HYDROLOGICAL PROCESSES
Hydrol. Process. **27**, 2171–2186 (2013)
Published online 4 April 2013 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.9740

Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems

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Abstract:

Despite significant recent advancements, global hydrological models and their input databases still show limited capabilities in supporting many spatially detailed research questions and integrated assessments, such as required in freshwater ecology or applied water resources management. In order to address these challenges, the scientific community needs to create improved large-scale datasets and more flexible data structures that enable the integration of information across and within spatial scales; develop new and advanced models that support the assessment of longitudinal and lateral hydrological connectivity; and provide an accessible modeling environment for researchers, decision makers, and practitioners. As a contribution, we here present a new modeling framework that integrates hydrographic baseline data at a global scale (enhanced HydroSHEDS layers and coupled datasets) with new modeling tools, specifically a river network routing model (HydroROUT) that is currently under development. The resulting 'hydro-spatial fabric' is designed to provide an avenue for advanced hydro-ecological applications at large scales in a consistent and highly versatile way. Preliminary results from case studies to assess human impacts on water quality and the effects of dams on river fragmentation and downstream flow regulation illustrate the potential of this combined data-and-modeling framework to conduct novel research in the fields of aquatic ecology, biogeochemistry, geo-statistical modeling, or pollution and health risk assessments. The global scale outcomes are at a previously unachieved spatial resolution of 500 m and can thus support local planning and decision making in many of the world's large river basins. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS global hydrography; large-scale hydrological modeling; river network routing; hydrological connectivity; Geographic Information Systems

Received 12 April 2012; Accepted 23 January 2013

INTRODUCTION

Water is a vital necessity to sustain life on Earth, and many Earth system processes depend on the spatial and temporal distribution of freshwater resources. Not surprisingly, the hydrological cycle and its underlying physical processes have been studied intensely over the past decades, mostly with a focus on small- to medium-sized catchments. In recent years, however, the increasing pressures on freshwater resources from a multitude of complex and interacting factors that span all scales led to a growing recognition of the importance of large river systems. Consequently, many research applications require hydrological or water resources information at regional to global extent. Prominent examples include the estimation of future climate and global environmental change effects related to floods, droughts, water supply, or hydropower generation; the analysis of global biogeochemical cycles, carbon and nutrient budgets; the sustainable management of international freshwater resources; the estimation of possible limits in global food production due to constrained water availability; the systematic planning for freshwater biodiversity conservation; or the assessment of regional health risks due to water-borne diseases or water quality issues.

As *in situ* measurements of many hydrologic variables at large spatial and temporal scales are difficult and expensive, global hydrological models (GHMs) have emerged as our preferred research tool to analyze current and future world water resources. Haddeland *et al.* (2011) reviewed eleven global water models that have recently been studied in the Water Model Intercomparison Project. They included five global land surface models, which historically have been designed for improving the vertical water and energy balances and their representation in atmospheric circulation models. In contrast, GHMs are typically tailored towards a more detailed assessment of global freshwater resources by simulating explicit processes of surface runoff generation and horizontal flow routing. Major goals of these models include the estimation of water availability, water use, and/or water scarcity at global or regional scales (e.g. Vörösmarty *et al.*, 2000b; Alcamo *et al.*, 2003; Arnell *et al.*, 2004; Oki and Kanae, 2006; Rost *et al.*, 2008; Döll *et al.*, 2009; Hanasaki *et al.*, 2010; Siebert and Döll, 2010).

More specialized GHMs consider the transportation of constituents other than water, e.g. sediment, contaminants, and nutrients, and simulate in-stream processes during the routing process. Such models improve our understanding of biogeochemical cycles and budgets in surface waters, for

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example the role of rivers in processing and transporting carbon, phosphorus, nitrogen, and silica to the ocean (Alexander *et al*., 2009; Alvarez-Cobelas *et al*., 2009; Beusen *et al*., 2009; Mayorga *et al*., 2010; Aufdenkampe *et al*., 2011). Similar models can be used to predict the transport of sediments in the river network to help understand the effects of dams on sediment retention and on coastal and delta geomorphology (Vörösmarty *et al*., 2003; Syvitski *et al*., 2009; Kummu *et al*., 2010). Chemical fate models have been developed to conduct risk assessments for substances from wastewater treatment plants or other sources (Feijtel *et al*., 1998; Wang *et al*., 2000; Anderson *et al*., 2004), yet few have been applied at larger scales (Pistocchi *et al*., 2009). In a recent integrated approach, Vörösmarty *et al*. (2010) conducted a study that combines various disciplines, models, and data sources in an attempt to holistically assess anthropogenic threats to global scale freshwater biodiversity and river systems.

Despite the increased attention, hydrological modeling at large scales has traditionally been hampered by a number of issues, including general limitations in our knowledge and understanding of the underlying processes for many regions of the Earth; incomplete, inconsistent, or highly uncertain data collections; a lack of spatial integration between models and datasets; and the difficulty to create models that support multi-scale or coupled approaches. Not surprisingly, the improved monitoring and modeling of global land surface hydrology at high spatial and temporal resolutions has been named as one of the 'grand challenges' for assessing the Earth's freshwater budget, and a call to strengthen engagement in this effort has been made upon the international hydrologic community (Wood *et al*., 2011). To achieve this goal, new and enhanced global datasets and tools describing the geographical distribution of hydrological features, characteristics, and processes will be required as this information is currently often unavailable or at low quality. The current research status is even more incomplete when looking at large-scale effects of human alterations to the water system, such as the impact of global reservoir and dam constructions on downstream river ecosystems (Lehner *et al*., 2011). While significant progress has recently been made in the development of global hydrographical data (see Data section below), many challenges remain for model development and improvement. In particular, a new generation of integrated models is required that support the linkage of hydrological processes with other fields, such as ecology, biogeochemistry, and water management (Aspinall and Pearson, 2000).

In this paper, we argue that there is currently no comprehensive framework that can fully support integrated hydro-ecological modeling at the global scale; yet the building blocks of such a framework already exist. We will illustrate the current status and outline new directions for global scale hydro-ecological modeling to study the world's large river systems. We propose an approach that combines existing and newly developed global scale hydrographic baseline data with a dedicated river routing model in a Geographic Information System (GIS) environment, and we will present preliminary results of our own model development. Finally, we will show that such a framework can enable a broad range of hydro-ecological applications and operate at scales at which local decision making and management becomes feasible.

CHALLENGES IN GLOBAL SCALE HYDRO-ECOLOGICAL MODELING

In this section, we formulate and briefly discuss five main challenges that need to be addressed in order to improve our ability to integrate global hydrological and ecological modeling approaches. The solutions we offer may also be applicable for other, related applications, such as biogeochemical or sediment transport models.

Challenge 1: Spatial resolution

The current spatial resolution of GHMs is not appropriate for many ecological or environmental management applications because of difficulties to accurately represent stream and watershed attributes and to precisely locate individual objects within the river system. GHMs have been developed at different spatial resolutions, ranging from basin scale lumped models to the most commonly applied 0.5° pixel resolution, and various lateral routing schemes have been developed accordingly (Oki and Sud, 1998; Graham *et al*., 1999; Renssen and Knoop, 2000; Vörösmarty *et al*., 2000a; Döll and Lehner, 2002). These rather coarse scales have been applied mostly for reasons of technical feasibility (i.e. computational demand) and due to the fact that important input information, foremost climate data, has been offered at these resolutions. In the most recent iterations, GHMs are moving towards 5 (or 6) arc-minute spatial resolution (e.g. Wisser *et al*., 2010; Schneider *et al*., 2011), but despite this improvement, two major limitations remain: First, the relatively coarse spatial resolution introduces bias and misrepresentation of hydrological processes and river topology. This can result, for example, in underestimation of river length and travel times (Gong *et al*., 2009; Verzano *et al*., 2012) and can lead to subsequent inaccuracies of travel-based attributes, e.g. sediment delivery to the ocean (Vieux and Needham, 1993). Second, and more importantly from a modeling perspective, the integration of local or fine-scale information is difficult, if not impossible. While sub-grid parameterizations allow representation of some hydrological processes, ecologists and water managers have long criticized large-scale models for being incompatible with their more localized needs, such as the explicit identification of habitat or flow characteristics for individual tributaries, or the linkage of species information to river reaches and small sub-basins. In raster format, the resolution needs to be particularly high to explicitly model river channels, which are the most important structures controlling hydrodynamics.

