Title: Building Virtual Watersheds: A Global Opportunity to Strengthen Resource Management and Conservation

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Abstract

Modern land use planning and conservation strategies at landscape to country scales worldwide require complete and accurate digital representations of river networks, encompassing all channels including the smallest headwaters. The digital river networks, integrated with widely available digital elevation models, also need to have analytical capabilities to support resource management and conservation, including attributing river segments with key stream and watershed data, characterizing topography to identify landforms, discretizing land uses at scales necessary to identify human-environment interactions, and connecting channels downstream and upstream, and to terrestrial environments. We investigate the completeness and analytical capabilities of national to regional scale digital river networks that are available in five countries: Canada, China, Russia, Spain, and United States using actual resource management and conservation projects involving 12 university, agency and NGO organizations. In addition, we review one pan-Euro and one global digital river network. Based on our analysis, we conclude that the majority of the regional, national and global scale digital river networks in our sample lack in network completeness, analytical capabilities or both. To address this limitation, we outline a general framework to build as complete as possible digital river networks and to integrate them with available digital elevation models to create robust analytical capabilities (e.g., virtual watersheds). We believe this presents a global opportunity for in-country agencies, or international players, to support creation of virtual watersheds to increase environmental problem solving, broaden access to the watershed sciences, and strengthen resource management and conservation in countries worldwide.

1.0 Introduction

Countries throughout the world face increasing challenges in balancing their use of natural resources with environmental protections. The diversity of resource uses and the need for environmental protection and conservation lead to numerous questions. What are the site specific effects of agriculture or forestry on water pollution and where would mitigation be most effective? Where do hydropower projects, road systems and energy pipelines present the greatest risk to water quality and aquatic environments? At what locations is wildfire most likely to cause impacts to residences and critical habitats, including by mass wasting? Where are the best locations for conservation activities to improve aquatic resources, including in the context of climate change?

Globally, these questions and others involving resource use and risk mitigation are answered in different ways at different scales. In small to moderate sized areas (10^1 to 10^3 km^2) involving research, high profile development projects or local assessments, studies are often intensive, requiring extensive field work, data compilation and modeling. For example, analysis of the Three Gorges hydropower project in China focused on the Yangtse River and encompassed aquatic ecology, heavy metal pollution, and erosion potential (Wang 2002, Lin et al. 2004). A field intensive plot study of forest road erosion and sediment delivery in the Oregon Coast Range was conducted by the U.S. Forest Service to elucidate the mechanisms responsible for surface erosion and sediment delivery to streams (Luce and Black 1999). Field inventories of salmon habitat in the Knik River basin (250 km^2) in southcentral Alaska by the U.S. Fish and Wildlife Service (2011) were used to increase the mapping of fish habitats for regulatory protection. There is a vast number of other pertinent examples.

Local scale, high profile projects that require intensive study for resource planning exist within larger landscapes, states and regions ($>10^3$ – 10^6 km^2) that have a very limited accounting of environmental conditions and stressors. For example, although high profile projects like the Three Gorges dam receive intensive study (Wang 2002), China's largest reforestation effort in the world, driven in part to reduce erosion due to deforestation, lacks national to regional prioritization based on soil erosion science, including the interactions between topography, soils and vegetation (Ji et al. 2013). Despite intensive plot scale studies of road erosion (Luce and Black 1999), the U.S. National Forest System (760,000 km^2), containing 47,000 km of mostly unpaved roads, lacks analysis of landscape scale aggregate effects of roads (Gucinski et al. 2001). Although progress is being made in field identification of valuable salmon habitats at the scale of the Knik River (250 km^2), mapping of available salmon habitats at larger watershed scales (10^4 km^2) is hindered by incomplete mapping of streams and rivers, and the absence of habitat models (Burnett et al. 2007, Bidlack et al. 2014). In addition, in the U.S. and Canada, large areas under agriculture and forestry generally lack detailed information on riparian processes and consequently most federal, state and provincial environmental regulations apply simple formulas of environmental protection (e.g., uniform vegetation stream buffers), even though such non spatially explicit approaches can lead to less efficient resource use and less effective conservation (Everest and Reeves 2007, Richardson et al. 2012). Despite applications of robust assessment methods in local areas, there is an increasing need for analyses at larger scales (landscapes, states, regions and entire countries) that can take advantage of readily available data to support resource management and conservation in agencies, NGOs and private sectors that do not require expensive research and development programs.

Resource management and conservation activities at landscape to national scales increasingly require the use of computer models to aid in analyses over large areas where more intensive studies, including field work, are impractical. In fluvial landscapes, this requires digital representations of river networks that work within Geographical Information Software (GIS) that are as complete as possible, inclusive of the smallest headwater channels. At the scale of states, provinces and entire countries, such digital river networks are often referred to as “national hydrography” that function as a spatial library of stream and river locations and names. In addition, most countries have their own digital representations of land surface or digital elevation models (DEMs) of varying resolutions (10 m to 30 m, and including sub-meter Light Detection and Ranging [LiDAR]). Global scale DEMs are also available at 1 arc-second resolution (approximately 30 m). The two baseline sources of data (hydrography and DEMs) form the basis for regional to national scale analysis capabilities to support land use planning, risk mitigation and conservation across a diverse range of stakeholders. Although computer based analysis is becoming increasingly necessary at landscape to country scales, complimentary field work and analysis should also be integrated to inform models, validate predictions and increase accuracy.

In this study, we evaluate the degree to which national scale hydrography, available DEMs, and their associated analytical capabilities are suitable for supporting actual resource management and conservation projects in five countries: Canada, China, Russia, Spain, and the United States involving 12 university, agency and NGO organizations. In addition, we review one pan-Euro and one global digital river network for the same purpose. Five analytical components are identified that are necessary to support project objectives. Where capabilities are lacking, we derive digital river networks directly from DEMs and integrate analytical capabilities within them to address project objectives. From this review, we outline a general framework, applicable to any country, which can guide the building of complete as possible digital river networks and to integrate them with DEMs to provide the analytical capabilities (called "virtual watersheds"). We believe this presents a global opportunity for in-country agencies and international parties to support the building of virtual watersheds to increase environmental problem solving, and inform resource management and conservation in countries worldwide.

2.0 Virtual Watersheds: Building Analytical Capabilities to Strengthen Resource Management and Conservation

A 'virtual watershed' is a computer-based geospatial simulation of riverine landscapes used to enumerate numerous aspects of watershed landforms and processes, and human interactions within them over a range of scales. We focus on several aspects of a virtual watershed including the DEM, digital hydrography, their coupling, and analytical components. We review these in five countries to evaluate whether they are sufficient to support actual resource management and conservation projects.

2.1 Digital Hydrography and its Completeness

The advent of GIS ushered in the realm of digital river networks or hydrography (terms used interchangeably in this paper); they are also commonly referred to as "stream layers" in GIS parlance. Digital hydrography comes in two forms, cartographic and non-cartographic, the latter referred to as 'synthetic hydrography' here. In cartographic digital hydrography, stream lines (in a GIS) are often digitized from paper topographic maps. For example, the majority of U.S. national hydrography (called the National Hydrography Dataset or NHD) is derived from 1:100,000 to 1:24,000 U.S. Geological Survey topographic maps, which in turn, were developed using mostly stereographic mapping technology utilizing aerial photography and other optical imagery. Thus, the extent and locations of cartographic digital stream lines originated from visual identification of channels using imagery. The NHD, like its counterparts in other countries (see later), functions as a national spatial library of a country's river networks and thus serves as a valuable resource. The completeness of cartographic hydrography (e.g., the extent to which it incorporates all channels, from the largest rivers to the smallest headwaters, including ephemeral channels) depends on the criteria and care used by cartographic analysts in their visual interpretation of fluvial landforms from aerial photography and other imagery.

