Role of Theory and Geocomputation in Describing and Simulating Landscape Performance

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Abstract

This paper summarizes the current state-of-the-art in geomorphometry and describes some of the innovations that are imminent and will be required to push digital terrain modelling forward in the future. This is a special moment in time given the new opportunities afforded by advances in computing on the one hand and the explosive growth in the numbers and kinds of elevation data sources on the other hand. The development and adoption of new methods and the coupling of theory and geocomputation will provide new opportunities to describe and simulate landscape performance, which refers here to how form and function (i.e. pattern and process) are likely to produce different outcomes in different settings.

Keywords: Geomorphometry, Digital Terrain Modelling, Landscape Performance.

1. Introduction

Great strides in digital terrain modelling have occurred during the past 50 years, spurred on six developments. The latter includes new sources of digital elevation data, the increasing use of theory to guide digital terrain modelling workflows, specification of many new land surface parameters, identification and extraction of landforms and other land surface objects, improving characterization of error and uncertainty, and development and sharing of new computer code to facilitate and support digital terrain modelling workflows. The rate of development has sped up during the past 15 years as well, motivated by pressing environmental challenges at the meso- and topo-scales and the rapidly evolving geocomputation resources that are now available to support digital terrain modelling applications.

The remainder of this paper has three parts. The first summarizes the current state-of-the-art, the second describes some of the innovations that are imminent and will be required to push digital terrain modelling forward in the future, and the third offers some conclusions and two examples of how the coupling of theory and geocomputation affords us new opportunities to describe and simulate landscape performance. The latter refers to how specific processes (i.e. saturated overland flow) produce different outcomes given different drivers (i.e. precipitation events) and landscape conditions (i.e. ground cover, antecedent moisture) that will likely vary over space and time. This information is helpful in both descriptive and prescriptive ways – as illustrated by the work of Kongjian Yu – that seeks to enlist the help of natural processes and systems (i.e. ecosystem services) to achieve specific outcomes (Saunders, 2012).

2. Current State-of-the-Art

Most digital terrain modelling applications in biogeography, climatology, ecology, geology, geomorphology, hydrology, pedology and natural hazards are scale-specific and the results will vary with the scale over which they are cast. The user is then left with the dilemma that they cannot determine whether the failure of a model to fit perfectly is due to the model itself, or to the relatively 'coarse' resolution of the elevation data, or both (Goodchild, 2011). In addition, relatively little attention has been given to the topological relationships among topographic features and this state-of-affairs helps to explain why all computed surface networks are scale-dependent, fuzzy, and vague and why their undisputed calculation remains elusive (Clarke and Romero, 2016).

The transition from cartographic to remote sensing data sources and the associated consequences – the large coverage and fine resolutions afforded by many of these new DEMs – has brought numerous changes to the typical digital terrain modelling workflow (Fig. 1). The potential benefits are enormous. The ASTER and SRTM DEMs, for example, provide coverage over much of the globe at a 30 m resolution that was only available for small and moderate-sized catchments until relatively recently. Similarly, LiDAR provides large numbers of high-density mass points that, if processed appropriately, can provide 1-3 m DEMs with high vertical accuracy and the preservation of the terrain structure (i.e. the shape).

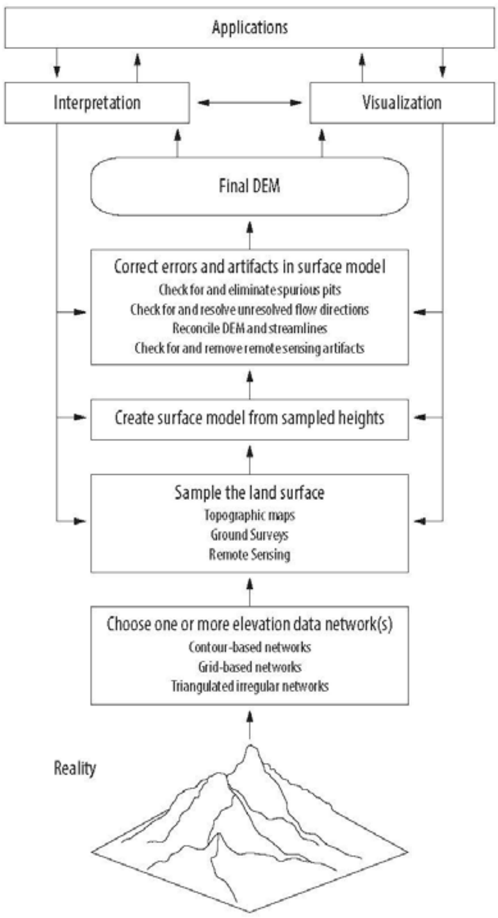

Fig. 1. The main tasks associated with digital terrain modelling. Source: Hutchinson and Gallant (2000, p. 30).