A possible solution is to move towards hyper-resolution hydrological modeling (Wood *et al*., 2011). Global digital drainage networks exist at fine scales, such as HYDRO1k at 1-km resolution (USGS, 2000) or HydroSHEDS at up to 90-m resolution (Lehner *et al*., 2008; Figure 1) and are

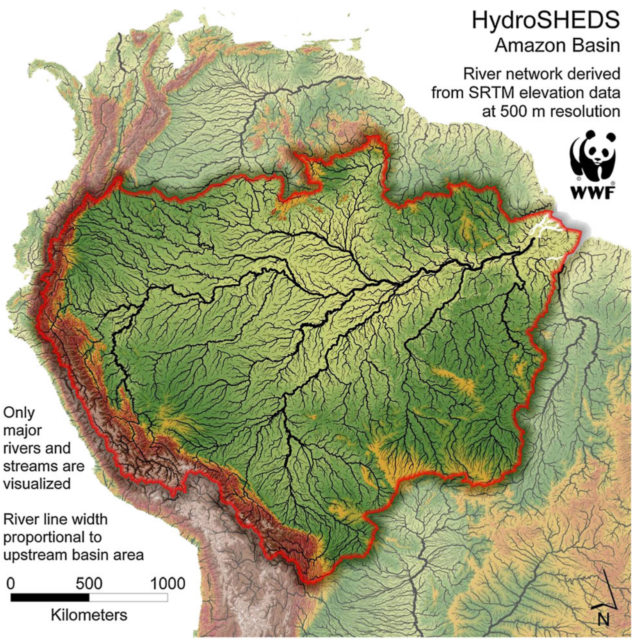

Figure 1. HydroSHEDS river network for Amazon Basin at 500 m resolution

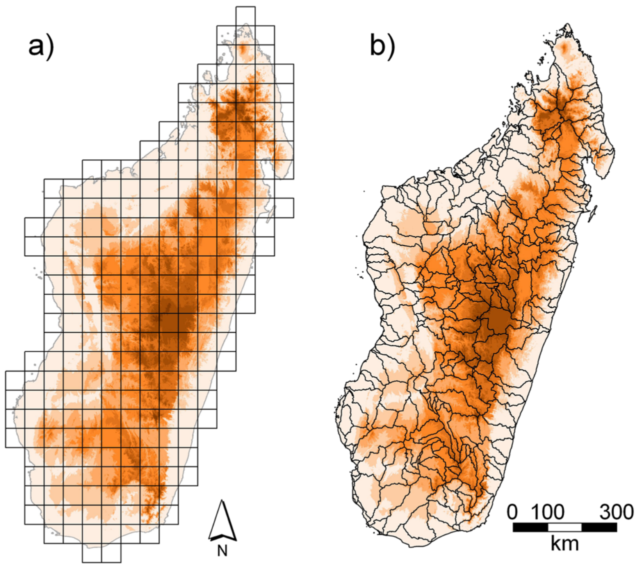

Figure 2. Sub-unit representation in half-degree grid format (a) and 500 m vector format (b) for Madagascar. There are a total of 250 half-degree pixels (a) *versus* 282 sub-basin polygons (b). Polygons are derived from the HydroSHEDS database

detailed enough to reference objects such as dams precisely to the corresponding rivers. Gong *et al*. (2011) demonstrated for two medium-sized basins that routing performance increases with the higher resolution hydrographic data of HydroSHEDS. However, computational demand to execute the necessary runoff-response-functions and cell-response-functions at a daily time step was high, and their model has yet to be tested at the global scale.

Given these technical difficulties, an alternative solution towards higher spatial resolution may be offered by integrating raster with vector concepts in the modeling framework (see also next challenge). In a raster environment, higher resolution can only be achieved by increasing the number of pixels, while in a vector environment, a sub-basin's geometrical resolution can be improved by simply applying a more detailed polygon outline; in this latter approach, the number of modeling objects remains constant while resolution improves (see Figure 2).

Challenge 2: Data structure (raster vs vector concepts)

Spatial information in GHMs is typically represented as layers of uniformly sized grid cells, also known as raster datasets. Vector datasets on the other hand consist of objects, represented as points at a certain location, or as a series of point locations chained together to form a line or polygon. The differences between raster and vector concepts in environmental models are frequently debated in the modeling community. Both approaches have advantages that could be harnessed in a hybrid modeling framework.

Raster models have traditionally been the preferred choice of hydrological modelers since the integration of topography in the form of rasterized Digital Elevation Models (DEMs) is a key requirement for many routing algorithms that trace water along drainage direction maps. Furthermore, many ancillary datasets stem from remotely sensed raster information (e.g. land cover, precipitation, etc.), and grids are relatively easy to process in any modern GIS.

A major limitation of the raster concept, however, is the difficulty to integrate objects or information from different sources or formats (such as the discharge time series of a gauging station; a reservoir outline; or a fish migration route) into one common framework, as linkages would have to be established to individual pixels. A vector dataset, on the other hand, can represent multiple objects (points, lines, or polygons) each of which can have multiple attributes associated in a related table. Within a GIS, links between the objects of different vector layers can be created similar to an 'object-oriented' relational database. If such a structure is established, river network routing using the vector structure greatly facilitates the integration of multiple objects from different domains.

Ideally, a modeling framework should support both raster and vector representations of the respective data layers to benefit from the advantages of both. This could be achieved by maintaining fundamental information at high spatial resolution as raster datasets, and to develop tools that allow for an easy transfer or linkage of this information to vectorized river reaches, sub-basins, or point objects. Modelers can use these tools whenever new information needs to be integrated into the model. This conceptual approach is followed, for example, by ArcHydro, a geospatial framework and toolbox within ESRI's ArcGIS software package (Maidment, 2002), which allows the user to create a set of hydrological vector datasets (river network, basins, etc.) from a DEM and to store the information in an object oriented geodatabase.

Challenge 3: Multi-scale approach

A vision to promote hydro-ecological and other integrated models requires means to analyze and simulate processes at multiple spatial scales (Lowe *et al*., 2010).

Yet, difficulties arise from inherent data and modeling characteristics. For example, certain types of geospatial hydrological data, such as runoff coefficients or flow directions, cannot be easily scaled by spatial resampling techniques. Scaling methods for rasterized river networks may provide a solution (e.g. Fekete *et al*., 2001; Yamazaki *et al*., 2009), but currently most data layers are developed for a specific resolution, and even small changes in scale require intense data reprocessing or even the development of new datasets from scratch. Thus tools and concepts need to be developed that support modeling at multiple sales and help transferring information between scales – from individual raster cells at the highest resolution, to river reaches, catchments, or entire basins. This can be achieved by means of hydrological nesting approaches, e.g. by applying hierarchical coding schemes to predefined sub-units, or by allowing accumulation and conglomeration of objects (e.g. sub-basins) based on their topology and connectivity.

Challenge 4: Representation of hydrological connectivity through river network routing

Hydrological connectivity is an important concept in both hydrology and ecology. Flows in traditional GHMs that include lateral transport occur on the premise of a river continuum whereby conditions at every location in the river network are influenced by upstream processes (Vannote *et al*., 1980). A more ecology oriented concept of spatial integration has been developed by Pringle (2003), who defined hydrological connectivity as the flow of mass, energy, and organisms in surface and groundwater. In this definition, hydrological connectivity occurs in both upstream and downstream direction (longitudinal); between rivers, wetlands, and floodplains (lateral); and between groundwater, surface water, and the atmosphere (vertical).