In contrast, synthetic digital hydrography is derived directly from DEMs using numerical algorithms that predict flow direction and accumulation. Various algorithms are available to model flow direction and accumulation, including one that restricts flow from any DEM grid cell to one of its eight neighboring cells (Jensen and Domingue 1988) and another that allows grid cells to be subdivided into triangular facets, thus allowing numerous flow directions and hence greater accuracy (Tarboton 1997). Depending on the DEM resolution and quality, smoothing of the surface and removal of closed depressions may be required to calculate flow directions and their accumulations downslope (referred to as hydro conditioning). Flow direction and accumulation are represented as gridded data in a GIS and flow convergence leads to digital representations of river networks (synthetic) while non-convergent flows represent the terrestrial landscape.

The completeness of synthetic hydrography depends upon the resolution of the DEM and how the DEM was derived. For example, a 90 m DEM (e.g., the length dimensions in x, y and z coordinate space) provides only a rough approximation of topography and the resulting synthetic river network may have inaccuracies in river network locations and may omit many headwater streams (Zhang and Montgomery

1994, Peñas et al. 2011). Although a 30 m DEM provides considerably more topographic detail, limitations may still include a low density of headwater channels (Clarke and Burnett 2003). A 10 m DEM can delineate the majority of the channel network and will support other characterizations, such as aquatic habitats and erosion processes (Burnett et al. 2007, Miller and Burnett 2007, Benda et al. 2007). The upper extent of the network and the resulting channel density (km km^{-2}, a measure of river network completeness) must be carefully defined based on factors that control upslope channel extent and the resulting channel density. For example, a minimum catchment area is required in the model 'ArcHydro' (Maidment 2002). A minimum drainage area per unit contour length is used in the model 'TauDEM' (Tarboton 1997) and a boundary condition for representative contributing area is needed to establish headwaters in 'HEC-GeoHMS' (USACE 2000). In the modeling platform 'NetMap' (Miller et al. 2002, Benda et al. 2007), factors include drainage area per unit contour length (Montgomery and Dietrich 1989), hillslope gradient, planform curvature, and channel-initiation criteria (Clarke et al. 2008). Often, the upslope extent of headwater channels is difficult to quantify and thus to represent within synthetic hydrography (and cartographic hydrography) due to ephemeral hydrology.

More recently, LIDAR (Light Detection and Ranging) technology is being used to map land surfaces to create high resolution DEMs (a few centimeters to a few meters). Delineation of synthetic hydrography is greatly improved using LiDAR, with resolutions that range from one to five meters (Mouton 2005, Peñas et al. 2011). For example, river network density (km km^{-2}) increased by more than 30% from 90 m to 5 m DEMs in Spain (Peñas et al. 2011). LiDAR data (2 m) significantly improved identifying and delineating stream channel heads compared to 10 m DEMs in Washington State, U.S.A. (Mouton 2005). However, due to its relatively high cost, LIDAR is of limited availability in many countries, although it is becoming increasingly common, particularly as its benefits become recognized. For example, as of 2012, less than 15% of the land surface of the U. S. was covered with LIDAR DEMs; the majority of the country has 10 m DEMs, derived from 1:24,000 scale topographic maps. However, that situation is rapidly changing and the majority of the contiguous U.S. may have LiDAR coverage by 2020 (U.S.G.S 2014).

2.2 Coupling of Digital Hydrography to DEMs and its Analytical Capabilities

Building analytical capabilities within a virtual watershed to address resource management and conservation questions requires digital river networks coupled to DEMs and integrated with certain analytical components. We identify five general analytical capabilities that are necessary to support resource management and conservation project objectives and we use those as a guide to evaluate the utility of in-country hydrography, DEMs and their capabilities to address actual resource management and conservation projects.

First, digital hydrography needs to transfer information downstream, such as sediment, solutes and pollutants, and information upstream, such as migrating fish and other aquatic organisms; this analytical component is referred to as “routing”. Second, every cell in a DEM needs to be characterized topographically to identify landforms including their elevation relative to the channel network, elevation relative to other areas (concavities, convexities), slope steepness, and flow convergence and divergence (curvature) etc.; this is required to identify floodplains, terraces, alluvial fans and erosional features etc. This component is referred to as “landform”. Third, digital hydrography needs to be spatially referenced to the terrestrial landscape (DEM) to allow for information transfer between them such as sediment flux from hillsides to channels and organic material transfer from rivers to terrestrial areas. In addition, all DEM cells need to be connected to all others to allow information transfer in any direction; this analytical component is referred to as “connecting”. Fourth, the digital hydrography and terrestrial DEM surface needs to be subdivided into facets of an appropriate spatial scale so that watershed processes (wildfire, erosion etc.) and the interactions among land use and landforms can be identified at sufficient detail and accuracy; this capability is referred to as “discretizing”. The fifth and final component is the assigning of watershed and stream attributes to individual segments within the digital hydrography to inform characterizing stream and watershed behavior involving physical and biological processes, including flow and sediment routing, aquatic habitats, and patterns of land use etc.; this component is referred to as "attributing".

There is a distinction between stand-alone hydrography (cartographic or synthetic) and a system of hydrography, coupled to DEMs, which include the five analytical capabilities listed above. Complete and accurate hydrography, including using standard models (such as ArcHydro [Maidment 2002], TauDEM [Tarboton 1997] and HEC-GeoHMS [USACE 2000]) may include some or none of the analytical capabilities listed above. Hydrography that is coupled to a DEM, inclusive of the five analytical capabilities, is most appropriately thought of as a complete, integrated (terrestrial – fluvial) system with a numerical data structure that is designed to simulate various watershed processes and human interactions and thus to support resource management, risk mitigation and conservation. We refer to this analytical system as a "virtual watershed'.

3.0 Methods: Evaluating National Digital Hydrography and Their Analytical Components in Five Countries

Using actual resource management and conservation projects in five countries involving 12 university, agency and NGO organizations, we evaluated whether the national to regional scale DEMs, the completeness of national to regional digital hydrography, and their associated analytical components were capable of supporting the project objectives in each country. Project locations included: 1) Rocky Mountain Foothills, Alberta, Canada; 2) Heilongjiang Province, Northeast China; 3) Sakhalin Island, Eastern Russia; 4) Cantabria Region, Northern Spain; and 5) Western Oregon and South-central Alaska, U.S.A. Each of this paper's authors was involved with the analysis projects in one or more of the five countries.

In addition, for each project in which capabilities were lacking, we developed synthetic hydrography, coupled to DEMs, with integrated analytical components using the desktop watershed modeling platform "NetMap" (Benda et al. 2007) to support each project's goals.

4.0 Results

4.1 Rocky Mountain Foothills, Alberta Canada: Channel Classification–Regulatory Compliance

In Alberta Canada, the University of British Columbia (UBC) and the Foothills Research Institute (FRI) initiated a project to advance the regulatory protocols for forest harvesting, road construction, and other activities that can impact aquatic resources (ASRD 2008). Project objectives included classifying hydrological channel types (e.g., ephemeral, intermittent, perennial) and delineating habitat extents for headwater dwelling fishes (e.g., bull trout [*Salvelinus confluentus*] and rainbow trout [*O. mykiss*]) (Table 1).