This transition means that most scholars and practitioners will not collect their own source data and prepare their own DEMs going forward and this will place an increased emphasis on the provenance of both the original data and the methods applied to them and the expertise of the people contributing the DEMs. This focus on provenance will improve the reproducibility and encourage users to consider questions surrounding the credibility (i.e. fitness-of-use) of the content for the task(s) at hand (McKenzie et al., 2016). Some scholars and practitioners will use unmanned aerial systems (i.e. drones) to collect their own elevation data and these systems will afford new opportunities to delineate how the form and function of specific landforms and landscapes vary over space and time.

The calculation and use of land surface parameters has long constituted the heart of geomorphometry (e.g. Moore et al., 1991, 1993; Wilson and Gallant, 2000; Hengl and Reuter, 2009) and there is now more than 100 primary and secondary land surface parameters in common use (Wilson, 2018). The majority are primary parameters derived from square-grid DEMs that measure site-specific, local or regional characteristics without additional input. The secondary parameters incorporate ≥2 of the primary parameters and additional inputs in some instances, and focus on water flow/soil redistribution or energy/heat regimes. Many of these land surface parameters incorporate flow direction and therefore make use of one or more of the 20-plus flow direction algorithms proposed during the past 30-plus years. Several of the newer algorithms combine square-grids and triangulated irregular networks (TINs) to avoid the shortcomings associated with square-grid DEMs and to take advantage of the additional discretization provided by TINs. However, it is difficult to assess the efficacy of these flow direction algorithms, and their impact on flow accumulation and the other land surface parameters that incorporate them. Buchanan et al. (2014), for example, recently calculated topographic wetness using >400 unique approaches that considered different DEM resolutions, the vertical precision of the DEM, flow direction and slope algorithms, smoothing vs. low-pass filtering, and the inclusion of relevant soil properties, and compared the resulting topographic wetness maps with observed soil moisture in agricultural fields.

Some applications have also focused on the extraction and classification of landforms and land surface objects. Fuzzy classification methods have featured prominently in these applications because many of the land surface objects and landforms that are of interest have fuzzy boundaries. Some studies have attempted to automate and extend Hammond's (1964) map of repeating landform patterns for the conterminous U.S. to the globe (e.g. Karagulle et al., 2017). Dragut and Eisank (2011) have borrowed concepts from remote sensing and data science to first segment the DEM and then classify the objects to avoid the problems of working directly with the DEM grid cells when extracting and classifying landforms and other land surface objects.

A number of recent applications have also tackled sources of error, the various ways uncertainty can be estimated and handled in terrain modelling workflows, how this knowledge can be used to assess 'fitness-for-use' in specific applications, and the new opportunities for multi-scale analysis and cross-scale inference afforded by the increasing availability of DEMs across a broad range of scales. Five exemplary case studies show how the measurement of error and uncertainty accompanying terrain modelling workflows can be used to improve our understanding of: (1) predictive vegetation modelling (Van Niel and Austin, 2009); (2) soil redistribution resulting from water erosion (Temme et al., 2009); (3) how catchment area calculations, slope estimates and numerical simulations of landscape development (Shelef and Hilley, 2013); (4) how soil-water-vegetation interactions in the LPJ-GUESS dynamic ecosystem model (Tang et al., 2015) are influenced by the choice of flow direction algorithm; and (5) how a new sub-grid TOPMODEL parameterization and the associated uncertainties influence the modelling of the spatiotemporal dynamics of global wetlands (Zhang et al., 2016). These works help to inform best practice and more studies like these will be required in the future to inform and support new digital terrain modelling applications.

All of the aforementioned studies have been enabled by software the supports the calculation of land surface parameters and the extraction and classification of landforms and other land surface objects. Six systems – ArcGIS, GRASS, QGIS, SAGA, TauDEM, and the Whitebox Geospatial Analysis Tools – stand out today because of the large numbers of terrain tools included, the availability of GIS functions, the large numbers of data formats supported, and their high levels of interoperability.

