Challenges in Continental River Dynamics

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Abstract

Continental River Dynamics (CRD) is herein defined as modelling the flow dynamics in all channels of a continental-scale river basin using the physics-based Saint-Venant equations. At the boundary of hydraulics and hydrology, CRD requires significant collaborative efforts to make new progress. Six constraints and seven challenges are identified in the areas of dynamics, dimensionality, resolution, uncertainty, model coupling, and data availability. Three key short-term needs for CRD are identified as (1) scaling up Saint-Venant river models to continental scales, (2) standards for integrating river and hydrology models, and (3) methods for effective use of lidar data and synthetic methods for approximating geometry for 1D dynamic models. An over-arching need for comprehensive data collection programs for river geometry is discussed.

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1. “A river runs through it”

1.1. Motivation

There are new challenges and opportunities in modelling large river networks – a discipline we might call “Continental River Dynamics”\(^1\). CRD is part of continental hydrological modelling, where new research is critical to make effective use of hyperresolution data (Wood et al., 2011). This view is not without its critics (Beven and Cloke, 2011), but nevertheless provides an underlying motivation for this commentary exploring the constraints and challenges for the next generation of

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\(^1\)Suggested by D.R. Maidment, pers. comm.
CRD models. Herein, *constraints* are underlying limitations of physics, numerics, and data that are the “box” around our present models. *Challenges* include changes in attitudes towards dynamic modelling, needs for new institutional support, and research opportunities both inside and outside the box.

1.2. CRD definition

The goal of CRD (as defined herein) is modeling all channels of a 10th to 12th Strahler stream-order basin using physics-based flow equations with sufficient streamwise spatial resolution to capture flow dynamics. This definition implies *dynamical* equations for both mass and momentum conservation, which is not to say that such equations are required for every hydrological purpose. Indeed, where calibrated reduced-physics models are deemed sufficient, they might be considered within a broader classification of Continental River *Modeling*. Thus, CRD is narrowly defined as a sub-area of CRM focused on conditions wherein time-accurate dynamics are important and cannot be modeled with reduced-physics equations. This includes processes such as timing and spatial extent of overbanking flows, backwater effects of flooding, and rapid erosion/aggradation that alters channel morphology.

What constitutes “sufficient” resolution for dynamic equations in continental-scale modeling is an open question that depends on the dynamical features of interest, but if the (Wood et al., 2011) hyper-resolution definition of $O(10^3)$ m is accepted as a hydrological goal for capturing spatial variability, then river hydraulics requires similar scales or one order finer to capture nonlinearities associated with streamwise gradients with landscape feedback.

1.3. CRD at the intersection of hydrology and hydraulics

Landscape models require an artful interplay between representation of catchment (hydrologic) and river (hydraulic) processes. Catchment-based models (e.g. David et al., 2009; Goteti et al., 2008) have a key question: how many catchments do you lump together before you define a river inflow? Equivalently – what is the lowest stream order modeled as a unique channel? Lumping catchments together creates a river network with fewer small tributaries. Similarly, a distributed model connects its overland flows to a river network (Beighley and Gummadi, 2011; Collischonn et al., 2007; Paiva et al., 2011) or ignores the river network entirely with a sheet flow approximation (Croley and He, 2005; Cunge et al., 1980; Ducuarne et al., 2003; Nijssen et al., 1997; Niu et al., 2011). The hydraulic/hydrology splitting is influenced by the availability of data, high-speed computers, models, and (perhaps most of all) the modeler’s experience. Thus, a *hydrological modeler chooses where*
hydrology ends and hydraulics begins. This choice has consequences and provides an over-arching motivation for CRD:

Motivation: When rivers are absorbed into a landscape model, a relatively well-understood process (channel flow) is modeled by a more complex abstracted process (landscape flow) through calibration, which limits the range of model validity.

The following sections explore six principal areas at the intersection of hydraulics and hydrology: dynamic modelling (§2); model dimensionality (§3); model resolution (§4), uncertainty (§5); coupling with hydrologic models (§6); and data availability (§7). Six constraints and seven challenges are proposed for advancing CRD.

2. Why dynamics?

Constraint 1: Neglected model physics that affect real-world behaviors are represented in reduced-physics models by calibrating the wrong process.

