, gradient, flow depth) to run experiments covering the known range of relevant parameters.

These flume experiments establishing a simple typology of bars have become the foundation for many aspects of fluvial morphodynamics (Dietrich, 1987; Yalin and da Silva, 2001). The results of these early experiments, and subsequent work (e.g., Ikeda, 1984; Fujita, 1989) defined the conditions of sediment mobility and channel cross-section shape under which each bar pattern (and related river morphology) occurred and the conditions for transition between types. The controlling variables (excess shear velocity and the product of slope and width-depth ratio) were established from dimensional analysis of the problem and then subjected to experimental tests. This demonstrated how experimental work both benefitted from and was used to stimulate theoretical analysis, as well as yielding fundamental observations and demonstrating the application of dimensional analysis (derived mainly from developments in river engineering) to problems and experimental modeling of river geomorphology. The flume results were directly related to observations of channel morphology and pattern in reaches of the Omoi River with differing morphology, and other rivers in Japan, demonstrating the applicability of the experimentally-derived predictions of morphological transitions and differences to real rivers (Ikeda, 1975). The variables identified by Ikeda (1973) from dimensional analysis and experiments were, in part, also the variables derived from mathematical stability theories for explaining bar modes and channel pattern formation (e.g., Parker, 1976). The distinction between single row and multiple row bars described by Ikeda (1973) has become a fundamental element of fluvial morphodynamics in relation to channel pattern development (e.g., Ferguson, 1987; Bridge, 1993). Experimentation continues to be used in refining these relations, testing theory, and validating numerical models of bar morphology and dynamics (e.g., Lanzoni, 2000; Jang and Shimizu, 2005).

A Recipe for Transformative Experimental Research

The previous section provided several examples of experimental geomorphic research deemed by the authors as transformative. This list is not exhaustive, it is decidedly biased, and it is restricted in time during a period where the financial support for engineering and science was different. Nevertheless, several commonalities amongst these studies do emerge, suggesting that these attributes may have played a role in producing research having high and long-lasting impact. These attributes are listed below.

1. <u>Visionary leadership</u>. It is not surprising that several transformative research efforts were initiated or supervised by now-recognized leaders within the geomorphic community. Each of these individuals was broadly trained and brought a strong affinity for field research into the laboratory.
2. <u>Scientific and/or societal need</u>. In each example presented above, the trigger to begin the endeavor is the same: a real or perceived scientific and/or society need to conduct the research. Moreover, none of the efforts could be considered incremental, as per the definition by NSF (2007).
3. <u>Involvement of a federal agency or institution</u>. It is remarkable that several examples had a federal agency or research institution serving as the primary entity conducting the work, with some cooperating directly with universities. This suggests that appropriated (potentially non-competitive) funds invested over a relatively long time frame (several years) facilitated in the

success of the research program. Interestingly, this research transpired unencumbered by competitive funding agencies and the professional expectations of academia.

4. New or repurposed facilities. As expected, new or repurposed experimental facilities, infrastructure, and instrumentation lay at the core of these research endeavors.
5. Straddling disciplines. Nearly all of the transformational research presented above straddle two disciplines: engineering and geosciences. Engineering emphasized hardware, technology, governing equations, and analytical tools. Geoscience emphasized the analysis of the processes that shape the Earth's surface over large time and scale scales. Yet the products of the research would be of interest to both disciplines, framed and presented accordingly.

Rationale for and Composition of the 46th Binghamton Geomorphology Symposium

There are three primary drivers for hosting a symposium entitled "Laboratory Experiments in Geomorphology," and two already have been noted. First, no BGS symposium has focused on the topic of laboratory experiments, in spite of enormous activity in this area. Second, few treatises currently are available to the geomorphic community that provide detailed information about the design, construction, and execution of laboratory experiments, and how these facilities can used for transformative research. Third, the importance of experimental facilities in research on Earth surface processes was recently highlighted by the National Research Council (2010). This report noted that experimental research can be used to develop, test, and validate geomorphic transport laws as well as examine the emergence of organized landscapes. The report also noted the rebirth in the use of relatively large experimental facilities such as St. Anthony Falls Laboratory's Outdoor StreamLab, University of Minnesota, and the Landscape Evolution Observatory research facility at Biosphere2, University of Arizona, both of which will be featured in the symposium. These relatively large facilities create or even necessitate interdisciplinary research opportunities, they can represent more realistic biotic processes, and they can reduce or even eliminate many issues related to scale.

There are many geomorphic themes that can be examined through experimentation. Owing to the short duration of the symposium, and to the single-session venue, the co-organizers identified eight (8) topics that could be represented at the symposium, which span a wide range of environments and scales. These topics are as follows: (1) granular flows and hillslopes, (2) fluvial processes, (3) aeolian processes, (4) coastal and marine processes, (5) glacial and periglacial geomorphology, (6) landscape and planetary processes, (7) biophysical and ecogeomorphic processes, and (8) large-scale facility development and data management. This is not an exclusive inventory, but it helped to frame the list of potential contributors.