3. New Opportunities and Needs

3.1. Provenance, Credibility, and Application-Context Knowledge

The rapid growth of the web and all this entails (i.e. web portals for sharing geospatial datasets and the provision of software-as-a-service), coupled with advances in our knowledge error and uncertainty and how these concepts can be used to clarify the 'fitness-for-use' of digital terrain modelling tools and data for specific applications, bring provenance and credibility to the fore. These elements are captured by metadata in the spatial sciences and it will be important for the geomorphometry community to adopt and use metadata to describe digital terrain modelling methods and datasets moving forward. However, the traditional metadata schema may be necessary but not sufficient because the typical digital terrain modelling workflow usually entails much work to prepare the final DEM (Fig. 1). It is difficult to include all of this knowledge in the metadata, and Qin et al. (2016) recently showed how case-based formalization and reasoning methods can be used to acquire this 'application-context' knowledge (as he and his co-authors referred to it) (Fig. 2). They selected 124 cases of drainage network extraction (50 for evaluation and 74 for reasoning) from peer-reviewed journal articles and used these cases to determine the catchment area threshold for extracting drainage networks.

Looking beyond these new methods, replicability and reproducibility should be incorporated into the design and implementation of future digital terrain modelling software by adopting the best practices for documenting and sharing research from data to software and provenance recently proposed by Gil and colleagues (e.g. Garijo et al., 2013; Gil et al., 2016; Stodden et al., 2016).

3.2. Rediscovering and Using What We Already Know

The development of global elevation datasets has brought into focus what geographers have long known; namely, the need to choose your map projections and coordinate systems carefully to suit the geographic extent of the study area of interest. The general strategy should be one in which spheroidal equal angular DEMs are chosen for large study areas (i.e. the globe, continents, and catchments of large rivers) and planar square-grid DEMs are chosen for small and moderate-sized catchments. Most of today's methods were developed for planar square-grid DEMs, but some algorithms have been proposed for calculating land surface parameters for spheroidal equal angular DEMs (e.g. Guth, 2009). The burgeoning interest in climate change impacts and the availability of new digital elevation data products that span the entire globe will encourage the development of new digital terrain modelling algorithms that work with spheroidal DEMs in the next few years (e.g. Florinsky, 2017, 2018).

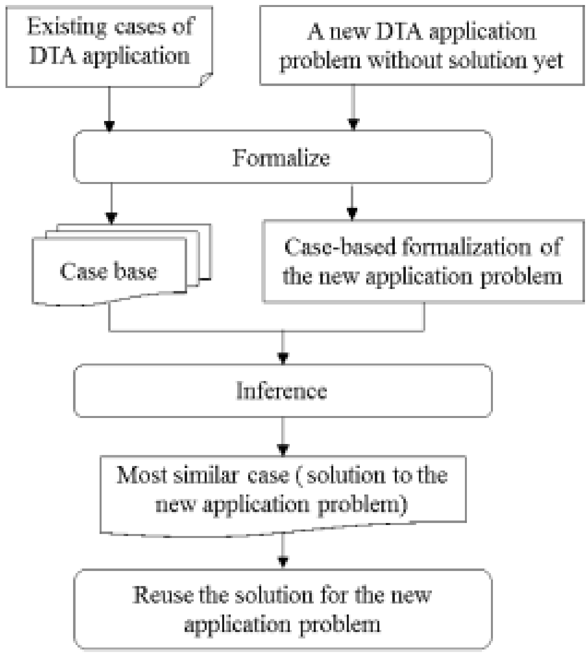

Fig. 2. Structure of the case-based formalization and reasoning method for digital terrain analysis application-context knowledge. Source: Qin et al. (2016, p. 3381).

3.3. Developing New Digital Terrain Modelling Methods

The continued development of new digital terrain modelling methods, like those noted in the previous section and the three examples highlighted below, is likely to yield substantial benefits as well. The three examples challenge the popular assumptions that have persisted for 30-plus years, due to the lack of high quality elevation data, limited computing resources, and our tendency to ignore the effects of scale.

All three of the studies described below propose potentially new and useful methods. For example, Krebs et al. (2015) recently proposed a new method to assess the vertical transverse and profile curvature. This method provides new opportunities to measure and visualize these two land surface parameters over a large range of scales. Byun and Seong (2015) proposed a new maximum depth-tracing algorithm to extract more accurate stream longitudinal profiles using depression-unfilled DEMs. Buttenfield et al. (2016) compared planar distance with eight measures of surface-adjusted distance to check whether or not the common assumption, that the improvements in distance estimation are so small that surface adjustment is not warranted, is true (or not) for specific applications.