The advanced implementation of hydrological connectivity in a modeling framework is an attractive concept because of its ability to integrate processes from multiple disciplines (such as terrestrial, climate, ecological and hydrological); because of its easiness to represent spatially explicit topology information of a river network and watershed landscape (up- and downstream relations); and because of its intrinsic ability to establish connections across multiple scales – from point locations and river reaches to nested catchments and entire basins. Hydrologic connectivity can be modeled in various ways. We propose that for hydro-ecological applications, models should at a minimum (i) include the possibility to conduct routing of water and substances along the hydrological flow paths; (ii) represent lakes, dams, floodplains, and wetlands in addition to river reach routing; and (iii) be based on a powerful tracing algorithm for up- and downstream routing to represent both active and passive dispersal of matter or species. We are currently not aware of models that can fully implement such advanced up- and downstream routing in a global framework.

The term 'routing' generally refers to the simulation of transport processes over space and time. For example 'flow routing' simulates the movement of water over the landscape and translates runoff into river discharge by passing the runoff generated in a specific landscape unit (e.g. sub-watershed or pixel) to the next downstream unit. A distinction is typically made between hydrodynamic routing and hydrological routing (Maidment, 1993). In hydrodynamic routing, flow is described by the Saint-Venant equations of mass and momentum conservation. The first equation governs the translation of mass between sections of the river, while the second relates changes in momentum to the applied forces (in particular pressure gradient, convection, acceleration). In hydrological routing the Saint-Venant equation of mass conservation still applies, but the momentum term is replaced by empirical parameters. In GHMs such as TRIP (Oki and Sud, 1998), HYDRA (Coe, 2000), WaterGAP (Döll *et al*., 2003), WBM/WTM (Vörösmarty *et al*., 1989; Fekete *et al*., 2006), and LPJmL (Rost *et al*., 2008), simple hydrological routing is implemented, where flow is passed along storages (e.g. rivers, lakes) in a linear sequence, and residence time is often modeled by assuming constant flow velocities. For variable representation of velocity, the introduction of simple parameters based on slope (or more comprehensive ones based on slope and friction) are used (Coe *et al*., 2009; David *et al*., 2011; Verzano *et al*., 2012). Basic in-stream processes, such as accumulation and solute transport along the river network, have also been implemented in these types of GHMs (e.g. Donner *et al*., 2002).

Hydrodynamic processes such as backwater effects and lateral flooding have critical implications on ecosystem functioning, and the inclusion of hydrodynamic principles allows for more advanced routing models. A recent study for the Amazon River Basin employed a diffusive wave routing approach in the CaMa-Flood model (Yamazaki *et al*., 2011) to demonstrate that floodplains have strong attenuating effects on flood waves and flood peaks in large basins. These improvements, however, come at the cost of additional and more complex computational efforts, model design, preparation, and parameterization. Thus, for the primary goal of a first-level integration of baseline hydrology with ecological and other applications at the global scale, we believe that the full implementation of hydrodynamic processes, though desirable, is currently not a stringent priority.

Beyond the type of routing, the direction of movement plays an important role. Multi-directional routing approaches, also characterized by the term 'tracing', are procedures that select a set of network elements based on certain connectivity rules, and then process the selected set in a predefined (directional) sequence. Within such a framework, many hydro-ecological connectivity applications can be supported, for example by simulating the effects of dams on plant dispersal through hydrochory and on the resulting riparian flora (Andersson *et al*., 2000); the distribution of fish species in river and lake networks in response to environmental factors and anthropogenic pressures (Lassalle *et al*., 2009); and the fragmentation of river networks and impedance of ecosystem connectivity through dams (see Applications section below). Advanced tracing can also help to better understand the structure of and processes in river networks through geo-statistical modeling: with the emergence of detailed hydrologically connected network datasets, a new class of geo-statistical tools can be developed, which uses distances along a curvilinear flow path, instead of the Euclidean distance space (Ganio *et al.*, 2005). Network tracing using weights and barriers, with subsequent routing, can provide a powerful framework for a wide range of applications that involve hydrological connectivity.

In conclusion and to widen the scope of routing, tracing, and connectivity in hydrological models, for this paper, we define the term 'river network routing' following the hydrological connectivity concept of Pringle (2003) as '*the simulation of movement of energy, material and species within a hydrological object space, based on flow routing, tracing and in-stream processing*.'

Challenge 5: An integrated data and modeling framework

Different GHMs operate at different resolutions, have been designed for different purposes, use their own specific routing schemes, and are based on different input for the representation of climate or topography. Thus, the coupling of these GHMs with ecological models or databases, such as fish species distributions, requires extensive individual data processing and adjustments in order to align spatial resolutions and data formats. We here propose to design a more integrated data and modeling framework which facilitates an easier linkage between hydrological and ecological information and is geared towards hydro-ecological research, applications, and management. A key characteristic of this approach is to utilize a harmonized database of hydrographic baseline information (i.e. river network, sub-basin delineations, and linked features such as dams, lakes, and gauging stations) and to develop assessment tools that couple hydrological model results and ecological information within this data framework. Using a common data space has the advantage that, for example, species data can be easily mapped to the same units as hydrological information, which facilitates the analysis of impacts, coupled processes, or feedbacks. In the following two chapters, we describe and outline the characteristics of existing global hydrographic baseline data, as well as a new approach to utilize these data within a custom-made river network routing model.

NEW GLOBAL HYDROGRAPHIC DATA DEVELOPMENTS

Large-scale hydrological modeling critically depends on the availability of adequate input data. Climate and land surface data and parameterizations are key elements for any water balance model, while many integrative hydro-ecological applications require complementary data sources, such as locations and amounts of human water use, the origin of point- or non-point-source pollution, and biodiversity and species information. Additionally, hydrologic measurements such as provided by gauging stations are important for validation purposes.

Tremendous improvements have been made over the past years in the availability, quality, and resolution of large-scale hydrographic datasets, not least due to the increased operational monitoring of the entire Earth surface via satellite remote sensing. There is a long list of recent data developments for many hydrology-relevant themes, including (to name only a few): new land cover data derived from remote sensing (Loveland *et al.*, 2000; Bontemps *et al.*, 2010); historical and current land use data (Ramankutty and Foley, 1999; Ellis and Ramankutty, 2008; Monfreda *et al.*, 2008; Portmann *et al.*, 2010; Klein Goldewijk *et al.*, 2011; MacDonald *et al.*, 2011); lake, reservoir, and wetland inventories (Lehner and Döll, 2004; Lehner *et al.*, 2011); irrigation maps (Siebert *et al.*, 2005); water use estimates (Wisser *et al.*, 2008; Döll *et al.*, 2009); soil parameterizations (FAO *et al.*, 2012), and many more.

There are various data portals and compilations available online to serve and distribute these data, e.g. the Digital Water Atlas of the Global Water System Project (http://atlas.gwsp.org/). Vörösmarty *et al.* (2010) offer a suite of 23 maps of driver sources at 0.5° pixel resolution globally which were part of their study on threats to global river systems (http://www.riverthreat.net/). We also increasingly utilize indirect measurements to derive hydrological variables, such as the derivation of discharge or lake volume changes based on high-accuracy, real-time altimetry measurements of water surfaces and other remote sensing information (e.g. Sahoo *et al.*, 2011; Seyler *et al.*, 2012). Even the measurement of incremental changes in the Earth's gravitational field as provided by the GRACE project enabled us to interpret changes, e.g. in groundwater storage or snow water equivalent at a planetary scale (Llovel *et al.*, 2010).

