Novel landforms: integrating people as key drivers of process and form in geomorphology

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Key Points:

- We analyzed the geomorphology literature across premier interdisciplinary and disciplinary journals and found that only 9% of the most highly cited works are from anthropogenically altered geomorphic systems.
- We develop a framework for moving forward as a research community organized around the concept of "novel landforms" or geomorphic units formed and maintained through anthropogenic alteration.
- One example insight gained from analyzing novel landforms together is that they converge in shape, increasing the drainage of the landscape.

Abstract

People alter the earth's surface in diverse and prolific ways, from enhancing physical and chemical erosion to controlling water transport across drainage networks. These modifications are often faster, more extensive, and wholly novel when compared to natural landscape evolutionary processes. Existing literature largely portrays people as independent of a landscape's geologic and climatic context. However, we suggest that humans are fundamentally embedded within the geomorphic system. Anthropogenic alteration of the earth's surface results in landscapes that reflect both the socio-economic-technological settings driven by human need *and* the underlying climate and geology. Given that human impacts create similar novel combinations of landforms across the world, we suggest an opportunity for focused study of these "novel landforms." Distinctly anthropogenic landscapes without natural analogues, novel landforms cannot be explained without incorporation of people as an explicit geomorphic process. We propose a unifying framework for the study of novel landforms and demonstrate the opportunities available for more systematic, generalizable research on human-coupled geomorphology.

1 Introduction

The foundation of geomorphology is in the processes that create gravitational or molecular shear stresses that act upon the Earth's surface (Strahler, 1952). From this simple foundation springs a complex set of landforms (e.g., rivers, mountains, beaches). Understanding the diversity of these landforms has been driven forward by the development of conceptual frameworks which capture their complexity as integrated systems which facilitate hypothesis generation and elucidate the emergence of landforms from simple interactions. For example, stream networks in steep, soil-mantled landscapes are shaped as the erosive power of streams and rivers remove sediment from their flow networks. In turn, the morphometry, topology, and extent of stream networks are controlled by the surface and subsurface characteristics of the landscape within which they are embedded (e.g., Montgomery & Dietrich, 1989; Perron et al., 2009).

As geomorphology has advanced, incorporation of other disciplines into geomorphological conceptual frameworks expanded the set of landscapes it can describe. For example, the sub-field of ecogeomorphology integrates biota into geomorphic systems by utilizing model geomorphic systems to drive fundamental understanding (e.g., coastal marshes characterized by a tight coupling between landform and biota; Marani et al., 2013; Ratliff et al., 2015). The incorporation of biota as an integrated component of conceptual frameworks opened opportunities for new fundamental questions and expanded the reach of the field (Dietrich & Perron, 2006; Reinhardt et al., 2010). This integration of two separate fields exemplifies something the field of geomorphology has very effectively done throughout its history: incorporating multiple components of a system into a framework that illuminates the simple interactions that give rise to Earth's diverse landscapes. We see a similar opportunity with the landscapes shaped by people.

People have altered the shape of the earth and the rate of landscape evolution for at least 12,000 years (Ellis et al., 2021). Operating as drivers of geomorphic change in parallel to natural geomorphic processes, people create fresh regolith through mechanical erosion and enhanced weathering (Haff, 2014; Hooke, 1999; Ross et al., 2018), control water and sediment transport across the landscape (Foucher et al., 2014; Rhoads & Massey, 2012; Paolo Tarolli & Sofia, 2016), and reshape the streams and rivers that carry and store water and sediment (Syvitski et al., 2005; Syvitski et al., 2022). These activities are broadly part of the "great acceleration" of environmental change associated with the expansion of industry, populations, and the material extraction required to maintain societal growth (Steffen et al., 2015). The geomorphology literature is full of examples of anthropogenic impacts on landscapes, and the subject has been reviewed several times (Gibling, 2018; P. Tarolli et al., 2019; Tarolli & Sofia, 2016; Wohl, 2013). A substantial portion of this literature incorporates humans and their actions by framing them as a characteristic forcing or a boundary condition on the landscape (Harden et al., 2014), rather than as an integrated component that both alters the geomorphic system and in turn is constrained and influenced by the system. Although people exercise increasing control over the design of landforms, they remain fundamentally embedded within – and at least partially constrained by – their geologic and climate systems (hereafter "geo-climatic setting"). For example, farmers in steep landscapes may install terraces to impede hillslope erosion while farmers in coastal plains may install ditches to enhance drainage. The resulting "novel landforms" reflect not only societal needs (e.g., agriculture, transportation, or others) but also the underlying geo-climatic settings and their interactions.

We see a research opportunity for the field of geomorphology: explicitly incorporating people into geomorphic systems to understand the characteristic forms, processes, and evolutionary trajectories of human created and/or modified landscapes. In part, we look to ecosystem ecology as a field that benefited from a similar effort, where researchers and practitioners have embraced the notion that the intensive and extensive changes people exert on the planet have created a range of ahistorical, de novo ecosystems (Hobbs et al., 2009; R.J. Hobbs et al., 2006). These “novel” ecosystems could not exist without human forces moving species into new places, altering the physical landscape over which existing species interact, and the myriad other ways we change biotic and abiotic conditions on earth. Critically, these systems are novel and unique even after direct human interventions cease, but they are still fundamentally a product of people and have properties that we still do not fully understand.

In geomorphology there are similar design, engineering, and restoration oriented literatures that provide guidance on how to build landscapes using geomorphic theory (e.g. mine restoration; Schor and Gray, 2007). However, no frameworks incorporating people into geomorphic systems have emerged, like novel ecosystems, despite a renewed focus on humans as geomorphic agents (Tarolli & Sofia, 2016) and sophisticated models that link human and geomorphic systems (Werner & McNamara, 2007). Forming a unifying framework to serve as a basis for discussion and research around people as part of the geomorphic system is a tremendous opportunity for the field. Here we attempt to unify some ideas towards that effort, breaking our synthesis into four sections: 1) an analysis of top cited geomorphology studies, 2) a conceptual framework for studying novel landforms, 3) a case study of three different human-impacted landscapes to illustrate both the variety of and similarities in novel landforms, and 4) an exploration of broader environmental impacts arising from novel landforms. With this effort, we hope to stimulate research and discussion in geomorphology, with people as core drivers of the creation and maintenance of novel landforms.