3.4. Adopting New (Geo-) Computational Methods

The rapid advances in computational power and changing models of computing (i.e. cloud computing, cyberinfrastructure, interoperability, software-as-a-service) offer new opportunities to develop analytical tools and thereby expand the geographic extent and heft of future digital terrain modelling projects. The four studies below illustrate the potential benefits of such methods.

The first is the TerraEx (Netzel et al., 2016) application, which is a freely available, full service web application to locate landscapes that are similar to a user-selected query and doubles as a convenient portal to support the distribution of 3 arc-second DEMs and global maps of geomorphons and terrain relief. The second is a scalable high performance topographic flow direction algorithm developed by Survilla et al. (2016) which eliminates the bottleneck caused by flow direction, one of the most computationally intensive functions in the current implementation of TauDEM (Tarboton, 1997). This new algorithm essentially transforms a local operation into a global operation to route flow across flat regions, by first identifying the flat areas and then using this information to reduce the number of sequential and parallel iterations needed to calculate flow direction. The third is a CyberGIS integration and computation framework to support high-resolution continental-scale flood inundation mapping as part of the U.S. National Water Model (NWM) project (Liu et al., 2018). The fourth and final example by Qin et al. [2017] proposes an efficient solution to calculate the differential equation for specific catchment area (SCA) proposed by Gallant and Hutchinson (2011) from gridded DEMs for small- and moderate-sized catchments.

3.5. Clarifying and Strengthening the Role of Theory

The emergence of fine-resolution elevation data, such as LiDAR, also provides new opportunities to assess fundamental questions about landscape form and evolution in geomorphology as well as other domains. There are two primary ways to proceed here. The first uses theory to guide the choice of workflow, whereas the second relies on experiments to test one or more of our existing theories.

The first approach seeks to take advantage of our existing knowledge of how processes work. Clubb et al. [2014], for example, have proposed a new algorithm for predicting channel head locations. This algorithm is partly informed by the stream power equation, which is a detachment-limited model that proposes that the fluvial incision rate is proportional to stream power that, in turn, represents the energy expenditure of the flow. The channel head locations are fundamental for predicting river discharge and flood behaviour (Fig. 3).

The second approach noted above seeks to test existing theory and can be illustrated using the work of Jensco and McGlynn (2011) which tested the relationship between upslope contributing area and the existence and longevity of the hillslope-riparian-stream shallow groundwater connectivity for a series of transects and the stream network for several watersheds in Montana (Fig. 4). The results showed how the internal catchment landscape structure acts as a first-order control on runoff source area and catchment response in these types of landscapes.

3.6. Developing and Embracing New Visualization Methods

The methods to visualize digital terrain modelling results have not kept pace with the rapidly evolving computational resources and the availability and use of fine resolution DEMs that cover large areas. This is an area of ongoing work and the examples highlighted below illustrate three promising areas for innovation.

The first is the various map generalization projects, including those funded as part of the U.S. National Elevation Dataset research program (e.g. Stanislawski et al., 2015). The second is the new tangible geospatial modelling system proposed by Petrasova et al. (2015) which supports the exploration of the impacts of various human interventions on physical and digital models of the Earth’s surface simultaneously.