Among the many input data layers, special attention is often placed on hydrographic baseline information in the form of river networks and watershed boundaries as they form the backbone or 'fabric' of the modeling framework. Examples of highly advanced regional versions include the US National Hydrography Dataset (NHD; developed by US EPA and USGS; http://nhd.usgs.gov/applications.html), a comprehensive set of digital geospatial data about surface water features such as streams, rivers, and lakes; or its successor NHDPlus, which incorporates the US National Elevation Dataset, and the Watershed Boundary Dataset. The Australian Hydrological Geospatial Fabric (Atkinson *et al.*, 2008) has been developed as a knowledgebase of the features within the Australian water system and their interactions, such as catchments, streams, aquifers, floodplains, storages, and wetlands. At the European scale, Vogt *et al.* (2007) created a consistent database of drainage networks and catchment boundaries for hydrological assessments and reporting within the Water Information System for Europe.

At the global scale, however, there are only limited sources for seamless high-quality hydrographic information. Data for many large international river basins are still patchy, and remote areas are often poorly mapped. Also, the hydrographic information is required in strictly defined digital formats that allow for flow routing along streams and watershed identification. HYDRO1k (USGS, 2000) offered a first version of such information, yet its quality shows strong regional variation. Below, we discuss the HydroSHEDS database (Lehner *et al*., 2008) which represents the most recent attempt to fill this data gap.

HydroSHEDS is a hydrographic mapping product created by World Wildlife Fund that provides river and watershed information for regional and global-scale applications in a consistent format (Lehner *et al*., 2008). It offers a suite of geo-referenced datasets at various resolutions ranging from 3 arc-second (approximately 90 m at the equator) to 30 arc-second, including river networks, watershed boundaries, and drainage directions. HydroSHEDS is based on high-resolution elevation data obtained during NASA's Shuttle Radar Topography Mission (SRTM) in February 2000. The extent of HydroSHEDS is near-global, currently only excluding regions above 60° northern latitude due to the lack of SRTM source data; the global extent is scheduled to be completed by inserting alternative elevation data within 2013. The data is available to the scientific community at http://www.hydrosheds.org.

Besides its core layers, HydroSHEDS is currently undergoing expansion to include a suite of attribute layers and to establish linkages to auxiliary datasets. Some efforts are already completed, some are in progress for release within the next year or two, and some are in proposal stage; Table I provides an overview of the prime developments. Consistency between the layers is ensured in terms of spatial alignment, and quality indicators are provided where possible. For example, the point locations of gauging stations have been snapped in a best-fit process to HydroSHEDS pixels and corresponding river reaches in a manually controlled and supervised process, and uncertainty has been assessed via discrepancies between reported and modeled watershed areas.

DEVELOPMENT OF A GLOBAL RIVER NETWORK ROUTING MODEL (HYDROROUT)

In nearly all GHMs, the implemented routing models operate on raster data. Only recently, some large-scale models started to shift towards a vector environment (e.g. Paiva *et al*., 2011) or use advanced sub-grid and/or hybrid structures (e.g. Yamazaki *et al*., 2011). We here propose to continue this transition towards a vectorized model framework at a fully global extent, and to implement versatile, multi-directional routing based on point, line, and polygon objects, such as gauging stations, river reaches, and sub-basins. One advantage of this approach is that vector routing can significantly reduce the required computational resources as compared to cell-based models because of the inherently simple 'object-to-object' routing scheme. In a cell-based approach, large homogeneous objects, such as lakes, consists of hundreds or even thousands of grid cells, each of which is treated as an individual 'cell object', which increases the number of processing steps – often without added benefit.

We are currently developing a new river network routing model (HydroROUT; Grill *et al*., in prep.) which provides vector-based routing capabilities and is fully integrated in the widely used GIS software package ArcGIS (ESRI, 2011). Figure 3 presents a schematic overview of the implementation of HydroROUT within the HydroSHEDS data framework. Only a small number of vector routing models have been developed so far (e.g. Feijtel *et al*., 1998; Wang *et al*., 2000; David *et al*., 2011; Paiva *et al*., 2011), and HydroROUT is conceptually similar to that of Whiteaker *et al*. (2006), who developed a processing engine – the 'schematic processor' – to accomplish basic river routing for vectorized river networks derived from ArcHydro.

The first function of HydroROUT is to establish hydrologic connectivity which is achieved by creating links within and between river reaches and sub-basins following the basic principles of Whiteaker *et al*.'s routing scheme. However, while their 'schematic processor' uses linear vector networks with connectivity relationships built via traditional attribute tables (FromNode-ToNode adjacency), our network is based on the concept of a 'geometric network', i.e. a directed network graph located in an ArcGIS geodatabase. Geometric networks are normally used to model infrastructures, such as electric utility lines and sewer systems, but they are also well suited to represent connectivity within dendritic river networks. Geometric networks are collections of line objects (e.g. river reaches) and point objects (e.g. locations of confluences of two river reaches) that possess a connectivity relationship based on the coincidence of the start- and endpoints of the river reaches. The connectivity information between river reaches and other objects are stored in connectivity tables, the so-called logical network. River reach geometries can thus be treated as individual elements for use in tracing and flow operations.

Geometric networks are optimized for routing and tracing. Connectivity relationships are based on the 'ForwardStar' concept, which is considered the most efficient network representation (Ahuja *et al*., 1993; Cherkassky *et al*., 1996). It is due to this effectiveness that we are able to conduct river routing at the global scale with several million objects on a single processor. Connectivity based on a 'ForwardStar' also allows flexible routing in both directions, during which the 'cost' or 'resistance' of traversal is being taken into account through network weights, and barriers that stop the trace may be included.

The second function of HydroROUT's processing engine is the routing of substances downstream the river network, which may include the accumulation of mass from different distributed sources in the river network (e.g. wastewater treatment plants) and/or constant or time-dependent decay functions, which diminish the substance to be accumulated gradually along its path. For example, for the routing of substances such as nutrients and pollutants, the dominant dilution mechanism is advection, which can be effectively modeled using stream length, velocity, discharge, and a decay function (Pistocchi *et al*., 2010). A 'plug-flow' model has been chosen similar to Feijtel *et al.* (1998) and Whiteaker *et al*. (2006), which is an adequate and frequently used approach in routing at the river reach

Table I. Recently completed and planned new data layers of the HydroSHEDS database. The attribute data is assigned to the river or sub-basin network at 15 arc-second (500 m) resolution

Layer	Description	Status[a]
Global Reservoir and Dam (GRanD) database	Coordinated by the Global Water System Project (GWSP) and based on a variety of sources, the locations of nearly 7000 of the world's largest reservoirs were georeferenced, and attribute data were compiled, including storage capacity and main purpose (Lehner *et al*., 2011). Corresponding dams are linked to the HydroSHEDS stream network via their coordinates. The data is available at http://www.gwsp.org/85.html.	Completed
GRDC gauging stations	The location of more than 7000 gauging stations (provided by the Global Runoff Data Center, Koblenz, Germany) were verified and co-registered to the HydroSHEDS river network. The data is available at http://grdc.bafg.de/.	Completed
Sub-basin delineation	Hierarchical nesting of sub-watersheds can support multi-scale hydro-ecological analyses (Fürst and Hörhan, 2009). HydroSHEDS has been enhanced by a vectorized watershed layer that subdivides basins into units of approximately 130 km^2 area. A coding scheme (following the 'Pfafstetter' concept; Verdin and Verdin, 1999) allows for topological up- and downstream queries as well as hierarchical aggregation.	Completed
Discharge	Estimates of long-term (1961–90) monthly discharge averages are derived through a downscaling procedure from the 0.5° resolution discharge layer of the global integrated water model WaterGAP (Alcamo *et al*., 2003; Döll *et al*., 2003). Individual river reaches can be distinguished down to stream sizes of 1 l/s average discharge. Although no global quality assessment has been completed yet, visual inspections show realistic results and patterns.	Release after validation in 2013
Habitat volume	Based on discharge estimates and simplistic hydraulic geometry laws (sensu Allen *et al*., 1994), a first-level approximation of the dimensions of channel width and depth will be derived for each river reach. These values are then used to calculate habitat volumes (i.e. in-stream habitat space).	2013
Names	River and sub-basin names will be provided.	2013
Global inundation mapping	River floodplains and inundated areas provide critical aquatic habitat for many species, yet there is currently no consistent, high-resolution map of inundation extents available at a global scale. A new global floodplain and inundation map is currently produced at HydroSHED's 500 m pixel resolution by combining global topography information with coarser scale inundation maps derived from remote sensing imagery (Prigent *et al*., 2007).	2013
Lake surface areas and volumes	The extent of open lake surfaces and the amount of water stored in lakes plays an important role for human water supply and many ecosystem processes. Information on lake volumes, however, only exists for the very largest of lakes while the vast majority of smaller lakes have never been assessed in a spatially explicit way (Pistocchi and Pennington, 2006; Hollister and Milstead, 2010). As part of the SRTM project, NASA provided a mask of more than half a million lake surfaces (NASA/NGA, 2003) which will be utilized in combination with statistical approaches and global elevation data to create a first-time estimate of water volumes for each individual lake. The approach has been successfully tested for a selection of 166 European lakes. Results will be integrated in the HydroSHEDS database.	2013–2014
Flow velocity	Using discharge, stream gradients, and global estimates of simplified Manning coefficients, Verzano *et al*. (2012) derived estimates of flow velocities. A similar methodology will be applied to estimate average velocities for the HydroSHEDS stream network.	2013–2014
Global River Classification (GloRiC)	River classifications provide researchers (and water practitioners) with basic modeling and planning units; deliver groups of similar or distinct river types to be applied in analyses of biodiversity patterns or threats; help prioritizing protection or restoration efforts; and support the development of guidelines and regulations for freshwater management purposes. The goal of the GloRiC project is to develop a first-time, high-resolution, spatially explicit global map of river typologies. Different river classes are distinguished based on a variety of criteria, including hydrological, physio-climatic, geomorphological, chemical, biological, and anthropogenic parameters.	2013–2014