Dynamics in CRD implies solution with momentum (force-based) equations – e.g. the Saint-Venant equations – which are not consistently used in hydrology. Reduced-physics equations (e.g. kinematic wave) are often considered suitable for many river branches (e.g. Vieira, 1983; Tsai, 2003; Mejia and Reed, 2011a). Such arguments presuppose flows are always near the conditions used to justify reduced physics. However, a CRD model covering a wide range of extremes should not assume that branches of a particular stream order, slope, or mean annual flow are adequately represented with reduced physics. Indeed, it seems a daunting task to prove reduced-physics validity under flow conditions ranging from flood-of-record to drought-of-record.

Dynamic river models are not widely used in state-of-the-art large-scale hydrology. This point is illustrated by three recent studies: the Solimões River subbasin of the Amazon (Paiva et al., 2011, 2013), the entire Amazon basin (Beighley et al., 2009), and the entire Texas river network (David et al., 2013). Only 1/3 of the Solimões reaches were modeled with the dynamic Saint-Venant equations (2500 computational elements at ~10 km spacing), whereas 2/3 of the basin was modeled with kinematic wave equations. Beighley et al. (2009) used a combination of kinematic wave and Muskingum-Cunge methods with 6000 elements in the drainage network, while David et al. (2013) used a Muskingum model with 68000 computational reaches at ~2 km resolution. In contrast, Liu and Hodges (2013) showed that more than $10^5$
elements at O(100) m resolution for $15 \times 10^3$ km of a river network can be readily modeled with a common desktop workstation using a dynamic model employing the latest computational techniques.

The principal difference between dynamic and reduced-physics models is the former requires cross-sectional area and depth data, which adds to model complexity, computational costs, and data requirements. Computational cost is sometimes used as a justification for applying reduced physics in large networks (e.g. Paiva et al., 2013). Also, where channel data is lacking, there is a temptation to use reduced physics so that model requirements match data availability. However, data availability should not be used as a reason to *a priori* reduce the modeled physics: the dynamic equations can be readily applied with either approximated or calibrated geometry when channel data is lacking. Thus, a challenge for the river modelling community is changing its attitude towards dynamic models:

**Challenge 1:** The application of reduced-physics models rather than dynamic models should require more than simple assertions of prior usage and successful calibration. This is not a call for full dynamic modeling for all purposes – but instead to quantitatively evaluate what we are missing with reduced-physics models. Where dynamics are important, a calibrated reduced-physics model can only match observations by making non-dynamic processes stand in for dynamic effects, i.e. getting the “right” answer for the wrong reasons.

### 3. Are 1D models still relevant?

**Constraint 2:** Full 3D modelling of continental scale networks is impractical, full 2D modelling is physically inconsistent, and 1D modelling cannot capture overbanking events.

Dynamic modelling can be conducted in 1D, 2D, or 3D. Although hydraulic/hydrological researchers perhaps intuit that 3D river models at continental scales will be impractical for the near future, some research agencies are skeptical about funding work with 1D models, which are deemed insufficiently “transformative.” A question has been posed: *since the atmosphere and oceans have been modeled at 3D for more than two decades, why are we still working with rivers in 1D rather than 2D or 3D?* Data availability (§7) certainly plays a role, but more important are (1) the state-of-the-art and (2) the fundamental differences between atmosphere/oceans and river networks that makes such
comparisons misleading.

In contrast to the large-scale studies with mostly reduced physics discussed in §2, the state-of-the-art for 1D Saint-Venant models over the last three decades has evolved studying short river reaches and small networks, typically \( \leq O(10^2) \) river km (e.g. Trigg et al., 2009; Zhu et al., 2011; Wu et al., 2004; Kim et al., 2012). Such models investigate flooding, aquatic habitat, and fundamental issues of fluid mechanics and modeling. Despite the wide variety of Saint-Venant solution methods (e.g. Rosatti et al., 2011; Crnkovic et al., 2009; Devkota and Imberger, 2009), none have demonstrated stable, efficient dynamic simulations of unsteady flow in a large network at continental or even regional scales. In scaling-up Saint-Venant models for continental networks, we simply do not know what problems will be encountered. The fact that rivers are networks creates a topological issue without any parallel in atmosphere/ocean models: problems at a single river cross-section can form a pinch point with numerical errors rapidly cascading through large sections of the network. In contrast, errors in a single computational cell of an atmosphere/ocean model cannot control on a large section of the domain – the modelled flow will merely diverge about a problem point. These scaling-up issues seem to be relatively unrecognized in the broader hydrological community, as encapsulated by the limited discussion of hydraulics in Wood et al. (2011), which only noted that solution of “the Saint-Venant equations appears to be computationally feasible at hyperresolution but will require more precise channel geometry information.”