Using these themes, the co-organizers assembled a long list of potential speakers, which was then whittled down in size. To accomplish this, the co-organizers were motivated to achieve strong diversity within the program on the basis of gender, geography, career stage, and perspective. Table 1 is the final list of those scientists invited to the symposium. In every case, the co-organizers were able to secure commitments from the top candidates in each thematic area. Several high-profile facilities and projects also are represented here including the National Center for Earth Surface Dynamics 2 (University of Minnesota), St. Anthony Falls Laboratory's Outdoor StreamLab (University of Minnesota), the USGS Cascade Volcano Observatory Debris-Flow Flume (Washington), the Landscape Evolution Observatory research facility at Biosphere2 (University of Arizona), the Total Environment Simulator (University of Hull), and the EarthCube and the Sediment Experimentalist Network (among others).

Table 1: Summary of BGS themes, invitees (alphabetical) and institutions, and topic areas.

Name	Institution	Topic
Granular Flows and Hillslope Processes		
David J. Furbish	Vanderbilt University	Hillslope processes
Gerard Govers	Katholieke Universiteit	Rill erosion
Richard M. Iverson	USGS Cascades Volcano Observatory	Debris flows
Fluvial Processes		
Maarten G. Kleinhans	Universiteit Utrecht	River and delta morphodynamics
Michael P. Lamb	California Institute of Technology	Steep river channels
Chris Paola	University of Minnesota	Clastic depositional systems
Elowyn M. Yager	University of Idaho	Coarse sediment transport
Aeolian Processes		
Keld R. Rasmussen	University of Aarhus	Wind tunnel simulation of planetary surfaces
Coastal and Marine Processes		
Heidi Nepf	Massachusetts Institute of Technology	Flow-sediment-vegetation interactions
Jeff Peakall	University of Leeds	Submarine channels
Glacial Processes		
Neal R. Iverson	Iowa State University	Laboratory experiments of glacial processes
Landscape and Planetary Processes		
Lucy E. Clarke	University of Gloucestershire	Alluvial fans
Fabien Graveleau	Université des Sciences et Technologies de Lille	Landform evolution
Biophysical and Ecogeomorphic Processes		
Anne F. Lightbody	University of New Hampshire	Biological boundary layers
Joanna C. Curran	Northwest Hydraulic Consultants	River restoration
Large-scale Facility Development and Data Management		
Leslie Hsu	Lamont-Doherty Earth Observatory	Data sharing
Stuart J. McLelland	University of Hull	Total Environment Simulator
Peter A. Troch	University of Arizona	Landscape Evolution Observatory, Biosphere2

The primary outlet for disseminating the results of the symposium is publication of peer-reviewed papers prepared by the invitees in a special issue of the journal Geomorphology. Authors were given freedom to explore these topics, and to include any co-authors, as they saw fit. The papers contained within this special issue are those submitted in support of the 46th BGS.

Conclusions

Geomorphology is a discipline that historically has been dominated by field-based research endeavors. Yet both numerical modeling and laboratory experimentation offer unrivalled methodological opportunities for the geoscience community. The Binghamton Geomorphology Symposium (BGS) is a highly visible annual meeting that has addressed a wide range of scientifically important and socially relevant topics in geomorphology. The 46th annual BGS will focus on the topic of laboratory experiments.

The two primary motivations of the experimentalist are to address the scale of geomorphic systems and to predict such phenomena in analytic terms. First, geomorphic processes often operate at relatively large time and space scales, which pose significant challenges to the field scientist. Laboratory experiments can effectively compress time and shrink scale, and there exists ample evidence to suggest that experimental results can be applied to field prototypes. Second, geomorphologists now seek to explain Earth surface processes and landform development in analytic terms. Laboratory experimentation can greatly facilitate the development and testing of generalized theory, which then can be applied to field observations.

It is contended here that laboratory experimentation of geomorphic systems has resulted in transformative research. Several examples, primarily from fluvial and aeolian research, are presented in support of this claim, and included the following: (1) rill networks and landscape evolution in soils, (2) flow and sediment transport in sand-bedded recirculating flumes, (3) wind erosion research, and (4) bar development and river channel pattern. These transformative research endeavors often were driven by visionary leaders in federal agencies or institutions where specialized experimental facilities were created or repurposed. Moreover, the research featured in these examples effectively straddled the disciplines of engineering and geoscience.

Laboratory experimentation of geomorphic systems is the focus the 46th Binghamton Geomorphology Symposium. Eight themes within geomorphology were selected as foci for the meeting. The symposium shall feature a strong and diverse assemblage of scientists with a wide range of perspectives, and it will report on several high-profile facilities and projects. This special issue of the journal *Geomorphology* presents as a group those papers submitted in support of this symposium.

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