Continues

Table I. (*Continued*)

Layer	Description	Status[a]
Aquatic biodiversity information	Freshwater biodiversity information (i.e. species lists) are currently coupled to the sub-basins of HydroSHEDS by partners such as the International Union for the Conservation of Nature, Cambridge, UK. The efforts are anticipated to result in comprehensive and spatially explicit freshwater biodiversity maps at a global scale.	2013–2014
Global waterfall mapping	Waterfalls and cascades are important indicators of natural discontinuities in the river network. A first-time global map of the location of major waterfalls and cascades is currently created through a combination of GIS procedures and extensive manual investigations. The waterfalls and cascades will be linked with the river reaches of HydroSHEDS to support studies of the longitudinal connectivity or discontinuities along the river network.	2014
Water temperature	Water temperature is a critical environmental factor used to distinguish different types of river habitats or to assess the status and quality of riverine ecosystems. Using established modeling approaches, temperature ranges can be derived based on combining global air temperature regimes with the flow routing scheme and discharge estimates of HydroSHEDS for each reach of the global river network.	Proposal stage
Urban water use patterns	Cities play a special role in terms of water management as they represent locations of highly concentrated water demand within the river network and their wastewater discharge can compromise the downstream freshwater quality. To allow managers to explicitly include cities in their large-scale planning, a first-time global assessment of the main water supply and use patterns will be compiled for the world's largest cities. The location of each city will be co-registered to HydroSHEDS to enable studies regarding the impact of cities on the global river network.	Proposal stage

[a] years indicate expected completion date (end of year)

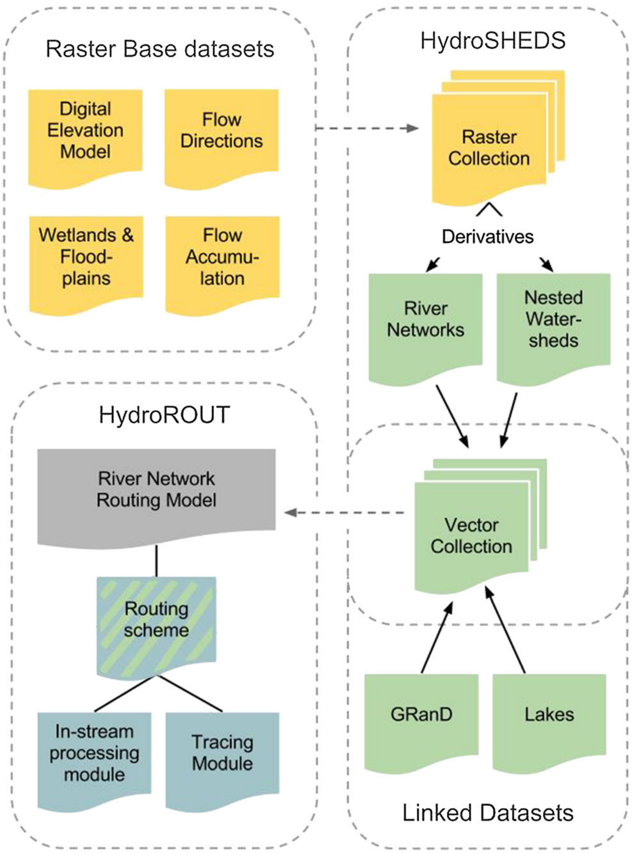

Figure 3. Overview of datasets, concepts, and models within the HydroSHEDS framework. HydroROUT is linked to the collection of vector datasets of HydroSHEDS through its routing scheme. The routing scheme currently consists of tracing and in-stream processing modules

level (Chapra, 1997; Anderson *et al.*, 2004; Pistocchi *et al.*, 2009). If no biogeochemical processes diminish the substance mass while traveling downstream (e.g. decay, nutrient uptake), then the value received from upstream is equal to the value passed downstream. If, however, dissipation of a biogeochemical substance is assumed, the substance is expected to decrease either by a 0^{th}-order decay function (i.e. a constant decay amount) or at a rate proportional to its value, and can therefore be represented through an exponential decay model.

During the routing process, lakes and reservoirs are considered objects treated differently than river reaches, primarily due to their different nature representing mixing, flow velocity, depth, and volume. Lakes are more appropriately modeled as 'completely stirred reactors' (Butkus *et al.*, 1988; Whiteaker *et al.*, 2006). The concentration of constituents in a lake is determined by the inflow concentration, a decay factor, and the volume of the lake.

As for future developments, we consider lateral routing into floodplains and wetlands an important next step. Beyond their role for regulating high discharges, floodplains and wetlands are ecosystems with increased biogeochemical activity. For example, deposition of nutrients and pollutants attached to sediments during a flood removes those substances from the river temporarily (or permanently), which allows for longer decay or uptake times and hence alters downstream biogeochemical budgets (James *et al.*, 2008). Another future development includes the application of the routing model at different spatial scales, which has rarely been attempted in global models. Beighley *et al.* (2009) use basin subdivisions calculated by the Pfafstetter method (Verdin and Verdin, 1999) to represent the land surface with varying degrees of resolution to derive 'irregular computational grids'. In HydroROUT, we plan to enable routing at the sub-basin scale and use the connectivity information between the sub-basins as the routing directions. A total of 12 levels of basin subdivisions are available in the HydroSHEDS database. Depending on the complexity of the model, researchers can choose the appropriate spatial scale at which they wish to model, while maintaining attributes at finer spatial scales.

HydroROUT is currently running as a beta version and required extensive data pre-processing and model development. A global river network with routing capabilities was created based on the 15 arc-second DEM of HydroSHEDS. River reaches are the finest scale on which HydroROUT operates, but routing or topology queries can also be performed at the level of sub-basins, e.g. by identifying all sub-basins upstream of a given location. At the 500 m resolution, there are more than 17 million global river reaches with an average length of 3.6 km, and more than 1 million pre-defined sub-basins with an average area of 130 km^2.