Differences in the scale relationships for rivers and atmosphere/ocean models provide insight into why 2D dynamic models are not the logical next step for modelling large-scale river networks. For atmosphere/ocean circulation, large-scale quasi-2D motions are affected, but not constrained, by the 3D boundary. The boundary variability is at smaller scales than the large circulations, so orography/bathymetry principally affects and constrains the vertical scales of motion. Thus, atmosphere/ocean 3D models have horizontal velocities \((u, v)\) that are significantly larger than vertical velocities \(w\), i.e. \(u, v \gg w\). In rivers the streamwise flow \((u)\) is affected (but not constrained) by bathymetry while both the cross-stream \((v)\) and vertical \((w)\) velocities are so constrained. Thus, for rivers \(u \gg v, w\), implying that 1D is the natural first-order approximation. However, river flows for deep, narrow channels in perennial rivers have different velocity scales than wide, shallow overbanking flows and braided streams: i.e. \(v \sim w\) and \(v > w\), respectively. Thus, 2D is the natural dimensionality for overbanking flows, but a 2D solution in a confined channel is inconsistent; i.e. keeping the cross-channel inertia in a model while simultaneously neglecting verti-
cal inertia of similar scale cannot be justified by the physics. It follows that 2D models are inappropriate for an entire river network.

Arguably, 3D dynamic models could be consistently used for an entire river network, but such models require complete geometric data (§7) and a model time-step that captures the non-hydrostatic vertical accelerations. To provide a feeling for the computational scales, a state-of-the-art 1D dynamic model of the Mississippi River network with 100 m element spacing would require $O(10^7)$ computational elements and a model time-step of $O(100)$ s for $O(10^{12+})$ computations per year of simulation, which is within the range of present tera- and peta-scale computing. However, to model the system in 3D would require $O(10)$ m streamwise spacing with $O(10)$ grid cells in the vertical and cross stream directions, along with an $O(1)$ s time step. The overall computational effort would increase by a factor of $10^5$, putting a simulation into the exa-computing range. For the next decade or further, it seems unlikely that exa-scale computing can be made broadly available within hydrology; thus advances 3D river network modeling cannot be expected to transform continental scale modelling in the absence of a major paradigm shift in the growth of computational power.

Synthesizing the above observations, advancing CRD will likely require 1D, 2D, and possibly 3D models in combination, rather than one method exclusively. As immersed river geometry changes through both time and space, the appropriate model dimensions for each river reach will also change with time and space. A 1D hydrostatic model is sufficient for narrow, deep river channels, whereas wide, shallow and overbanked channels require 1D-2D hybrids (e.g. Finaud-Guyot et al., 2011; Chen et al., 2012; Kuiry et al., 2010) or full 2D models (e.g. Fewtrell et al., 2011; Legleiter et al., 2011; Gallegos et al., 2009). Furthermore, we might hypothesize the existence of “hot spots,” such as some river junctions, where 3D non-hydrostatic processes play critical and controlling roles in the flow.

Challenge 2: Dynamic models should smoothly transition from 1D to 1D/2D to 2D and 3D; the model configuration should automatically adapt in both space and time as appropriate for the physics.

4. Model resolution

Constraint 3: All sub-element physics must be represented either explicitly or implicitly (through calibration) in empirical sub-models.
A critical question for CRD is how computational element spacing should vary throughout a network as a function of channel geometry, and how this choice affects the model uncertainty (§5). From a physics perspective for a dynamic model, the “optimum” 1D element length is some multiple of the bankfull width (Castellarin et al., 2009). Lidar and multi-beam sonar provide finer resolution data, but there is no consensus on up-scaling this data in coarser resolution models while capturing the implied physics. Directly using 1D cross-sections at the $\leq O(1) \text{ m}$ resolution of lidar/sonar is questionable – i.e. with cross-section averaging, gradients over distances smaller than the channel width cannot be accurately simulated. The selected element spacing constrains the model by controlling the physical scales represented in sub-element models (typically requiring calibration).