2 Studying human geomorphology

Where is geomorphic research conducted?

We surveyed the most highly cited geomorphic literature in high impact interdisciplinary, earth science focused, and geomorphology journals to assess the “naturalness” of the study sites and their geographic characteristics (i.e., climate and landform; See Methods). Most studies identified were conducted in mountainous, cool regions of North America and Europe. Further, we found that most studies (75%) focused on sites or have objectives that seek to understand geomorphic systems unaltered by people (hereafter “natural”; Figure 1). Human-altered landscapes (hereafter “altered”) made up 9% of the studies in our literature review, while research that focused on or compared both natural and altered systems (“both”) were 3%. Studies that focused on the effects of climate change on geomorphology (“climate”) made up 12% of the studies. Climate change studies were kept separate because of their intrinsic connection to human actions, even when the landscape in question might fall under the "natural" category. We rely here on the authors’ designation or description of their study sites. Of course, some studies purporting to study natural systems may reflect the very naivety about the extent of human impacts on landscapes we seek to highlight (e.g., the extent of stream alteration illustrated in Walter & Merritts, 2008).

Taken together, these findings underline a strong bias towards “natural” landscapes within the highly cited literature, coupled with a similarly strong bias towards mountainous regions of wealthy countries. This latter finding aligns with other findings about the geographic bias in science (Hickisch et al., 2019; Martin et al., 2012; Reddy & Dávalos, 2003). It is particularly notable considering that many regions with few or no studies are also some of the most anthropogenically impacted places in the world (Losfeld et al., 2015; Salvador et al., 2020).

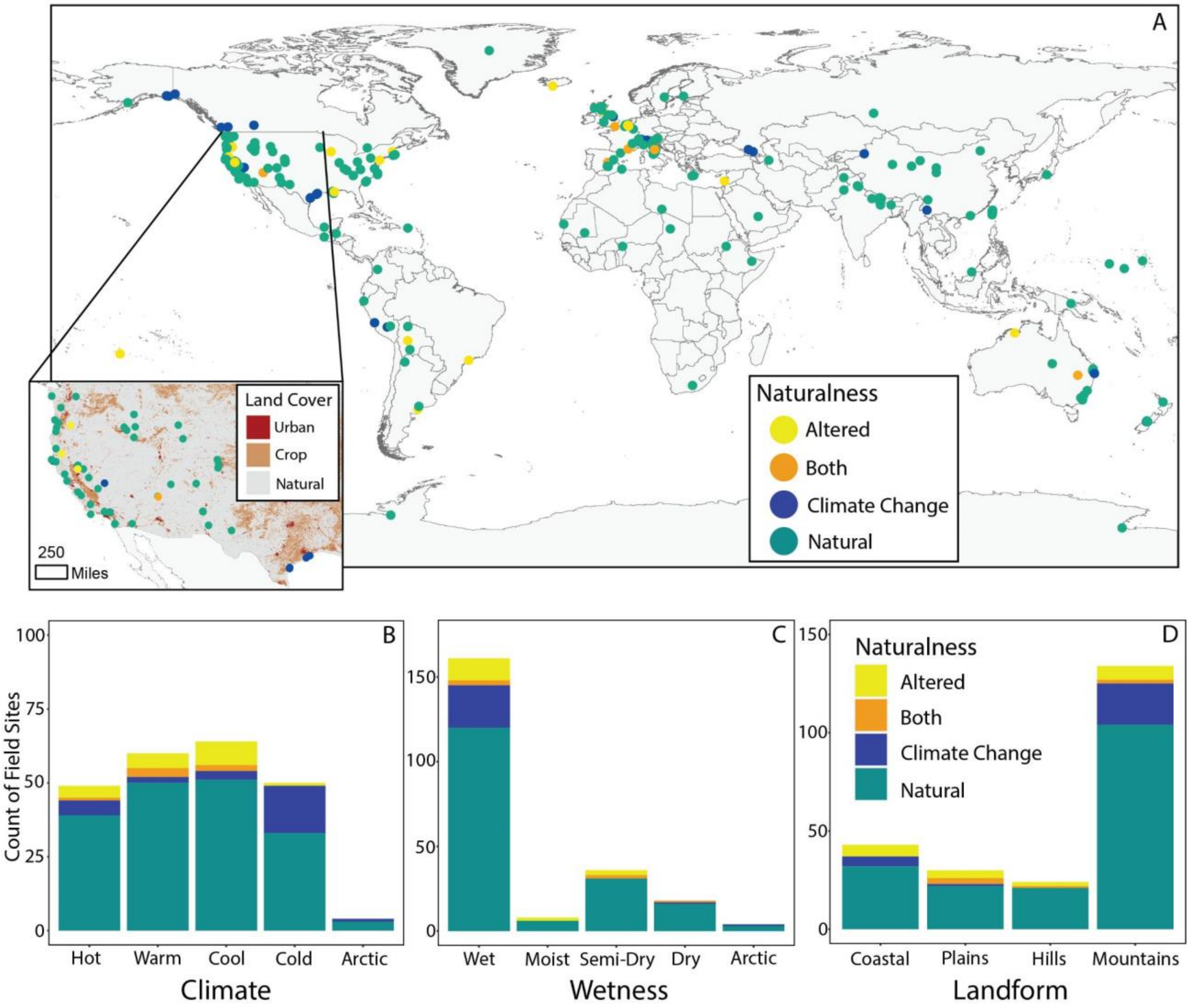


Figure 1: *A review of well-cited literature in the field of geomorphology found that the most important works are from mountainous, temperate, and wet systems in western countries. Panel A is a map of the study sites reported in the literature and the broad type of system coded by the authors. Studies were classified as pertaining to a natural system (natural), a human altered system (altered), studies that compared or studied both natural and altered sites (both), or climate change related studies (climate). Panel inset zooms in on the western United States with land cover data* (Dewitz & Survey, 2021). *We used the World Ecological Land Units dataset* (Sayre et al., 2014) *to determine climate (B), wetness (C), and landform (D).*

Novel landforms: analogy to novel ecosystems

We find the analogy to the novel ecosystems literature a useful one (Chapin & Starfield, 1997; Hobbs et al., 2006). Morse et al. (2014) provide a concise, updated definition (Morse et al., 2014), “A novel ecosystem is a unique assemblage of biota and environmental conditions that is the direct result of intentional or unintentional alteration by humans,… sufficient to cross an ecological threshold that facilitates a new ecosystem trajectory and inhibits its return … The resulting ecosystem must also be self-sustaining.” This concept has utility in ecology because it provides a unifying framework to discuss seemingly disparate ecosystems in common terms. It incorporates a spectrum of ecosystems from “recovered” agricultural fields to those disturbed by invasive species. There are over 575 publications using “novel ecosystems” as a keyword (topic search, Web of Science, October 2023), providing ecologists a framework to better integrate humans as ecological processes and stimulating dialogue in the community (Hobbs et al., 2014; Miller & Bestelmeyer, 2016).