In the current version of HydroROUT, discharge is derived by accumulating land surface runoff along the river network, yet the underlying simulation of runoff generation is not performed within the model itself. Instead, we employ decoupled, external runoff estimates provided by the GHM WaterGAP at 0.5° raster resolution, which we spatially downscale to fit the 500 m resolution of HydroSHEDS (see Table I; for advantages and disadvantages of this model design see Discussion section below). In a first validation of the downscaling results, we compared the discharge of 73 randomly distributed stream gauges for the provinces of Ontario and Quebec from the Canadian HYDAT network (Environment Canada, 2012) to the discharge of the closest HydroROUT river reaches. To avoid spatial mismatch, stations were selected based on agreement between reported and simulated catchment areas and only those with a discrepancy of less than 10% were accepted. For long-term (1961–90) annual average discharge (Figure 4a), we found a very strong correlation (adjusted R^2 of log-linear model = 0.982; $p < 0.0001$). We also conducted a comparison for low-flow conditions as these are commonly used in risk assessments. We aimed to test an index similar to Q90, i.e. the discharge that is exceeded at 90% of time. However, as the climatic input of the underlying WaterGAP model is given in monthly time steps, daily flow estimates, as typically applied for Q90, are not realistic. Instead, we calculated the long-term (1961–90) flow regime and then adopted the lowest month of the year as a first-level proxy for low-flow conditions. The comparison between modeled and observed values (Figure 4b) revealed a slightly lower correlation than

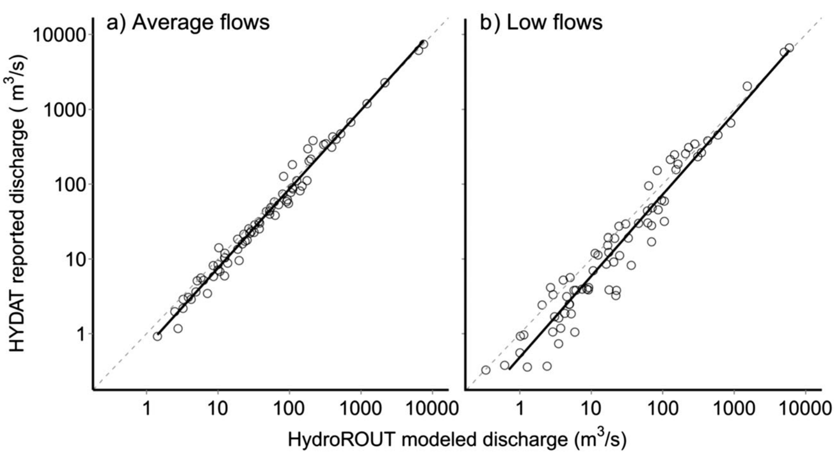

Figure 4. Comparison of discharge observations (as reported at 73 HYDAT gauging stations in Ontario and Quebec) and model results (HydroROUT; based on WaterGAP runoff estimates) for long-term (1961–90) average flows (a) and lowest monthly flows (b). For more explanations, see text

for average flows (adjusted $R^2 = 0.936$; $p < 0.0001$). Despite these good findings, it should be noted that some results contained significant errors, in particular for smaller streams, and that the model showed a tendency to overestimate low flows. More complex discharge parameters, such as the shape of the annual flow regime, inter-annual variability, monthly time series, or extreme events, are yet to be evaluated. Nevertheless, long-term averages and low flows can provide a first avenue for new applications.

APPLICATIONS

In this chapter, we illustrate three case studies performed with HydroSHEDS data and the HydroROUT model that demonstrate the capability of tracing operations; vector routing using river reaches, lakes, and dams; as well as accumulation and decay functions.

Degree of regulation from dams at a global scale

The alteration of the downstream river flow regime is widely recognized as one of the main adverse environmental impacts of dam and reservoir construction (Bunn and Arthington, 2002). In the absence of operational dam release rules, the proportion of a river's annual flow that can be withheld by a reservoir or cluster of reservoirs, i.e. the degree of regulation (DOR), can serve as a first-level approximation of the potential impact on flow regulation (Lehner *et al*., 2011). A high DOR value indicates an increased probability that substantial discharge volumes can be stored throughout a given year and released in a managed (i.e. non-natural) behaviour. Following this approach, DOR values have been analyzed in a recent global study by Lehner *et al*. (2011). For this purpose, the new Global Reservoir and Dam database has been coupled with the HydroSHEDS river network (Table I), and DOR values were calculated as 'total upstream storage capacity divided by total annual flow volume' for every reach of the river network (Figure 5). Results show that 7.6% of the world's rivers with average flows above 1 m^3/s are affected by a cumulative upstream reservoir capacity that exceeds 2% of their annual flow. The impact is highest for large rivers with average flows above 1000 m^3/s, of which 46.7% are affected. In a related assessment, Richter *et al*. (2010) have further analyzed these results to estimate the global number of potentially affected people living downstream of dams. These examples demonstrate the capability of river network routing using basic accumulation procedures.

Ecosystem fragmentation from dams in the Mekong River Basin

A new study of ecosystem connectivity at the scale of the entire Mekong River Basin (Grill *et al*., in prep.) provides an example where river network routing includes extensive tracing operations. Using HydroROUT, we calculated the individual and cumulative impact of 84 proposed dams on ecosystem connectivity in the Mekong Basin (Figure 6). The model used tracing operations to distinguish network fragments, calculated statistics for each fragment (such as habitat volumes and number of connected ecosystems), and finally derived several cumulative indices, including the Dendritic Connectivity Index (Cote *et al*., 2009). The overall result is an index-based ranking for the individual dams, which may provide guidance for decision makers wishing to include basin wide effects into dam planning. The model results illustrate the importance of considering hydrological connectivity, expressed by the location of

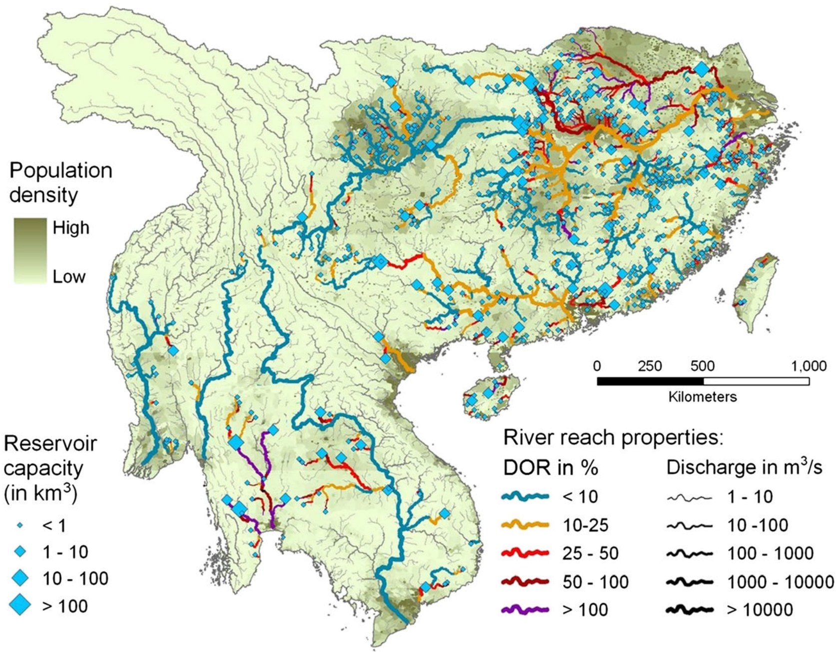

Figure 5. Degree of regulation (DOR) for Southeast Asia. The DOR ratio measures the total upstream storage capacity divided by the long-term average discharge at each river reach. Discharge estimates are taken from HydroSHEDS database; reservoir locations and storage capacities are taken from the Global Reservoir and Dam (GRanD) database (Lehner *et al*., 2011); background population density is from GRUMP database (http://sedac.ciesin.columbia.edu/gpw/)