In most large-scale 1D models, all sub-element physics are wrapped into a single drag term – typically the overworked Manning’s $n$. Non-hydrostatic pressure drag driven by fine-scale bathymetry and helical flows driven by channel curvature (Hodges and Imberger, 2001) are just two of the effects layered onto the roughness parameter during calibration. As a result, roughness is functionally dependent on the element size rather than simply the bed material and must be calibrated to obtain a best fit to measured data at the selected model resolution (e.g. Vidal et al., 2007). This problem has been previously recognized, but existing data and models are unable to separate the different processes within a 1D model (e.g. De Doncker et al., 2009).

If hyperresolution data can be made broadly available (§7), we will have a new opportunity for CRD to move beyond this “calibration of roughness” paradigm. By combining detailed bathymetric data with modelling at reach scales (e.g. Legleiter et al., 2011; Aggett and Wilson, 2009), we should be able to develop models of sub-reach processes. The optimum element spacing in a 1D model should be determined by these sub-reach process models. However, the traditional approach to cross-section spacing in hydraulic models implies smaller elements in higher-order streams, which leads to increased computational efforts for small features – an undesirable effect for continental scales.

Challenge 3: A new methodology is needed to quantify the required computational element scale at different stream orders, along with the resulting relationships between model resolution and calibrated processes.

5. Model uncertainty

Constraint 4: Uncertainties of a landscape model combine with uncertainties of a river network model to affect the
accuracy achievable in CRD.

Selection of the model resolution (§4) engenders a trade-off: finer resolution requires more computational power, while coarser resolution requires better models for the sub-element processes. Both fine and coarse models require better data representing the sub-element bathymetry. In either case, uncertainty in the underlying river geometry may prove the defining issue. Uncertainty is a recognized problem for all hydrological modelling, particularly effects of spatial heterogeneity on process representation (e.g. Beven and Cloke, 2011, and citations therein).

In overland flow modelling the fundamental uncertainties are arguably *aleatoric*, i.e. associated with inherent variability of the system. In contrast, the dominant uncertainties for river hydraulic modelling are *epistemic*, i.e. the processes are well understood and can be successfully modeled at relatively coarse scales with data that is obtainable (albeit presently not broadly obtained, §7). To date, there is little quantitative work evaluating uncertainties for Saint-Venant models of a large river network. These uncertainties include: (1) the evolving shape of the boundary, (2) the boundary material roughness, and (3) landscape runoff and groundwater interactions. The first two issues are closely related to the aleatoric uncertainty of turbulence, which can be reduced with more comprehensive geometric data. However, unlike modelling flow around an airplane or automobile, we can never *exactly* know the boundary shape and material roughness of a riverbed – thus creating a lower bound on flow modelling uncertainty (Legleiter et al., 2011). Despite these constraints, the principal driver for uncertainty in CRD is likely to be in the third issue – the uncertainty in fluxes between the landscape, river, and groundwater.

**Challenge 4:** There is an open question as to how far CRD can practically reduce uncertainty through improved model resolution and increasingly detailed data before uncertainties of modeled landscape fluxes become dominant.

### 6. Coupling CRD and hydrology

**Constraint 5:** A river network model requires coupling with a hydrological model for flux boundary conditions.

This constraint inhibits development of large-scale CRD models in two ways: first, we lack recognized benchmarks or test case data for any large river network, making it difficult to validate a new model; second, the lack of accepted standards for data exchange between models...
makes it difficult to test a river network model with multiple hydrological models (and vice versa).

Unfortunately, the coupling between landscape and river models is significantly different from that for atmosphere-hydrology. Moving between landscape and atmosphere requires transforming only $[x, y]$ spatial data; this interpolation problem is not trivial, but is understood (David et al., 2009). In contrast, a 2D hydrological model provides 1D fluxes to a river model, typically defined by distance upstream/downstream of junctions rather than by $[x, y]$ coordinates. There are no standard conventions for river geometry or topology, so different model coupling methods use different conventions.