The Province of Alberta maintains a national hydrography (cartographic, derived from 1:20,000 topography) that includes a single-line network with a drainage density of 1.1 km km^{-2} (AENV 2000) (Table 2). Rivers larger than 20 m in width are well represented but numerous smaller watercourses are classified as poorly distinguished (indefinite class) or are not included (McCleary et al. 2011) (Figure 1). The inadequately represented headwater streams, which comprise more than 60% of the total length of the river network in the Rocky Mountain Foothills region (McCleary et al. 2008), are ecologically important and require regulatory protection (ASRD 2008). In addition, the Alberta cartographic hydrography lacks many attributes, landforms, discretization and connectivity (Table 3).

To overcome these limitations, UBC and FRI built synthetic hydrography using 1m LIDAR DEMs (Figure 1). The synthetic river network density is 5 km km^{-2} and the average channel reach length is 140 m (compared to Alberta's cartographic stream segment lengths that average 675 m, Table 2). Attributes in the synthetic hydrography required for channel and habitat classification included drainage area, channel gradient, mean basin slope, and channel longitudinal profiles (McCleary et al. 2011); attributes readily available in a virtual watershed. The regional-scale empirical stream hydrology classification included uplands, swales, seepage-fed channels, and fluvial channels and they can be used to apply variable width vegetation buffers along water courses to protect water quality and aquatic habitats.

Table 1. Study objectives in each of the five countries.

Location	**Project Objectives**
Rocky Mountain Foothills, Alberta Canada	Create channel hydrologic classification; Predict fish habitat types.
Heilongjiang Province, Northeast China	Characterize soil erosion potential due to deforestation; Predict sediment delivery potential to streams.
Sakhalin Island, Eastern Russia	Predict hydraulic geometry and substrate; Map floodplains; Characterize salmon habitats.
Cantabria Region, Northern Spain	Characterize channel geometry; Predict aquatic habitats; Delineate riparian zones; Map erosion potential; Delineate floodplains; Classify valley types.
Western Oregon and South-central Alaska, U.S.A.	Characterize channel geometry; Delineate floodplains; Predicting salmon habitats; Predicting landslide potential; Predicting debris flow potential.

Table 2. Data types and resolutions of national to regional scale DEMs and hydrography.

Location	**DEM resolution**	**Hydrography[1]**	**Drainage density[2] (km km^{-2})**	**Segment length (m)[3] (average)**
Spain	Variable 5 – 20 m	(1:25,000), Cartographic	1.3	5 – 5,000 (600)
Spain JRS-IES CCM[5]	90 m	SRTM 3 arc second (100 m)[4], Synthetic	0.7	100 – 24,000 (2,400)
Alberta Canada	20 m	(1:50,000), Cartographic	1.1	100 – 10,000 (625)
Alberta Canada	1 m LiDAR	LiDAR (1m)[4] Synthetic	4.6	1 - 150 (95)
Russia	30 m	(1:200,000), Cartographic	1.6	100 – 8,000 (850)
U.S. NHD (Oregon Coast Range)	10 m	(1:100,000-1:24,000), Cartographic	Variable 1.3 – 7.8	5 – 6,800 (900)
China Low res	12 m	(1:500,000), Cartographic	<0.1	225 – 4,000 (800)
China High res	2 m LiDAR	(1:50,000), Cartographic	0.7	50 – 250 (125)
HydroSHEDS[6]	30 – 90 m	30 – 90 m[4] Synthetic	<0.2	500 – 18,000 (4,700)

[1] Derivation of in-country hydrography.

[2] Drainage density; density < 3 km km^{-2} is considered incomplete.

[3] Spatial scale of individual channel segments within digital hydrography.

[4] DEM resolution used in synthetic network derivation.

[5] Joint Research Centre, Institute for Environment and Sustainability (IES), Catchment Characterization and Modelling 2008; http://ccm.jrc.ec.europa.eu/php/index.php?action=viewandid=23

[6] HydroSHEDS; http://hydrosheds.cr.usgs.gov/index.php.

Table 3. Review of hydrograph completeness and analytical components in individual countries for specific resource management and conservation projects. Low, moderate (mod) and high ranking refers to a qualitative scoring of the different analytical capabilities and network completeness.

Network Completeness and Analytical Capabilities[1]	**Spain**	**Spain CCM2**	**Canada**	**Canada**	**Russia**	**U.S.**	**China**	**China**	**Hydro SHEDS**
River network completeness[2]	Mod	Low	Mod	High	Low	Mod - variable	Low	Mod	Low
Network Routed[3]	Yes/No 2 of 4	Yes	No	No	No	Yes	No	No	Yes
Network Attributed[4]	Mod	Mod	Low	Mod	No	Low	No	No	Mod
Landforms[5]	No	No	No	Wet Areas	No	Lakes	No	No	No
Discretization[6]	Low	Mod	Low	Low	Low	Mod	Low	Low	Low
Connectivity[7]	No	Mod	No	Low	No	Mod	No	No	Low
Relative Score[8]	Low	Mod	Low	Mod	Low	Mod	Low	Low	Low[9]

[1] Complete as possible hydrography, and analytical capabilities of routing, landform classification, connecting, discretizing and attributing.

[2] Completeness of digital river network, from headwaters to mainstems. High refers to almost all channels included, Low refers to very low network density. See Table 2 for network densities.

[3] Network routed, reaches referenced up- and downstream. Yes/No.

[4] With attributes necessary to inform project objectives (Table 1). High-Moderate-Low (reach lengths not applicable).

[5] Landforms, as described in text. Yes/No, and types.

[6] Discretization of streams, networks, landforms, terrestrial data and land use activities (Figure 7). No, High-Mod-Low.

[7] Connectivity by various types (e.g., Figure 6). No, High-Moderate-Low refers to the number of connectivity types.

[8] Relative score is the central tendency of the various rankings.

[9] Overall low score due to extremely low global river density as well as other lower rankings.