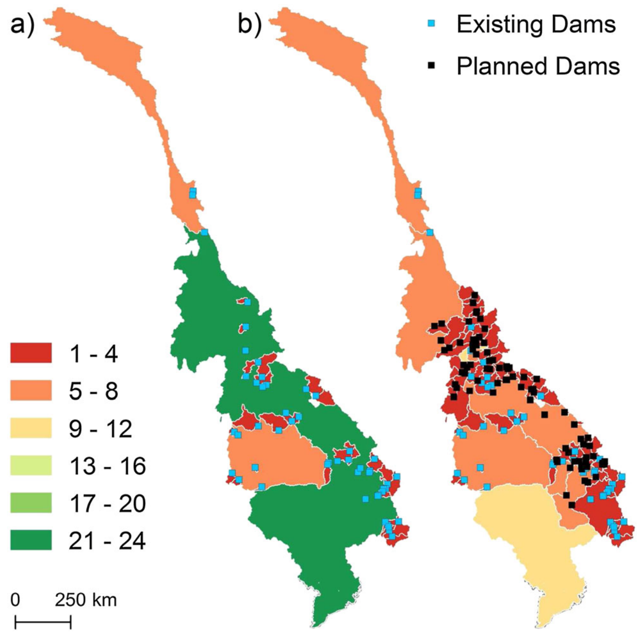

Figure 6. Overview of ecosystem connectivity in the Mekong River Basin for today (2011) and the future (2022) if 84 proposed dams were built (MRC, 2009). Colored regions show the number of different habitat classes found in the remaining connected river network sections. The number of connected ecosystems is strongly reduced for the future development scenario

dams, both individually and in relation to other already existing dams. First results from a subsequent global comparison (Figure 7) show that if all 84 additional dams that are currently under consideration were built, the Mekong River Basin would experience strong alterations in the fragmentation index over the next decade, placing the basin among other heavily impounded rivers in the world.

Geospatial fate and transport modeling for pharmaceuticals in the St. Lawrence River Basin

In a third study, HydroROUT was applied to model the fate of contaminants, specifically the pharmaceutical 'Diclophenac', a common anti-inflammatory drug, in the river network of the lower St. Lawrence Basin (Grill *et al*., in prep.). We calculated the spatial distribution of in-stream concentrations by combining the distribution of river discharge with the substance load at the outlet of sewage treatment plants and accumulated the loadings downstream. A new layer of lakes (as described in Table I) was integrated, and we allowed photo-degradation in both lakes and rivers along the flow path (Buser *et al*., 1998). In addition to concentrations, a risk index for each river reach was calculated using predicted no-effect concentrations of the contaminant, and risk hot-spots were identified in the basin

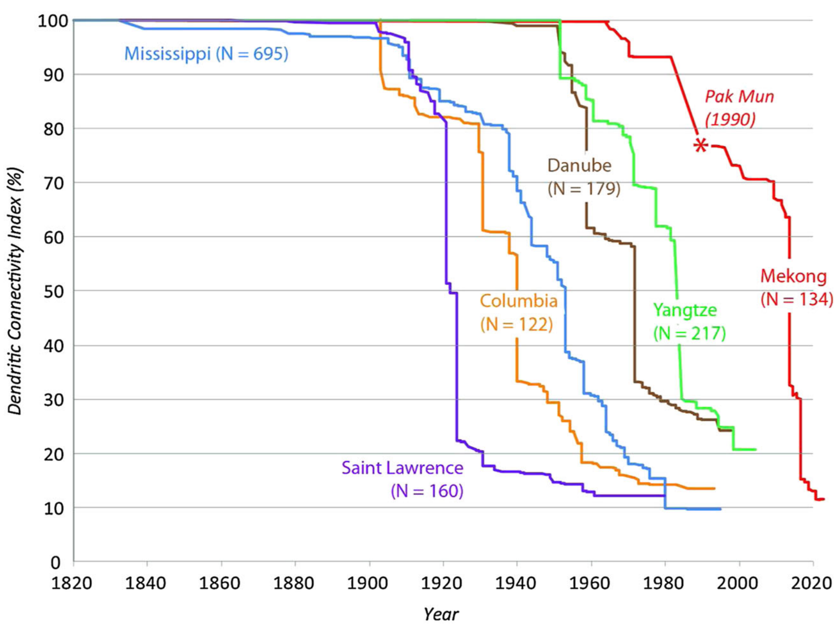

Figure 7. Fragmentation history for selected large river basins. The Dendritic Connectivity Index (DCI; Cote *et al*., 2009) decreases over time as dams are built in the river network. Historic dam constructions prior to 2011 are based on the GRanD database (Lehner *et al*., 2011), while future connectivity in the Mekong is calculated based on a database of 84 proposed dams with commission dates (MRC, 2009). Connectivity decreases rapidly until 2022 if dam development proceeds as planned. N represents the total number of investigated dams in the basin

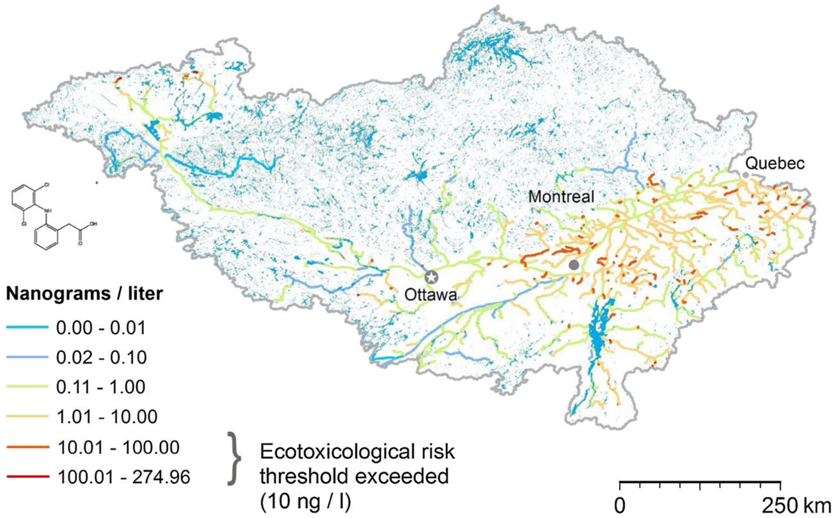

Figure 8. Pharmaceutical concentrations in the St. Lawrence River Basin (downstream of Great Lakes). Predicted Diclophenac concentrations in surface waters based on HydroROUT model results

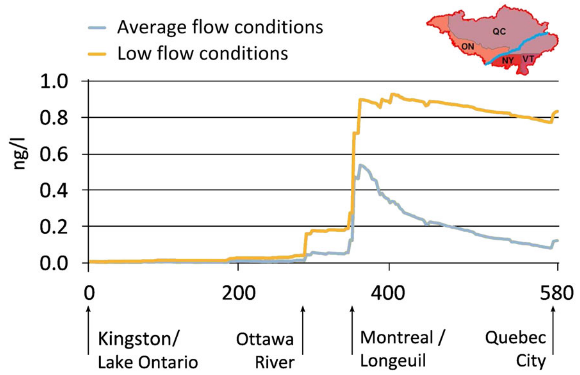

Figure 9. Modeled pharmaceutical concentrations in the St. Lawrence main-stem (downstream of Kingston, Ontario) based on HydroROUT results. Scenario 1 predicts concentrations based on long-term average discharge values. Scenario 2 calculates concentrations under low-flow conditions (monthly Q90 flow)

(Figure 8). By mapping concentrations along flow paths, we identified river confluences with unusually high chemical concentrations as well as locations at which major concentration spikes occurred due to inflows from urban conglomerations (Figure 9).

DISCUSSION

The data and model descriptions outlined above, as well as our case study examples, are aimed at demonstrating the direction and potential of recent advancements in large-scale hydrological and hydro-ecological modeling. Yet this review is far from being complete, and there are many other developments targeting similar goals. In particular, due to the continued increase in computational power, existing models move towards higher resolution both in space and time (Wood *et al*., 2011) and are enhanced by more complex process representations, such as hydrodynamic routing (Yamazaki *et al*., 2011) or the inclusion of advanced water management schemes (e.g. Hanasaki *et al*., 2006; Döll *et al*., 2009). As for our suggested approach to couple new hydrographic datasets with a tailor-made, vector-based flow routing scheme, a number of limitations must be noted regarding the described data and model performance. These limitations, at the same time, provide avenues for future improvements and research requirements.