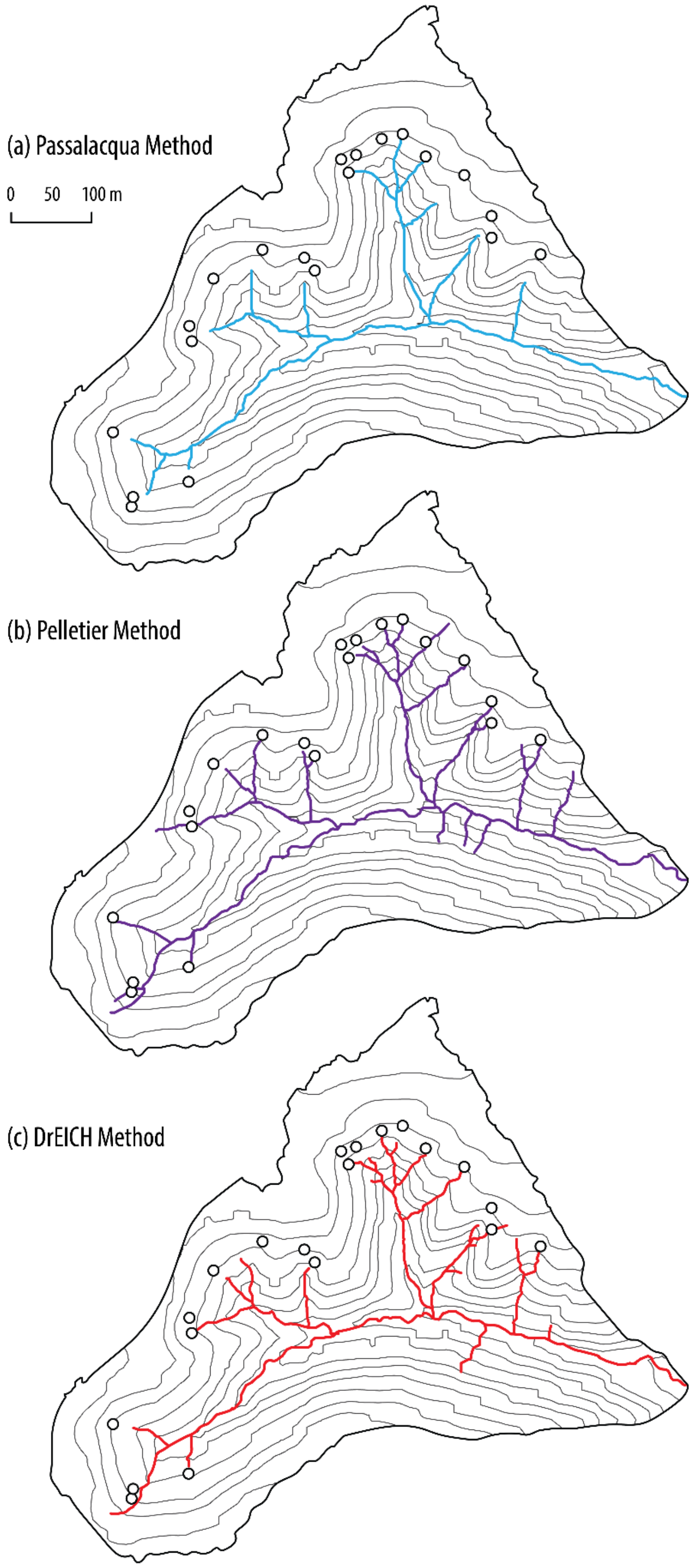

Fig. 3. Contour maps showing the results of using three methods to predict channel head locations for a catchment in Indian Creek, Ohio. The circles indicate mapped channel heads and the contour interval is 10 m. The three maps show the stream networks resulting from the Passalacqua et al. (2010), (b) Pelletier (2013), and (c) DrEICH (Clubb et al., 2014) methods as well. Source: Modified from Clubb et al. (2014, p. 4294).