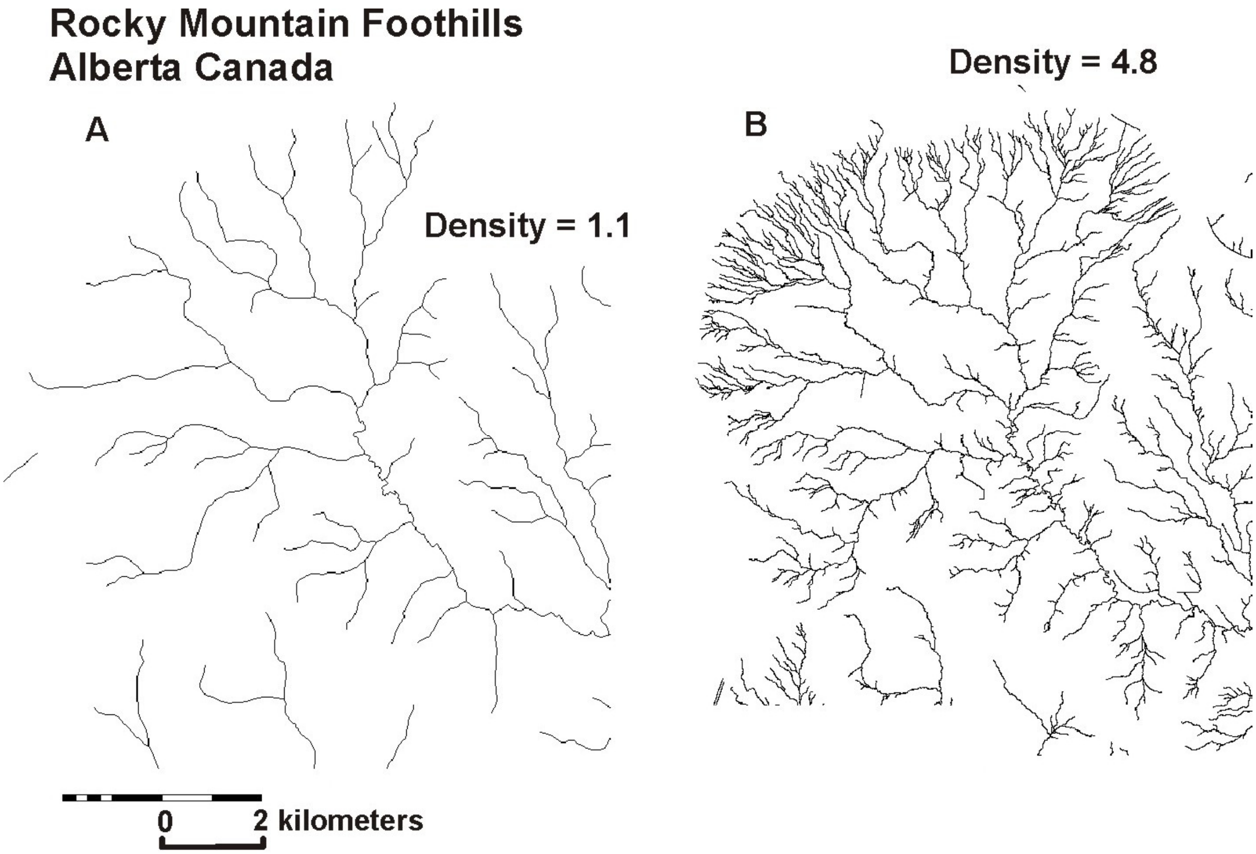

Figure 1. (A) A cartographic Provincial stream layer in Alberta, Canada with a low stream density (most headwaters omitted). (B) A synthetic stream network built using 1 m LiDAR is shown for comparison.

Alberta also has regional synthetic hydrography derived from 1 m DEMs that is being used to identify stream-adjacent wetlands for regulatory compliance (Murphy et al. 2009, White et al. 2012). The LiDAR-based synthetic hydrography has a density of 4.6 km km^{-2} and thus accurately identifies the majority of the channel network (Table 2). However, the synthetic hydrography is created at the scale of LiDAR DEM tiles (14 km x 16 km) and flow lines do not consistently match up at tile borders (Benda et al. 2015). In addition, the synthetic hydrography, coupled to the LiDAR DEM, does not contain the necessary attributes, landform characterization and discretization to support channel and fish habitat modeling and classification (Table 3).

Alberta’s LiDAR based hydrography was combined with NetMap’s watershed modeling platform to build a hybrid system, one that takes advantage of the LiDAR hydrography and adds to it the five virtual watershed analytical components (routing, landform, connecting, discretizing, and attributing). This provides an example of how existing, high resolution in-country synthetic hydrography can be updated with capabilities to address resource management and conservation objectives.

4.2 Heilongjiang Province, Northeast China: Deforestation and Erosion Potential - Planning/Restoration

Accelerated soil erosion due to deforestation and agriculture is an important resource concern in China (Wang et al. 2005) resulting in the largest reforestation program in the world. The Northeastern Forestry University in Harbin is involved with improving restoration strategies. The Yongcui catchment (50 km^2) in Heilongjiang Province was selected as a demonstration site. Project objectives included building complete as possible digital river networks with the analytical capabilities to predict soil erosion potential and sediment delivery to streams (Ji et al. 2013) (Table 1).

The China national cartographic stream layer (derived from 1:500,000 scale topographic maps) has a stream density of 0.1 $km\ km^{-2}$ (Table 2) and thus includes only the largest rivers (omitting about 90% of the actual channel network; Figure 2). In addition, the national stream layer contains long channel reaches (average 800 m) and it lacks routing, attributes, landforms, discretization and connectivity (Tables 2 and 3).

A few catchments in China, including the Yongcui, have a higher resolution stream layer for research purposes (Figure 2). However, the higher resolution cartographic stream layer (derived from 1:50,000 scale topographic maps) also has a low stream density (0.7 $km\ km^{-2}$, Table 2) and omits most headwater channels. In addition, the higher resolution stream layer is not routed and lacks attributes, landforms, discretization, and connectivity (Table 3).