Geomorphic research will benefit from a similarly flexible and inclusive concept that captures the novel combination of landforms people leave in our wake. Over human timescales, altered landforms exhibit many of the characteristics of novel ecosystems: impossibility of returning to the previous form, alteration of geomorphic processes in the landscape, and creation of long-term changes to environmental processes (Hobbs et al., 2006). The origins of novel ecosystems are firmly embedded in human agency, or the direct alteration of ecosystem characteristics whether intentional or not (Morse et al., 2014). By borrowing from this literature and emphasizing the connections between these fields of study, geomorphologists studying “novel landforms” will expand our understanding of earth surface processes.

A novel landform framework

Perhaps one of the primary barriers to incorporating novel landforms into a conceptual framework is their diversity (Table 1). Novel landforms range from artificially maintained coastal dunes (Lazarus & Goldstein, 2019) to ponds and ditches formed in explosive craters and trenches as centuries old legacies of war (Ilyés, 2010). While these landforms are all novel to their landscapes, they vary across a set of general characteristics: the intentionality of their formation, whether the forcing that created them was local or distal, and the extent to which they are being maintained (Table 1). Here we suggest a starting point for a novel landform framework which includes these characteristics of novel landforms and incorporates socio-economic needs, technological advancement, and geo-climatic settings of novel landforms (Figure 2).

As with novel ecosystems, people alter landforms to achieve socioeconomic goals but within the limits of their technological capabilities. Further, both the driving needs and resulting modification are fundamentally constrained by their geo-climatic context (Figure 2). Landform alteration starts by changing topography to achieve some new form or process goal related to a socioeconomic need (Figure 2). For example, agricultural terraces (novel landform) are built to limit erosion (form or process goal) to create better farmland in steep landscapes with significant precipitation (geo-climatic context).

Novel landforms have a life after creation, often persisting beyond human lifetimes into a new socio-economic-technological setting (Figure 2). These landforms may be maintained for further use if the goal of the landform is still relevant, or the landform is utilized for another purpose (reassessment of use). Large, expensive infrastructure that results in novel landforms, such as dams, is often maintained past its intended lifespan because of the continued value to communities or because removal is cost prohibitive (Born et al., 1998). Geomorphic feedbacks and processes may also maintain structures past their time of usefulness. Although rice plantations along the southern United States coast were not maintained after the abolition of slavery (Carney, 1996), the ditches from the rice cultivation in marshes can exist for centuries after their abandonment through the continued geomorphic processes therein. Finally, once geomorphic structures are past their usefulness, they are often abandoned or not maintained. For some structures that are in societally important areas, people attempt to “restore” the system to the pre-altered state for more natural functions or goals as the social-economic-technological setting changes through time (Miller & Bestelmeyer, 2016). Of course, these final outcomes, as presented within this framework (Figure 2), can then become chained together and feedback into the system with subsequent alterations for similar or distinct socioeconomic needs.

Table 1: Analysis of examples of novel landforms to determine the intent, proximity, and maintenance

Example	Citation	Intentional/ Accidental	Distal/ Local	Are people maintaining it?	**Geomorphic form**	**DOI**
Bulldozer in a storm	Lazarus and Goldstein 2019	Intentional	Local	Yes	Overwash during coastal storms	10.1029/2018JF004957
War geomorph (bomb hummocks, trenches)	Ilyés 2010	Accidental	Local	No	Ditches, holes, etc.	10.1007/978-90-481-3058-0_14
Ditches	Clifford and Heffernan 2018	Intentional	Local	Mostly	Features draining flat, wet areas	10.3390/w10081096
Dams	Petts and Gurnell 2005	Intentional	Local	Yes	Features that retain water - creating reservoirs	10.1016/j.geomorph.2004.02.015
Dams	Brandt 2000	Accidental	Distal	Yes	Features that change water and sediment discharge and delivery downstream	10.1016/S0341-8162(00)00093-X
Terraces	Tarolli, Preti, and Romano 2014	Intentional	Local	Mostly	Cut platforms for agriculture on slopes	10.1016/j.ancene.2014.03.002
Water Features (man made lakes)	Podolak et al. 2013	Intentional	Local	Mostly	Serpentine lakes	10.3368/lj.32.1.51
Stream channels and mill dams	Walter and Merritts 2008	Accidental	Local	No	Incised stream channels resulting from historic mill dams	10.1126/science.1151716
Gullies/Erosion	Jefferson and McGee 2013	Accidental	Local	No	Gullies caused by erosion	10.1016/j.jhydrol.2007.05.017
Floodplain sedimentation	Brown et al. 2013	Accidental	Local	No	Increase in floodplain sedimentation due to agricultural development	10.1016/j.ancene.2013.06.002
Viticulture	Townsend 2011	Intentional	Local	Yes	Hillside terracing	10.1111/j.1749-8198.2011.00449.x
Marshes formed behind train trestles	Yellen et al. 2020	Accidental	Local	No	Marshes forming behind anthropogenic barriers due to the changing conditions	10.1002/esp.5045
Incised Stream Channel	Knox 2006	Accidental	Distal	No	Incised river channel from increased rates of floodplain sedimentation	10.1016/j.geomorph.2006.06.031
Ponds	Jeffries 2012	Intentional	Local	Sometimes	Ponds developed for farming, mining, and golf courses	10.1007/s10750-011-0678-4
Causeway	Marriner et al. 2007	Intentional	Local	Yes	Constructed causeway turned into an isthmus	10.1016/j.earscirev.2011.06.006
Irrigation structures	Zimmerer 1995	Intentional	Local	Yes	Canals and terraces for farming in Andean communities	10.1038/378481a0
Agricultural Ditches	Rhoads and Massey 2012	Intentional	Local	Mostly	Drainage ditches in the midwest used for agriculture and to improve land drainage	https://doi.org/10.1002/rra.1430