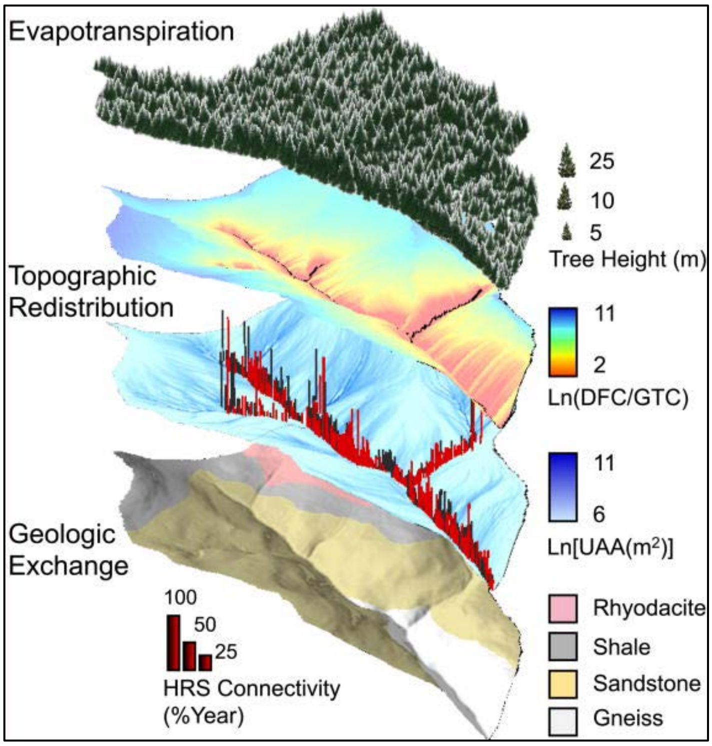

Fig. 4. A conceptual diagram illustrating the hierarchical controls on runoff generation across 11 Tenderfoot Creek Experimental Forest catchments. Combinations of median tree height, ratio of flow path length and gradient, and sandstone overlain by upslope accumulated area (UAA) > 5,000 m^2 explained a significant amount of the variability in catchment streamflow yield per unit connectivity (CON_{yield}) across the flow states. The ratio of flow path length and gradient (DFC/GTC) and vegetation height were significant predictors at the annual time scale. The variability in CON_{yield} during wet and transitional periods was described by DFC/GTC. During base flow the percentage of sandstone overlain by UAA > 5,000 m^2 was the only significant predictor of CON_{yield}. Source: Jencso and McGlynn (2014, p. 13).

The third and perhaps most promising of these three developments uses virtual reality and mobile augmented reality along with high quality 3D scenes and a variety of state-of-the-art digital terrain modelling outputs to explore the Earth's surface environments (e.g. Mower, 2009; Kim et al., 2012, Fedorov et al. 2016).

3.7. Developing High-fidelity Multi-resolution DEMs

The importance of multi-scale analysis and cross-scale inference will grow in the future as well. These applications rely on the availability of high-resolution DEMs and methods to build such DEMs. The need or desire for accurate topographic representation across a relatively narrow range of geographic scales has motivated most of the work thus far. This provides two challenges.

The first concerns the types of surfaces represented with some of the new radar and stereo optical imagery sources. The default surface is the top of the structures or vegetation and many, but not all, geomorphic applications will need a bare earth DEM. However, this is not true of biological applications and Guo et al. (2017) recently demonstrated the use of airborne LiDAR data for regional mapping of 3D vegetation structure to support biodiversity monitoring as well as wildlife habitat mapping and species distribution modelling.

The second is the need for high fidelity, multi-resolution DEMs that work with global environmental simulations. These applications often adopt sub-grid schemes to express topographic heterogeneity for empirical parameterization rather than accurate topographic representation (i.e. maps and similar kinds of visualizations) (Duan et al., 2017). The traditional focus on the latter outcome may lead to greater uncertainties and bias in these types of simulations.

4. Conclusions

The seven innovations highlighted in the previous section show how the adoption and use of modern computing platforms can modify the digital terrain modelling workflows that many of us have used with standalone personal computers during the past 30-plus years and thereby advance our craft. These innovations will encourage the pursuit of digital terrain modelling projects that will produce "actionable" knowledge and outcomes. The final two applications described below show how the adoption of these innovations and coupling of theory and geocomputation afford us new opportunities to both describe and simulate landscape performance over multiple scales.

In the first study, Woodrow et al. (2016) examined the impacts of DEM grid resolution, elevation source data, and conditioning techniques on the spatial and statistical distribution of field-scale hydrological attributes for a small agricultural watershed in Ontario, Canada. The results showed how the decision to use one DEM conditioning technique over another and the constraints of available DEM data resolution and source can greatly influence the modelled surface drainage patterns for individual fields. These kinds of results can help with the design of best management practices for reducing soil erosion and runoff contamination within agricultural watersheds and thereby in helping to manage nonpoint source pollution at the source.

The second application is the U.S. National Water Model (NWM) project. This large, multi-disciplinary project forecasts streamflow over the continental U.S. at intervals of 1 hour, 18 hours, 10 and 30 days for 2.7 million stream reaches. The NWM uses the WRF-Hydro and Noah-MP land surface models to simulate meteorological conditions and terrestrial hydrology. Several ArcGIS Hydro and TauDEM (Tarboton, 1997) terrain modelling functions are included in WRF-Hydro and these provide the essential 'glue' and are used to route water across the land surface to the nearest stream channel. The NWM outputs can be accessed via interactive maps (http://water.noaa.gov/map) and once incorporated in the daily workflows of the relevant agencies (public safety, water resources, etc.), they will fundamentally change the ways in which local, state, and federal agencies prepare for and anticipate floods and related water challenges.

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