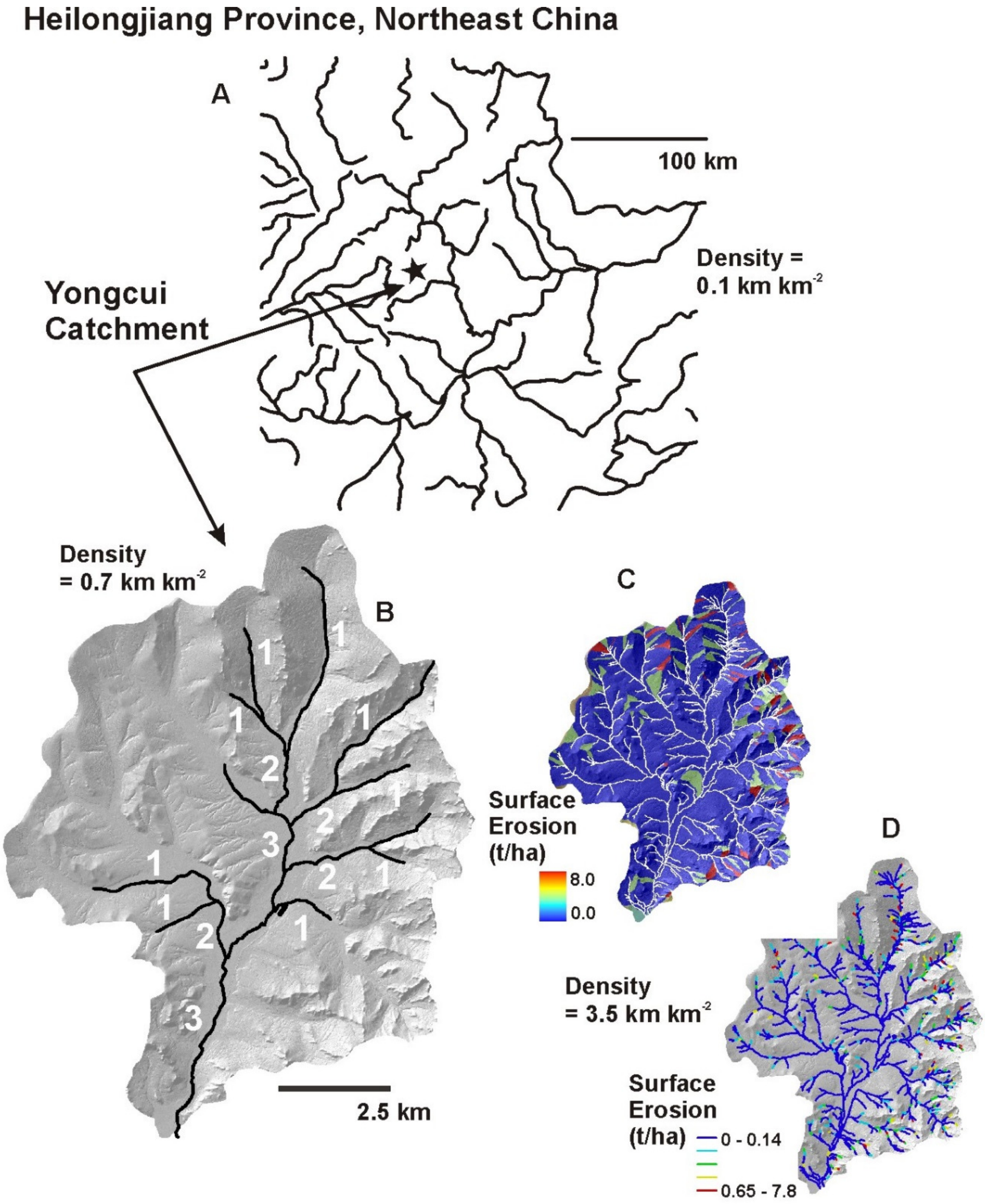

Figure 2. (A) The China national cartographic stream layer includes only the largest channels (density = 0.1 km/km2) and it omits about 90% of the actual channel network (Table 2). The stream layer contains multi kilometer segments, is not derived or coupled to the DEM, is not routed and omits attributes, discretization and connectivity (Table 3). (B) A stream layer of higher resolution exists in the Yongcui catchment of northeast China although it's drainage density is only 0.7 km/km2, and omits the majority of headwater streams. (C). The synthetic river of the virtual watershed contains significantly more streams (density = 3.5 km/km2) with segments of 50 to 200 m in length, is routed, coupled to the DEM, has discretization, and is attributed with numerous parameters. Shown is the predicted spatially

variable surface erosion potential related to deforestation. (D) Surface erosion potential is reported to channel segments, offering a fish-eye view of an environmental stressor.

The Northeastern Forestry University built digital synthetic hydrography using a 2 m LiDAR DEM (a higher resolution DEM was available for the research watershed, although 12 m DEMs exist for a majority of China). The synthetic network density was 3.5 km km^{-2} and the average channel reach length was 150 m (Figure 2). In addition, a surface erosion model (Elliot et al. 2001) was integrated into the virtual watershed to address the impacts of deforestation on soil erosion and its potential impacts on streams and rivers (Ji 2014). The erosion model uses slope steepness, slope profiles, soil types, and frequency and magnitude of rain storms; all attributes readily obtained using the five analytical capabilities in a virtual watershed. The model was run under two scenarios to develop a sensitivity analysis of the basin's susceptibility to surface erosion: a condition of full forest (as exists today) and the hypothetical condition of full deforestation, followed by slash burning.

Under the simulated climate and fully forested conditions, no surface erosion is predicted in the study basin, due in part, to the low gradient topography in the basin, full forest vegetation and low 24-hr storm magnitudes (Ji 2014). Under deforested and burned conditions, the model predicts significant surface erosion and sediment delivery to streams but only in certain areas of the catchment due to variable hillslope steepness and the proximity of hillsides to streams (Figure 2). The analysis could be used to prioritize areas for reforestation to reduce erosion potential in other areas of China. The analysis also produces information about where erosion may be greatest under deforested conditions and thus it could be used to plan timber harvest and road development in the watershed.

4.3 Sakhalin Island, Russia: Fish Habitat Modeling–Conservation Planning

Sakhalin Island, the largest island in the far east portion of the Russian Federation, provides habitat for 11 species of salmon including Taimen (*Hucho taimen*) and Masu (*Oncorhynchus masou*), which are limited to the western Pacific. Sakhalin Island is the target of international conservation planning (U.S. AID, Wild Salmon Center), a collaborative process that promotes conservation and sustainable use of wild salmon. Project objectives include constructing models of salmon habitat (spawning and rearing) and to use those to guide future resource use, including forestry activities (Table 1).

The Russian cartographic hydrography covering Sakhalin Island (derived from 1:200,000 scale topographic maps) has a density of 1.6 km km^{-2} and therefore is incomplete (e.g., lacking headwaters; Figure 3, Table 2). The cartographic layer also contains lengthy channel segments (average = 850 m), and lacks attributes, landforms, discretization and connectivity (Table 3). These limitations make it unsuitable for aquatic habitat modeling and conservation planning.

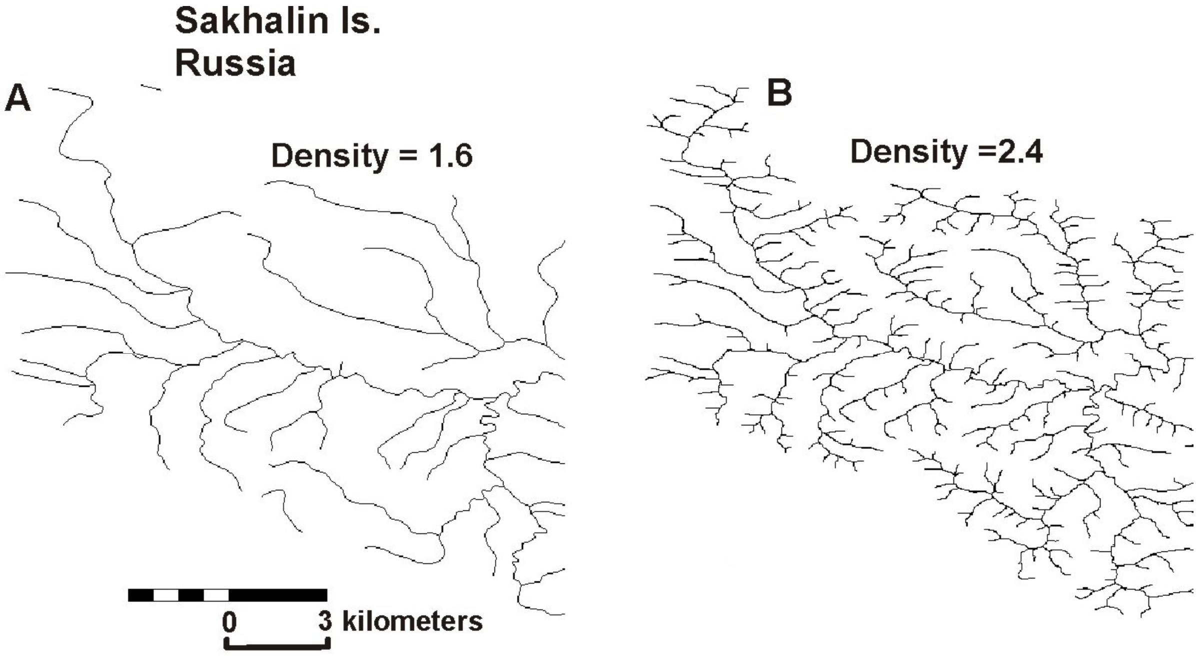

Figure 3. (A) The Russian cartographic stream layer for Sakhalin Island has a low stream density (Table 2). (B) A synthetic stream layer built using 30 m DEMs has a higher channel density but still comparatively low because of the low resolution DEMs (Table 2).

The Sakhalin Salmon Initiative built synthetic hydrography using NetMap employing ASTER 30 m DEMs to model salmon habitats. The synthetic river density was 2.4 km km^{-2} (Figure 3); the lower density relative to the other synthetic hydrography is due, in part, to the coarser nature of the DEMs (30

m) used to derive the network (e.g., many headwaters are not topographically discernible). The synthetic river was attributed with drainage area, channel gradient, channel width, flow depth, flow velocity and substrate size (attributes available in a virtual watershed). The synthetic hydrography in the three watersheds in Sakhalin Island (Naicha, Taranai, Kura Rivers) was used to model fish habitats and to support hydrological analysis and stream monitoring (Wild Salmon Center 2013). The goal is to use island-wide fish habitat maps to guide resource use (such as timber harvest and road construction) and to protect the most valuable aquatic environments.