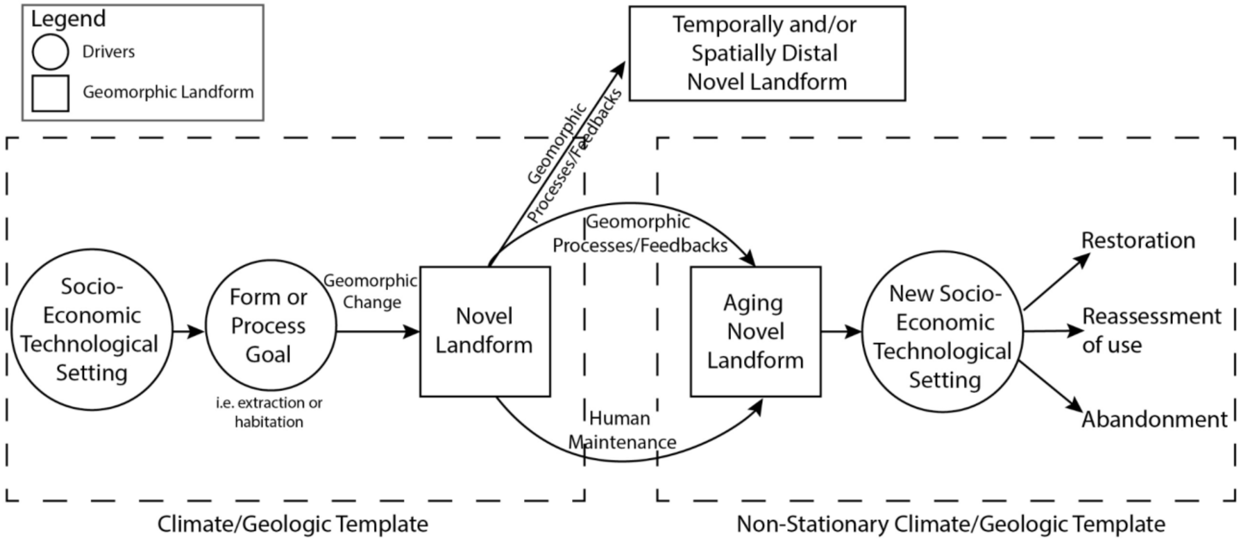


***Figure 2**: Socioeconomic and/or cultural goals or values drive the initial creation of novel geomorphic forms or processes. Through these novel geomorphic landforms, both aging novel forms and distal process changes can lead to unintended effects on geomorphic systems.*

3 Novel Geomorphic Case Studies

To highlight the utility of a unified approach to understanding novel landscapes, we present three case studies of novel landforms which vary in their land-use, intentionality, human impacts, and degree of maintenance: 1) ditched salt marshes, 2) agriculturally driven gullying, and 3) mountaintop mining. We compare hypsometry of natural and novel landforms at each site and explore landform-specific metrics that highlight distinctions between natural and novel landforms.

Agriculturally driven gullying in the Southeastern Piedmont, U.S.A.

Gullying is a prevalent novel landform across the Southeastern Piedmont of the United States – an unintended consequence of agriculture and one shared with many agricultural regions worldwide. Gullies are channels on a hillside that are eroded by running water and normally lack perennial flow (Kirkby & Bracken, 2009). After European settlers supplanted the indigenous population in the 18th century, their cultivation of crops was characterized by widespread deforestation. These denuded landscapes, underlain by deeply weathered regolith, were highly prone to sheet and rill erosion (Trimble, 1975). Although the farming landscape in the region was mostly abandoned and restored to a mixture of pines and hardwoods, the legacy of this massive and widespread landscape modification remains below the canopy in the form of densely gullied drainage networks, altered hillslopes, and long-abandoned terraces (Figure 3b; (Richter et al., 2014). Altered geomorphic processes have maintained the landscape in its novel state past agricultural abandonment and restoration.

We detected the signatures of these novel landforms with high resolution topographic data (Figure 3b) to explore differences in hypsometry between modified and unmodified landscapes (Figure 4; see Methods). A hypsometric curve is the proportion of a landscape's area above normalized elevations for that same landscape. It provides a generalized and low-dimensional characterization of a landscape's topography, and in general, a higher inflection point or integral under the curve indicates a "younger" stage in a landscape's evolution (e.g., Figure 2 in Willgoose & Hancock, 1998).

Because the initial modification of the Southern Piedmont took place prior to high-resolution topographic data, we rely on identifying less modified watersheds as counterfactuals to heavily modified watersheds (Figure 3a, b). We find a strong contrast to the three heavily modified watersheds with a more even distribution of elevations in the less modified areas (Figure 4a). Additionally, identification of geomorphic channel heads illustrates that below a watershed area of about 5 ha there were no observed channel heads in the natural watersheds. This finding shows that erosion in modified watersheds caused the initiation of channels at much smaller areas. Taken together, these two findings illustrate consistent novel landform signatures across landscapes and determining metrics unique to the landscape to reveal geomorphic changes.

Ditched salt marshes along the Atlantic Coast, U.S.A.

Ditches in salt marshes are a significant geomorphic change to ecologically and societally important coastal ecosystems. "Mosquito ditches" in the Northeastern U.S. were often dug in relatively flat salt marshes to drain standing water and reduce mosquito habitat, covering over 90% of marshes from Maine to Virginia (Corman et al., 2012) and 94% of marshes in New England (Crain et al., 2009). Ditches add additional channels to the natural tidal creeks of salt marshes, leading to new hydrodynamics and inundation patterns that are persistent and can last for hundreds of years (Corman et al. 2012). Similar to the more modern ditching in the Northeast, on the rice plantations of the Southeastern U.S., enslaved peoples dug ditches to turn tidal marshes into rice paddies, affecting over 150,000 acres (Carney, 1996; Carney & Porcher, 1993). The legacy ditches from this subjugation system still exist along the coastlines of South Carolina and Georgia. These ditches are novel landforms, persistent over human relevant time scales and affecting coastal wetland hydrology and long-term persistence.