The simplest solution for linking models is “loose-coupling” through an Application Program Interface (API) such as OpenMI\(^2\) (Castronova and Goodall, 2013). However, efficient operation for continental-scale applications requires common data structures addressed directly by each model. Data structures are available for landscape/atmosphere model coupling within the Earth Surface Modeling Framework\(^3\) (Hill et al., 2006) and other community systems (Lu and Piasecki, 2012). However, it is not clear whether a simple and more general landscape/river data exchange standard can be abstracted from any existing modelling framework. There is a need for a community-accepted standard for a common 2D/1D data interchange structure that can be easily implemented in new and legacy models and operate either with or without ESMF/OpenMI model coupling. This data structure should allow multiple approaches, e.g. ASCII text file, netCDF binary file, and file-less communication through an API. Models using the common data structure should be readily interchangeable, allowing cross-comparison of a river model driven by different hydrologic models, and vice versa. Without development and widespread adoption of standards for 2D-1D interchange, we will remain stuck in a world where data discovery, reformatting, and re-inventing models consume too much of our productive research time.

Challenge 5: New regional- to continental-scale benchmark test cases and standards for data exchange between hydrologic and hydraulic models should be developed collaboratively across the disciplines.

\(^2\)http://www.openmi.org
\(^3\)http://www.earthsystemmodeling.org
7. Data availability and usage

Constraint 6: Detailed river geometry data is rarely available, or when available can be finer than practical model resolution.

For most rivers, submerged geometry and roughness are known (if at all) only through cross-sectional profiles. However, recent advances in hyperspectral lidar and multi-beam sonar imaging make it possible to rapidly obtain 3D bathyscapes from aircraft or boat surveys (e.g. Hohenthal et al., 2011). There are signs that the NSF EarthCube will provide a home and distribution for such data. Unfortunately, to date there does not appear to be a concerted effort to collect and make geometric data available for any complete river basin, let alone a continental-scale network.

As fine-grained $O(1)$ m data becomes available from lidar and multi-beam sonar, we will need methods for abstracting data to coarser model resolution and new up-scaling ideas to estimate the contribution of unresolved geometry to drag. We cannot throw out data and still call ourselves scientists, so the fine-detail bathymetry that cannot be resolved should be used to reduce the calibration burden (§4) on Manning’s $n$. Where too little data is available – which will likely be the long-term condition for most of the developing world and high-order streams – we need new ideas, methods, and models to develop synthetic river geometry. We need better understanding of the relationships between channel geometry and flow effects (e.g. Mejia and Reed, 2011b), perhaps extending the ideas of hydraulic geometry (Leopold and Maddock, 1953; Beighley and Gummadi, 2011). A goal should be developing synthetic cross-sections from remotely-sensed data that are sufficiently approximations for CRD modelling.

Challenge 6: New and continuing institutional support is needed for comprehensive river geometry data collection.

Challenge 7: New hydraulic modeling methods are needed for both too much and too little geometric data.

8. Conclusions

CRD is a building block for continental-scale hydrology: rivers are perhaps the only element where we have both physical equations from first principles (e.g. Decoene et al., 2009) along with a reasonable expectation of obtaining sufficient remotely-sensed data for calibration (Andreadis et al., 2007; Giustarini et al., 2011; Plant et al., 2009; Pramanik et al., 2010). By removing the easier channel physics from the
harder problem of hydrological runoff, we can reduce the uncertainty caused by parameterizing channelized flow in a land-surface model.

The key short-term technological hurdles to advancing CRD are: (1) existing Saint-Venant river models have not been shown to scale-up to continental networks; (2) integration of an array of river models with an array of hydrologic models is difficult and time-consuming, and (3), we do not have good quantitative methods for CRD to use hyperresolution lidar data or to synthesize approximate river geometry in the absence of detailed data.

A further roadblock is in river geometry. Data collection, storage and dissemination are rapidly advancing (Gichamo et al., 2012; Hutton et al., 2012; King et al., 2009; Legleiter, 2012; Overton, 2005; Passalacqua et al., 2012), but there does not seem to be the institutional framework or willpower to embark on a comprehensive data collection effort for river geometry that would provide a major leap forward in CRD.

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