4.4 Cantabria Region, Northern Spain: Integrated Catchment Management

MARCE is involved with developing a spatial framework for integrated catchment management in northern Spain (http://marce.ihcantabria.es/). The aim of the project is to improve understanding about the relationship between human impacts (dams, weirs, sewage outflows, embankments) and aquatic and riparian ecosystems through the use of environmental monitoring data gathered to comply with the European Union's Water Framework Directive (2000) and use of different modelling approaches. Project objectives include characterizing physical attributes of channel networks within their watersheds, including channel geometry, riparian zones, aquatic habitats and erosion potential (Table 1).

The project area is covered by Spain's national cartographic river network (1:50,000) used for establishing Water Framework Directive river typologies. However, the cartographic network omits all channels with drainage areas less than 10 km^2 and thus has a very low channel density of 0.3 km km^{-2} (Table 2, Figure 4), has an average stream segment length of 15 km, and does not contain landforms, discretization and connectivity (Table 3). There exists another cartographic network in Spain (1:25,000) with a higher density (1.3 km km^{-2}) administered by Confederación Hidrográfica del Cantábrico water agency but it is incomplete (lacks headwaters) and has lengthy segments (average 2200 m), and lacks landforms, discretization and connectivity (Tables 2 and 3).

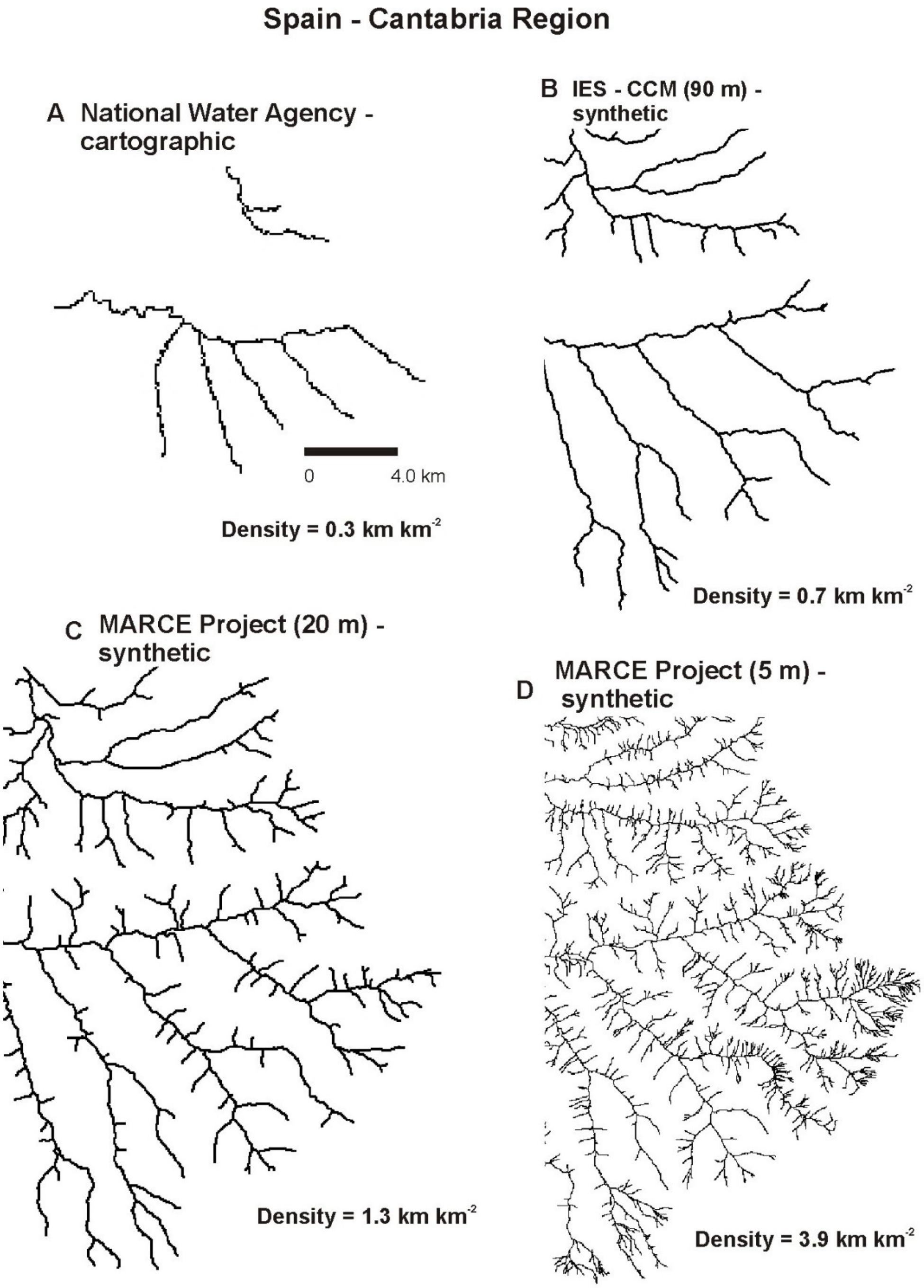

Figure 4. A – D shows digital hydrography of the same area in northern Spain (Pas River watershed). (A) Spain’s national cartographic stream layer (1:50,000) omits streams with drainage areas less than 10 km^2. (B) A pan Euro synthetic stream layer is derived from SRTM 3 arc-second (~90 m resolution) DEMs. (C) The MARCE project synthetic stream layer built using 20 m DEMs. (D) The MARCE project synthetic stream layer built using 5 m DEMs. Note how the completeness of the stream networks (as shown with channel densities) increases with DEM resolution. Field and aerial photo validation confirmed stream density in D. See Tables 2 and 3 for additional comparative analysis.

A pan-European synthetic hydrography (Catchment Characterization and Modelling) that was created by the Institute for Environment and Sustainability (IES) using SRTM 3 arc-second (~100 m resolution) DEMs also extends across the project area (Table 2). The CCM2 database (2008) is used to support the EU Water Framework Directive and the European Environment Agency's modeling of hydrological processes (Vogt et al. 2007). The CCM synthetic network has a density of 0.7 km km^{-2} and omits most headwater and intermediate size streams and thus is incomplete (Figure 4). Subbasins are included and scaled by Strahler (1952) stream orders. The river network is routed and contains some attributes (length, drainage area, gradient, stream order). The combined DEM and digital hydrography lacks landform mapping capabilities, discretization and other modes of connectivity necessary to support MARCE project objectives (Table 3).

To overcome these limitations, the Institute of Environmental Hydraulics (University of Cantabria) built synthetic hydrography using a 20 m DEM across approximately one quarter of Spain (125,000 km^2) in support of MARCE objectives. The resulting river network is routed and has a density of 1.3 km km^{-2} (Figure 4). The relatively low drainage density in the synthetic network is a consequence of the coarse (20 m) DEMs used to derive the hydrography. Relevant attributes in support of MARCE in the virtual watershed included channel length, drainage area, gradient, floodplain width, and channel width and depth.

Within the MARCE project area, NetMap's modeling platform and its integrated analytical capabilities were applied in two catchments on the Atlantic and Mediterranean coasts including the Pas and Hijar River watersheds (650 km^2 and 250 km^2). In these locations, synthetic hydrography were built using higher resolution 5m DEMs; the resulting drainage density was 3.9 km km^{-2}, much closer to field conditions (Figure 4). The analytical environment supported analysis of floodplains, valley types and transitions, riparian areas, tributary confluence effects, and erosion potential. This resulted in a catchment scale perspective of watershed and river restoration (Benda et al. 2011, Barquín et al. 2011), an approach for delineating riparian zones (Peñas et al. 2011, Fernandez et al. 2012a) and a method for predicting riparian quality over entire river networks (Fernandez et al. 2012b).