To understand how ditched marshes (Figure 3f) differ from un-ditched or "natural" wetlands (Figure 3e), we used high resolution DEMS to calculate marsh hypsometry and identify channel outlets from marsh island platforms (see Methods). Although the shapes of novel and natural hypsometric curves are similar, there is a greater amount of area with low elevations in novel systems (Figure 4e). Our elevation analysis results show that ditching decreases the elevation of the marsh through the creation of drainage channels (Figure 4e). Additionally, our results show that channel outlets increase with marsh island area in ditched regions (Figure 4f). Ditching increases outlets to effectively drain waterlogged tidal marsh platforms and lower the water table (Corman et al., 2012). We find that ditched marshes have different "plumbing" or novel geomorphology, leading to changes in the hydrodynamics of the systems.

Mountaintop mining in the Central Appalachians, U.S.A.

Mountaintop mining (MTM) is one of the most extreme forms of intentional landscape alteration on the planet. Covering more than 6,000 km^2 of land in the Southern Appalachians, USA (Pericak et al., 2018), MTM techniques are employed where shallow coal seams that underlie 10s-100s of meters of bedrock are accessed by removing bedrock, then depositing this unconsolidated "overburden" into adjacent valleys (Ross et al., 2016). Overall, the post-mining landscape is completely altered from its pre-mining configuration, with shallower slopes (Ross et al., 2016), engineered streams with channel heads built at lower drainage thresholds (Jaeger & Ross, 2021), and reduced stormflow (Nippgen et al., 2017). These novel landforms are likely to

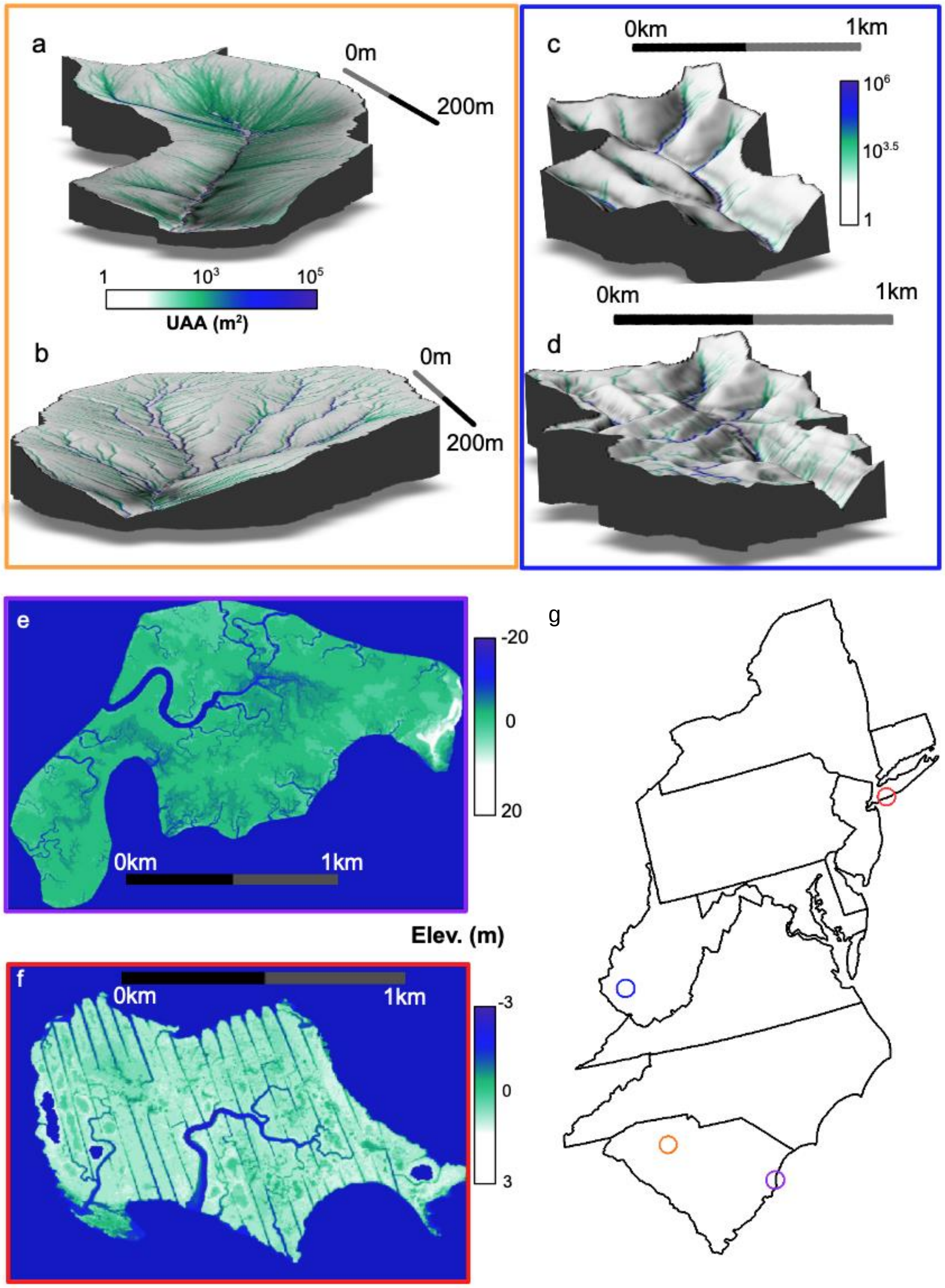


Figure 3: *Comparison of novel landforms to "natural" geomorphic system in the three study sites examined: southeastern piedmont region of South Carolina (Calhoun Experimental Forest, yellow dot- g; panels a, b), mountaintop mining (West Virginia, blue dot - g; panels c, d), and salt marshes along Atlantic seaboard (South Carolina and New York, purple and red dots - g; panels e, f). Panels compare less altered landforms (panels a, c, e) and altered or novel landforms (panels b, d, f).*