Our definition of river network routing transcends beyond discharge routing, as it encompasses the movement of energy, material, and organisms. Yet although the primary goal was to develop novel tools for assessing hydrological connectivity, discharge remains a master variable in the model. In the current version of HydroROUT, discharge is based on external runoff calculations that are spatially downscaled to fit our high-resolution river network. An advantage of this decoupled approach is that different global land surface and hydrological models, or even ensembles, can be employed to provide runoff estimates using independent settings and parameterizations, allowing for comparisons and uncertainty assessments. A major disadvantage, however, is that feedbacks between climate, landscape, and hydrological conditions cannot be modeled directly in HydroROUT, rendering it less dynamic than coupled models which include runoff generation, floodplain inundation and evaporation, and hydrological routing simultaneously. A further source of uncertainty in the discharge estimates is the currently applied temporal resolution of monthly averages and the very preliminary validation of long-term conditions only, while inter-annual variability or extreme events are not tested yet. Hence, time-sensitive model results such as seasonal water quality or low-flow substance concentrations need careful interpretation. Finally, the runoff downscaling approach itself may not be able to correctly reproduce local conditions, adding small-scale uncertainties in the discharge estimates.

Another limitation of our current ‘stand-alone’ routing model is the rather simplified routing mechanism: the applied ‘plug-flow’ and ‘completely stirred reactor’ models simulate the transport of constituents as a linear storage-based routing process. This type of model is only valid where uncertainty from friction and backwater effects can be tolerated. At large scales, these effects may be less dominant, and the error terms may be reasonable for applications that aim at general ecological management rather than highly accurate hydraulic flow predictions. For certain regions, however, such as large floodplains, hydrodynamic processes should be integrated in the model to enable a more realistic simulation.

Associated with the routing scheme is uncertainty from simulating flow velocity. River velocities can greatly vary between river types, e.g. steep mountain streams *versus* large lowland rivers. In the examples we presented, we set velocity to a constant value of one meter per second, due to lack of reliable river velocities at the global scale – a widespread limitation in large-scale routing models. The next iteration will include attributes of variable velocities both in the HydroSHEDS database and the HydroROUT model, using similar approaches as suggested by Ngo-Duc *et al*. (2007), Fiedler and Döll (2010), and Verzano *et al*. (2012). For large floodplain areas, additional inundation modeling should be applied to improve flow velocity simulations (Yamazaki *et al*., 2011).

There are various limitations related to the underlying baseline hydrographic data of HydroSHEDS. Besides the current lack of high-quality coverage for regions above 60° northern latitude (see Data section above), HydroSHEDS follows a simple 'D8' concept to represent flow direction: each pixel points towards exactly one of its 8 neighboring pixels as the next downstream one. While this concept is mathematically easy to calculate and allows for proper simulation of main-stem river channels, it cannot represent river bifurcations (i.e. splits into multiple flow channels), braided river systems, or the secondary channels in river deltas. Also, even at 90 m resolution, highly detailed and complex topographic features such as floodplain channels that regulate local hydrological connectivity are still not adequately represented (Yamazaki *et al*., 2012).

Finally, there are limitations related to the new lake database that is used in HydroROUT. While surface areas are mapped at very high resolution and quality, lake volumes are only coarse estimates (see Table I) and are associated with difficult-to-assess uncertainty. Initial tests against a selection of 166 European lakes indicated an acceptable overall match in average lake volume, yet the values of individual lakes may be greatly over- or underestimated.

Despite the many current limitations related to the quality and implementation of both the HydroSHEDS database and the HydroROUT modeling framework, results have to be judged against large-scale needs of ecologists or water resources managers. For example, even if discharge values are prone to substantial uncertainty and error, ecological changes in the river network are often most pronounced at confluences between small tributaries and large main-stem rivers, where flow magnitudes can differ by one or several orders of magnitude. Many critical characteristics along the river network, such as highly altered conditions, disruptions in connectivity, 'swimmable river length', or contributing catchment areas are well represented in the current model version, despite errors in discharge, due to the very high spatial resolution of the hydrographic baseline data. Major changes between river orders or within geographical regions can easily be mapped and related to species distributions; and detailed objects, such as effluents from a sewer plant, can be included as part of the assessments, even if uncertainties in the exact hydrological values are present.

CONCLUSIONS

This paper has been prompted by the challenge to strengthen the currently limited capabilities of GHMs in conducting more integrated hydro-ecological studies – i.e. studies that are able to support comprehensive water resources management; systematic freshwater biodiversity and conservation planning; health assessments related to waterborne diseases and water quality; or risk analyses of future climate and global change impacts on society (e.g. water supply, floods, or hydropower generation). The main limitations identified are related to spatial resolution, data structure, quality of data, inclusion of hydrological connectivity, and support of multi-scale and integrated modeling approaches. In response, we proposed a versatile global hydrological modeling framework that addresses these limitations, providing support for a broad range of applications. We described the enhancement of a global hydrographic database (HydroSHEDS) and the coupled development of a new river network routing model (HydroROUT) as the backbone of our framework. The main novelty over existing approaches is given by the combination of the following characteristics:

- The extensive development of new global data layers (e.g. dams, a hierarchical sub-basin breakdown, lakes, floodplains, etc.) and their harmonized integration with existing HydroSHEDS layers provides a unique baseline geospatial fabric.
- The hybrid model architecture supports linkage and integration of both raster (e.g. DEM, land cover) and vector layers (e.g. river reaches, nested sub-basins, point features). The vector structure enables routing at a spatial precision that is orders of magnitudes higher than in current global pixel-based models, supporting local-scale decision making. Vector routing is also fast to process and allows for more complex analyses (e.g. repeated execution; tracing using weights or barriers) and more natural, object-oriented modeling.
- The river network routing model can couple river reaches with lakes, reservoirs, dams, and floodplains and provides the potential for simulating various routing processes (transport, diffusion, mixing) at multiple spatial scales.
- Powerful routing and tracing capabilities in both upstream and downstream direction provide support of hydrologic connectivity in a broad ecological sense and for a wide range of objects, such as organisms, nutrients, and pollutants; and for the routing of more abstract concepts such as stressors or human impact indicators.
- The implementation of the modeling framework in a high-resolution GIS-based computing environment increases the suitability for hydro-ecological applications, which typically require river-reach scale resolution.

We argue that our integrated data and modeling framework supports a novel set of integrated studies, specifically to estimate the impact of human activities on hydrological functioning and connectivity, and on ecosystem services at large. We summarized ongoing research in support of such studies, e.g. the impact of dams on natural flows and ecosystem fragmentation, and the effects of anthropogenic pollutants on water quality in river networks. We believe that many more applications can be facilitated by our model framework in a variety of related fields, including aquatic ecology, biogeochemistry, geo-statistical modeling, and health risk assessments.

Our case studies showed the potential of the model and data development to facilitate and conduct hydro-ecological research at the global scale. The outcomes may also be used for general education and mapping purposes. New global information portals and data repositories started to incorporate parts of the HydroSHEDS database, including a planned integration into web services such as Google Earth or World Water Online (by ESRI). We hope that this user-friendly and accessible dissemination of data and information, together with the high spatial resolution of the results will support research, planning, and decision-making efforts for many large river basins in the world.

ACKNOWLEDGEMENTS

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada; World Wildlife Fund, Washington, DC; the EU FP7 BioFresh Project, Berlin, Germany; the Global Environmental and Climate Change Centre (GEC3), Quebec, Canada; and McGill University, Montreal, Canada. The authors wish to thank their many colleagues who contributed to this research and the manuscript.

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