4.5 Western Oregon and Southcentral Alaska, United States: Fish Habitat Delineation-Conservation and Resource Management

Agriculture and forestry in western Oregon are partly responsible for habitat loss of Pacific salmon; coho salmon (*O. kisutch*) in the Oregon Coast Range is listed as an ‘endangered species’ (NOAA Fisheries 2012). The U.S. Forest Service and Oregon State University created the Coastal Landscape Analysis and Modeling Study (CLAMS) to design forest management policies to ensure a sustainable timber supply while protecting salmon habitats, specifically for coho, Chinook (*O. tshawytscha*) and steelhead trout (*O. mykiss*). Project objectives included predicting fish habitats and landslide and debris flow potential in headwater streams (Table 1).

The U.S. national cartographic hydrography (NHDPlus 2012), derived from 1:100,000 and 1:24,000 scale topographic maps, contains coverage across the Oregon Coast Range (as well as across the entire U.S.). The NHDPlus cartographic product in the Oregon Coast Range (1:24,000) contains a variable density of streams (8.4 to 1.3 km km^{-2}) reflecting its variable origins and methodologies (Table 2, Figure 5). In some areas there are too many headwater channels while in other areas there are too few; such areas can be located adjacent to one another (Figure 5). The NHD digital hydrography is coupled to a 30 m DEM through the process of “burning in” which the DEM is excavated to enforce channel locations and “walls” are built at subbasin boundaries to enforce the cartographic stream lines within basins; the forced integration of hydrography and DEMs results from a hydrography that is not derived from the DEM. In addition, the NHD has long channel reaches (average 900 m, precluding fine-scale discretization) and contains few attributes necessary to model fish habitats, and no landforms (with the exception of lakes) (Table 3). The NHDPlus has the ability to route (using event tables) and includes catchments for discretization, although they are large (multi-kilometers) which limits the ability to isolate watershed processes, landforms and land use interactions at small, individual hillside and stream segment scales (tenths of a square kilometer and a hundred meters respectively, Tables 2 and 3). Despite these limitations, the NHDPlus has advantages such as the inclusion of artificial channels (water divisions can be a substantial component of flow routing in certain locations) and its incorporation of certain hydrologic variables (i.e., average annual precipitation, average daily temperature, among others).

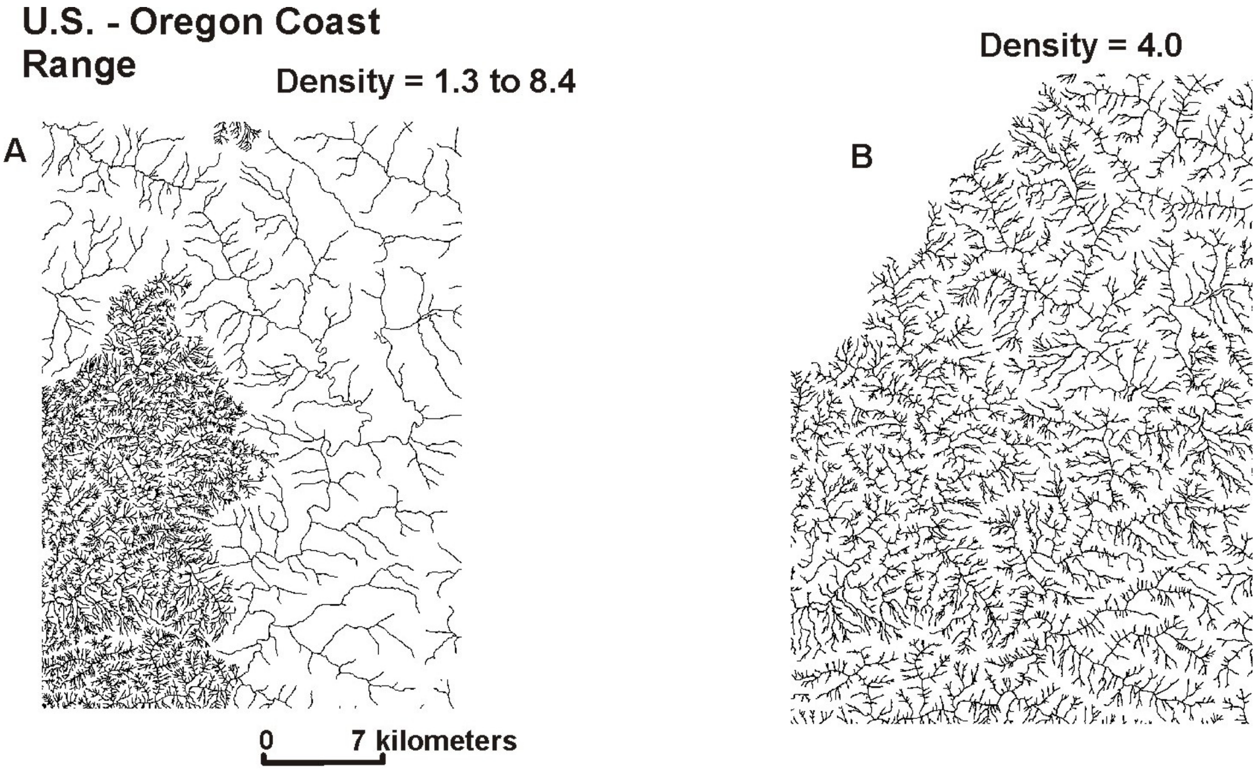

Figure 5. (A) The U.S. National Hydrography Dataset (NHDPlus) has variable stream densities in the Oregon Coast Range. (B) A consistent and field validated density of streams occurs in the synthetic stream layer as part of a virtual watershed in the same area.

Given these limitations, the CLAMs project built synthetic hydrography using 10 m DEMs to characterize spatial relationships among forest age, fish habitat, and land use (Spies and Johnson 2007). The resulting, more complete and consistent synthetic channel network had a density of 4.0 km km^{-2} (Figure 5) and includes the majority of headwater streams; measured channel density in the Oregon Coast Range using aerial photography and field surveys is 4.6 km km^{-2} (Benda and Dunne 1987). Channel reaches averaged 120 m. Attributes required for models of fish habitat, landslides and debris flows included channel gradient, channel width, mean annual flow, drainage area, valley width and confinement, hillslope gradient and curvature, and tributary junction angles (Miller and Burnett 2007, 2008); all attributes available in a virtual watershed with analytical capabilities.

The CLAMs analysis provided spatially explicit information on locations of the best fish habitats and those most vulnerable to land use activities (Burnett et al. 2007, Burnett and Miller 2007). When combined with land use patterns and forest growth projections, the analysis provided a basis for assessing regional forest management policy (Ohmann et al. 2007). Coupling fish habitat maps, with predictions of landslides and debris flows, has informed stream protection strategies, including in headwater channels (Pickard 2013, Reeves et al. in press).

The NHDPlus cartographic hydrography was used to guide locations of NetMap's synthetic hydrography in watershed areas where low relief compromised the ability of the flow direction and accumulation algorithms to accurately delineate channels. This indicates how existing cartographic hydrography can be usefully combined with hydrography derived directly from DEMs, including in the context of building virtual watersheds. In addition, the additional attributes of the synthetic network can be conflated to NHD stream segments, thus adding value in support of resource management and conservation.