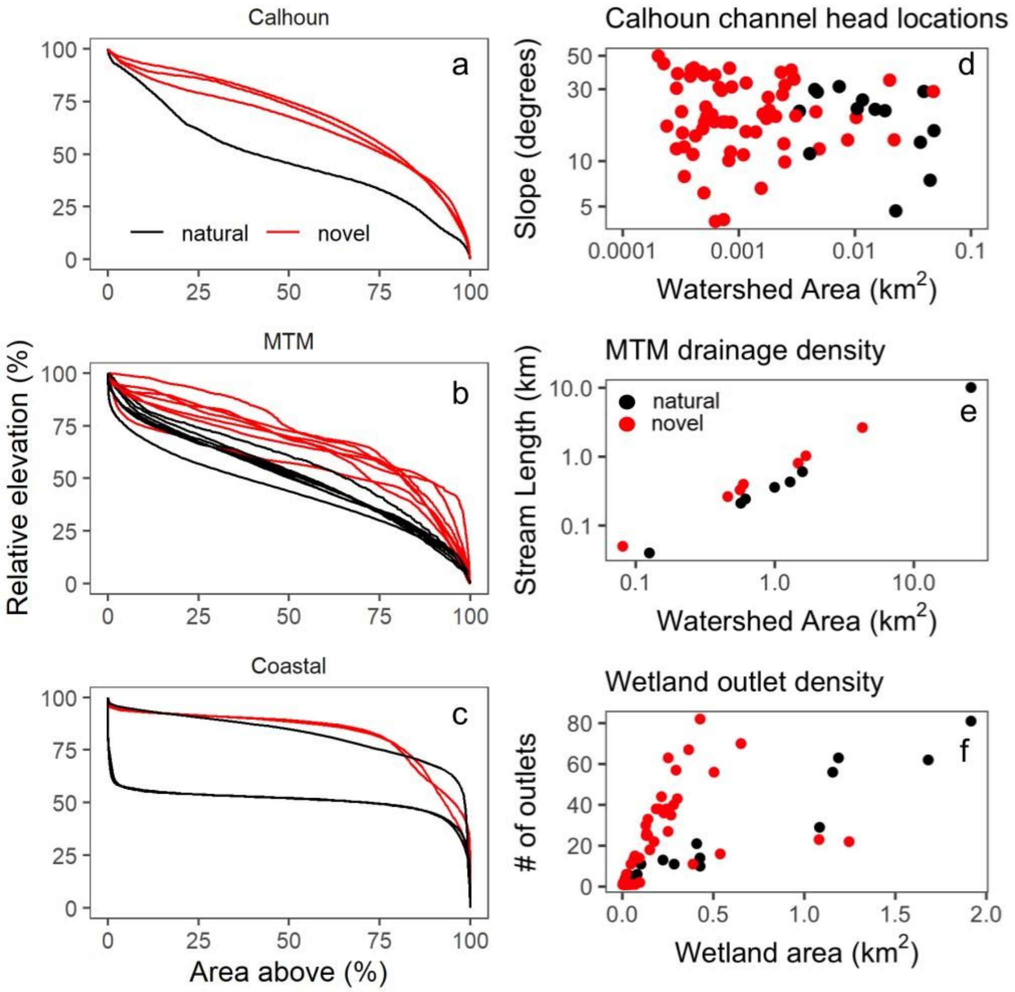


Figure 4: *Hypsometry (a, b, c) and measures of drainage density (d, e, f) show differences in more natural (black) and novel landforms (red). For watersheds in the Calhoun experimental forest (a, d) areas with novel landforms have a less even distribution of elevation and channels at smaller watershed areas. In the Appalachian Mountains (b, e) watersheds have more mass at higher elevation and longer streams per watershed area. For the salt marshes in South Carolina and New York (c, f), ditched marshes have more area at low elevation and higher numbers of channel outlets on the marsh platform.*

persist for thousands of years (Hancock et al., 2016; Ross et al., 2021) with unknown landscape evolution trajectories (Jaeger & Ross, 2021).

Changes to the MTM landscape are detected by comparing pre-mining landforms generated from historic DEMs to post-mining landforms from LiDAR DEMs (Ross et al., 2016). For the purposes of this case study, we highlight two distinct shifts (Figure 3 and 4). First, post-mining landscapes have more of their mass at higher elevations, making them appear to be ‘younger’ landforms in the traditional hypsometric curve space (Montgomery et al., 2001). This shift highlights the landscape reset from a landscape evolutionary perspective. However, this reset is not analogous to geologic forcings like volcanoes, because stream-features and valleys are designed directly onto the landscape (Figure 3). In this engineered landscape drainage density is 4-times higher in post-mining landscapes than pre-mining landscapes, based on manually identified drainage structures (Jaeger & Ross, 2021). This designed drainage structure likely directly impacts both current and future erosion trajectories and landscape features (Reed & Kite, 2020).

Across the three case studies, we find that humans had consistent and likely predictable impacts. Further, similarities exist despite differences in the intentionality and ongoing maintenance. Specifically, human creation of novel landscapes tends to leave signatures of "younger" landscapes (Figure 4a, c, e), and tends to create (either directly or indirectly) more efficient and extensive drainage networks on the landscape (Figure 4b,d,f). These findings stand as motivation for the task of incorporating humans into the field of geomorphology. While numerous outstanding analyses remain, we believe the concept of novel landforms and these case studies illustrate the theoretical and analytical opportunities ahead.

4 Novel landforms impact environmental processes

The impact of novel landforms mirrors that of any geomorphic change by altering the geomorphic template with which other environmental processes interact. The resulting changes to hydrology, biogeochemistry, ecology, sediment transport, and others have been documented across a variety of disciplines. Although generally not framed within the context of novel landforms, the literature is rich with examples of novel landforms altering environmental systems including MTM valley fills, coastal ditches, and urban landscapes.

MTM valley fills represent deep excavation, restructuring, and redistributing of mountainous landscapes. In landscapes characterized by these novel landforms, water is more slowly routed through highly fractured and minimally weathered valley fills as opposed to the surface stream systems that preceded them (Nippgen et al., 2017). These subsurface, slower flowpaths cause chemical weathering at a much faster rate than background weathering and lead to elevated salinity downstream (Ross et al., 2018). Further, streamflow out of valley fills is often higher in toxic compounds that can bioaccumulate in the food chain, such as selenium loading in riparian organisms downstream of alkaline mine drainage (Gerson et al., 2020).

Ditches in coastal wetlands were designed to remove water from wetland landscapes more efficiently. These novel landforms both lower the water table (Corman et al., 2012; Turner & Lewis, 1996) and decrease the density and size of surface water pools (Adamowicz & Roman, 2005). Ditches increase the potential for saltwater intrusion (Bhattachan et al., 2018), facilitate the creation of "ghost forests" (Ury et al., 2021), and serve as ideal dispersal vectors for invasive species (Hulme, 2009). Consequently, these systems often support unrecognized ecosystems, providing ecosystem services to surrounding communities that are poorly understood (Clifford & Heffernan, 2018).

Finally, urban landscapes represent multiple alterations to preceding landforms all towards homogenized environmental impacts. A prime example of these effects is the well documented "urban stream syndrome" (Walsh et al., 2005). Armored channels, impervious surfaces, and extensive storm drain networks lead to substantially more responsive (i.e., flashier) streams (e.g., Sillanpää & Koivusalo, 2015). These changes, in turn, lead to flashier biogeochemical signals (Blaszczak et al., 2019) and degraded stream ecosystems (Paul & Meyer, 2001; Walsh et al., 2005). Further, the relatively homogenous needs of cities with respect to water resources have led to the increase in water bodies in arid areas and the decrease of water bodies in temperate areas. As a result, research in the United States has shown that land cover has become a stronger predictor of presence of water bodies than topography or climate. (Steele et al., 2014).

Each of these examples illustrate how socioeconomic needs drive the wide variety of novel landforms observed on Earth. They further illustrate the set of environmental impacts, intended or otherwise, arising from this geomorphic change. Such environmental impacts represent both motivators for the incorporation of novel landforms into the study of geomorphology and a springboard for collaboration between geomorphologists, ecologists, biogeochemists, and others.

5 Conclusions and Future Directions

Across the globe, humans alter the geomorphic template to suit societal goals. As drivers of geomorphic change, people create novel landforms including profound alterations to bedrock structure and drainage networks. Yet, these novel landforms and landscapes are understudied by the geomorphology community. We find the need for more systematic research of novel geomorphic systems. Through this paper, we identified several future directions and research opportunities for the field:

Expanding the basis of geomorphic knowledge

- Increase capacity for research in locations outside of North America and Europe.
- Develop field sites in flatter, hotter, and drier regions.
- Synthesize ideas across disciplines on effects of novel landforms on ecology, hydrology, and biogeochemistry.

Integrating humans into the discipline

- Collaborate with other fields, such as human geography, archeology, and economics, to create a framework where humans are truly included in the geomorphic system.
- Determine the anthropogenic processes that lead to novel landforms.
- Study decision making about novel landforms as they age.

Harnessing the data revolution

- Develop remote sensing methodologies to identify the types and extent of novel geomorphology (see Tarolli et al., 2019).
- Use existing data (DEMs, National Hydrography Database, etc.) to determine how novel landforms affect drainage networks across the landscape.
- Determine how pervasive novel landforms are across the globe.

Incorporating novel landforms into the geomorphology discipline

- Determine how altered landscapes function similarly or differently in relation to more natural systems. Determine how novel systems fit within geomorphic theory.
- Ascertain the evolution of novel landforms. Over what timescales do these novel landforms maintain themselves?

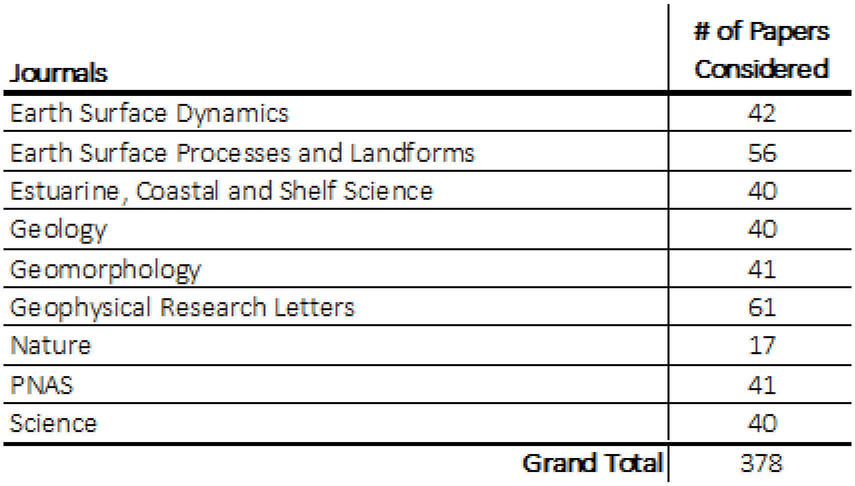
Although untested, we hypothesize that the homogenization of novel landforms has led to increasing similarity in hydrological conditions and biogeochemistry, thereby leading to the homogenization of ecosystems across the globe. We predict that through technological advances in engineering that were used to create habitable urban areas and extract resources across the world, places are more similar to one another now than before the industrial revolution and modern urbanization (Groffman et al., 2017; Groffman et al., 2014; Steele et al., 2014). Through this work, we have identified the need to place geomorphic systems within broader Socio-Environmental Systems (SES; Werner & McNamara, 2007). Future work should incorporate other fields to better understand the SES context that produces novel geomorphology and the homogenization of novel geomorphology around the world.

Our concept integrates the study of novel landforms into the field of geomorphology. Understanding the impacts of people on the landscape requires identifying, mechanistically understanding, and conceptualizing profuse novel landforms that dictate the hydrology, biogeochemistry, and ecology of our world. This paper presents a new conceptual model of the systems that create novel landforms, their persistence or abandonment with age, and their effects on the geomorphic system. This work is vital because these landforms are not the exception, but are the rule because humans directly shape the majority of the ice-free land surface. As the world continues to rapidly change and landscape alteration expands, cross-pollination among siloed sub-fields is crucial to understand how these novel systems are created and operate. The concept of novel landforms will substantially expand the domain and societal utility of the geomorphic field given the accelerating coverage of anthropogenic landscapes and data availability across the globe.

6 Methods

Literature Review

Our review used the Web of Science (Clarivate Analytics) to find the most highly cited geomorphic literature in high impact interdisciplinary, earth science focused, and geomorphology disciplinary journals (more than 1 citation; range: 1-997 citations). To determine the most cited papers in the geomorphology community, we used the following list of high impact interdisciplinary, earth science focused, and geomorphology disciplinary journals: Earth Surface Dynamics; Earth Surface Processes and Landforms; Estuarine, Coastal and Shelf Science; Geology; Geomorphology; Geophysical Research Letters; Nature; Proceedings of the Natural Academy of Science of the USA; and Science. Using the Web of Science (Clarivate Analytics), we searched for all papers using variation of the keyword *geomorph* and landforms (* denoting wild cards). We sorted the papers by the number of citations, recording the highest cited papers in each journal (378 total papers assessed). We assessed at least the first 40 most highly cited papers. Nature did not have enough cited papers to reach 40, so we included 17 papers that had at least one citation.



Journals	# of Papers Considered
Earth Surface Dynamics	42
Earth Surface Processes and Landforms	56
Estuarine, Coastal and Shelf Science	40
Geology	40
Geomorphology	41
Geophysical Research Letters	61
Nature	17
PNAS	41
Science	40
Grand Total	378

We then culled papers to retain only those that are relevant to the study. Papers not applicable to terrestrial and fluvial geomorphology, such as geomorphology on Mars, plate tectonics, or subtidal geomorphology, were not included in the literature review. We also removed papers primarily focused on models, model development, reviews or synthesis, and those focused on other disciplines (i.e., ecology). After excluding these types of papers, we ended up with a pool of 157 papers. We recorded the latitude and longitude of the study site included in the paper, estimating the location using satellite imagery if only place name and no coordinates were provided by the authors.

We coded the papers for "naturalness" based on the content of the abstract. Papers that focused on the natural aspects of geomorphology and undisturbed study sites were labeled "natural." Studies that focused on man-made impacts or alterations to geomorphology were labeled "altered." For the studies that had aspects of both, or compared natural and disturbed sites, we labeled the papers "both." Finally, we coded papers that were researching the effects of climate change on geomorphology "climate change." We separated these papers because they are a unique case where anthropogenic pressure is an indirect force on geomorphology through climate and these papers are a group of highly cited papers.

After categorizing the studies, we overlaid the study site coordinates with the World Land Cover dataset to determine climate (hot, cool, etc.), wetness (wet, dry, etc.) and landform (plains, mountains, etc.; Sayre et al. 2014). Each paper was analyzed to determine how many places were included in the research. If there were multiple study locations, each site was analyzed separately for climate, landform, and wetness. Site locations that were over water due to latitude and longitude accuracy were moved to the closest terrestrial area. If the study was about coastal wetlands, we labeled them as coastal rather than moving the site location. Through the results of this analysis, we determined how and where natural and anthropogenic geomorphologies are studied across the globe. These classes provided globally consistent categories for comparison across continents. Finally, we used the National Land Cover Database (Dewitz and U.S. Geological Survey, 2021) to determine degree of alteration of study sites in North America (Fig. 1, inset).

Terrain Analysis Methods

A combination of high-resolution topographic data, vector data delineating coastal wetland islands, and point data designating outlet points of study watersheds were used to compare across all 3 case study sites. We used: 1) hypsometric curves of case study site subunits (wetland islands or watersheds) and 2) site-specific metrics of drainage network characteristics. Digital Elevation Models (DEMs) for the Southern Piedmont site (Calhoun Critical Zone Observatory) were 1 m. resolution raster elevation data derived from LiDAR point clouds acquired by the National Center for Airborne Laser Mapping (NCALM) on February 2016 (https://portal.opentopography.org/raster?opentopoID=OTSDEM.072016.26917.2). Watershed outlets were mapped by physical survey using survey-grade GPS. DEMs for the Atlantic coastal site are derived from multiple sources including the 2016-2017 NOAA NGS Topobathy Lidar DEM: Coastal South Carolina (https://www.fisheries.noaa.gov/inport/item/53372) and 2014 NOAA Post-Sandy Topobathymetric LiDAR: Void DEMs South Carolina to New York (https://coast.noaa.gov/htdata/raster2/elevation/Post_Sandy_DEM_2014_4967). Wetland island polygons were derived from the US Fish and Wildlife Service's National Wetland Inventory (NWI).

For the two upland sites (Southern Piedmont and Appalachian Mountains), watersheds were delineated from DEMs using Whitebox tools (https://www.whiteboxgeo.com/) and its frontend R package, *whitebox* (https://giswqs.github.io/whiteboxR/). DEMs were preprocessed by breaching depressions (*wbt_breach_depressions*) internal to the DEM to maintain downgradient flow. Then a flow accumulation raster was created using the DInf algorithm (*wbt_d_inf_flow_accumulation*) for the Southern Piedmont site and the Appalachian mountains site. Finally, watersheds were delineated at each upland site using the previously acquired outlet points and the flow accumulation rasters for each (*wbt_watershed*).

We classified each watershed or wetland island as “natural” or “novel” based on the presence or absence of novel landforms within each. For the mountain site, this meant a known history of MTM. For the piedmont site, this meant the presence of highly eroded gullies. For the coastal site, this meant the presence of highly linear ditches in the immediate area of the island. We calculated hypsometric curves for each watershed (upland sites) or wetland island (coastal site). Generally, these curves show the percentage of a geographic region’s area above a given elevation; for our analysis, elevations were normalized to facilitate cross-site comparison. For each individual watershed or island, elevation was normalized between 0% and 100% of its max elevation. Then, for each 1% increment of relative elevation, the percent of the watershed or island area above that area was calculated. These curves are then plotted together for each site, classified by natural or novel, and shown in Figure 2a, c, e.

We compared drainage density between natural and novel watersheds (Figure 2b) at the Appalachian site by first delineating drainage channels using the flow accumulation rasters for each watershed. Drainage density for each watershed was then calculated as the total length of drainage channel divided by watershed area.

Channel head initiation thresholds at the piedmont site were also compared between natural and novel watersheds (Figure 2d). Geomorphic channel heads were identified in each watershed through a mixture of field surveying and manual delineation via hillshade raster derived from LiDAR DEMs. These points were defined as the upstream most point where flow and erosion processes could be observed within defined channel banks. Flow accumulation area at each point was extracted from flow accumulation rasters for each watershed.

Finally, we compared the density of channel outlets from wetland islands between natural and novel islands (Figure 2f). For each wetland island, outlets were manually counted as an observable, open-water connection between surrounding coastal water bodies and the island interior. We confirmed each outlet in ArcGIS using a combination of satellite imagery to observe open water and LiDAR DEMs to confirm elevation below mean tidal water level. Outlet density was explored as the number of outlets relative to wetland island area.

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Data Availability Statement

The citation data used for literature review in the study are available at Harvard Dataverse via https://doi.org/10.7910/DVN/31MDDO with a CC0 1.0 Universal license.

Author Contributions

This paper was a collaborative effort. All coauthors contributed equally to the development of the ideas presented in this paper, conducting the literature survey, analyzing the case studies, and writing and editing the manuscript.

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