The second example from the U.S. is from the Copper River watershed in south-central Alaska. The State of Alaska has poorly resolved cartographic hydrography with a network density of 1.0 km km^{-2}; Table 2). To improve the fidelity of channel networks for more comprehensive mapping of potential salmon streams, Ecotrust and the U.S. Forest Service built synthetic digital river networks using a combination of 20 and 30 m DEMs. The attributed river networks (including the parameters of channel gradient, width and extent of glaciation) was used to build a Chinook salmon habitat model which increased the mapped extent of potential Chinook habitat by 300% (Bidlack et al. 2014). A similar effort (funded by The Nature Conservancy) to build a synthetic river network within a virtual watershed for improved salmon habitat mapping is currently underway in the Matanuska-Susitna watershed (68,000 km^2) located near Anchorage, Alaska.

4.0 Discussion

4.1 Evaluation of Existing Hydrography and Associated Analytical Capabilities in Five Countries

Existing digital hydrography, combined with DEMs, available in five countries were evaluated to determine whether they could meet objectives of actual resource management and conservation projects (Table 1) by 12 university, NGO and agency organizations between 2008 and 2014. In the Canadian, Spanish, Russian, and Chinese examples, they include incomplete mapping of channel networks in the national to regional scale cartographic digital hydrography (typically excluding all or many headwater streams), lengthy segments, lack of routing (with exception of two of four Spanish stream layers) and the omission of key attributes, landforms, discretization and connectivity (Tables 2 and 3, Figures 1 through 5). The Spanish pan-Euro CCM2 (2008) network dataset contains many valuable features, but was judged inadequate because of its incomplete nature (low drainage density, 0.7 km km^{-2}) and other limitations with respect to the MARCE project objectives (Table 3).

The U.S. national stream layer (NHDPlus) has upstream-downstream routing, large scale discretization (catchments), landforms (lakes), and routing (Tables 2 and 3). However, the NHDPlus has inconsistent channel densities because of its cartographic derivation, including by multiple agencies (Figure 5). The NHDPlus also lacks attributes necessary for predicting freshwater habitats and hillslope characteristics, such as erosion potential. Its lengthy segments preclude fine scale discretization (Tables 2 and 3). The NHDPlus inexactly couples the river network to a 30-m DEM (through the process of “burning in” and “walls”), a consequence of the cartographic hydrography not derived from DEMs. The NHDPlus, however, does have advantages given its incorporation of artificial channels (diversions, flumes, and canals) and inclusion of certain hydrologic variables.

The NHDPlus in western Oregon is an example of how two different technologies can be usefully combined to enhance both. Derivation of the synthetic hydrography utilized the NHD digital stream lines in areas of low relief and low gradient to enforce locations of the larger rivers in the synthetic network within a virtual watershed. Concomitantly, the enhanced attributes of the synthetic network can be conflated to NHD stream segments, thus adding value in support of resource management and conservation in those agencies that utilize the NHD.

The Canadian-LiDAR derived hydrography (White et al. 2012) is highly accurate in channel density and location but lacks other capabilities to support resource use planning and conservation. However, it provides an example of how regions or countries with their synthetic hydrography can be expanded to include characteristics of virtual watersheds, taking advantage of the expanded capabilities to support resource use and conservation.

The relatively poor nature of many countries' cartographic hydrography might be addressed by newly available global scale synthetic river networks created using DEMs. HydroSHEDs is a U.S. G. S. – World Wildlife Fund global set of synthetic river networks built using 3 arc-second DEMs (90 m, depending on latitude). The goal of HydroSHEDs is to support regional watershed analyses, including hydrological modeling and freshwater conservation planning. However, the channel density of HydroSHEDs synthetic networks is extremely low (< 0.2 km km^{-2} for an area in the Oregon Coast Range that has an actual density closer to 4 km km^{-2}), on par with the lowest cartographic national stream layer we evaluated (China) (Figure 6, Table 2). This limitation alone renders HydroSHEDs inadequate to address the resource management and conservation projects outlined in this paper (Table 1).

Our review of regional, national and global scale digital hydrography in five countries reveals that most are incomplete, generally lacking headwater channels. Incomplete fluvial networks would greatly hinder many applications in resource management and conservation (e.g., Table 1). Added to this limitation is the general absence of analytical capabilities that are needed in the projects including attributing river and terrestrial landscape elements with key stream and watershed data, characterizing topography to identify landforms, discretizing land uses at scales necessary to identify human-environment stressors, and connecting channels downstream and upstream, and to terrestrial environments.

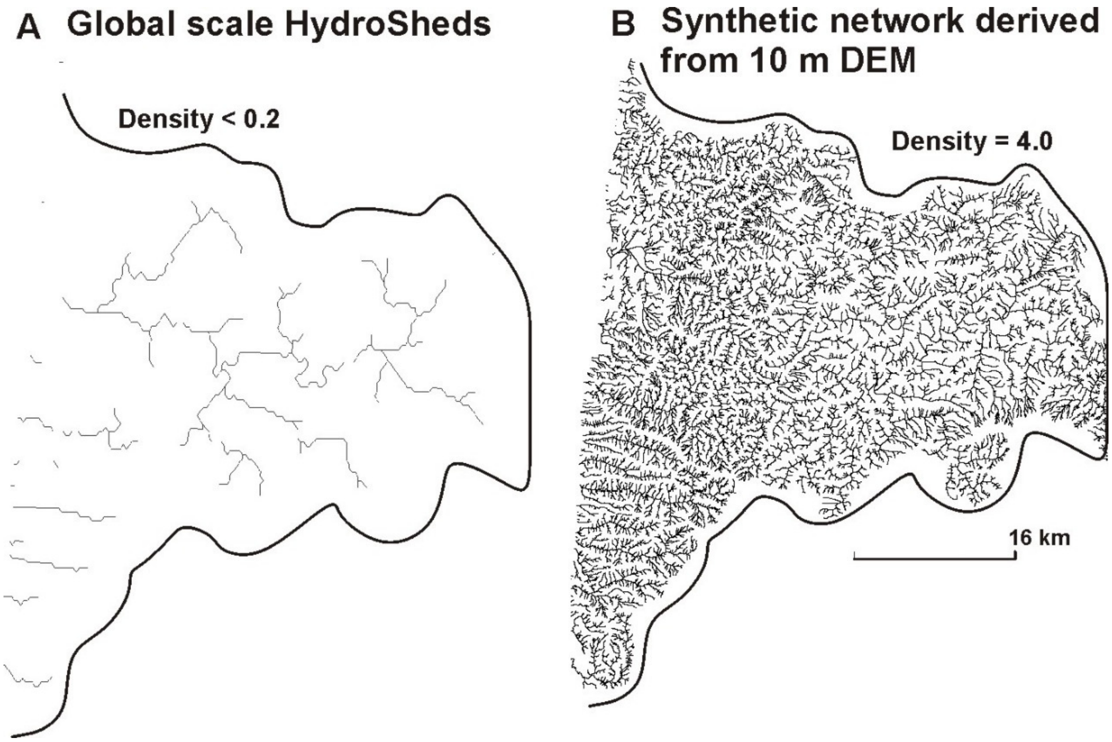

Figure 6. (A) The global scale HydroSheds has a very low drainage density in the Oregon Coast Range, U.S.A. (B) The same river network showing the synthetic hydrography built using 10 m DEMs in a virtual watershed.

Our review of the completeness of hydrography and its analytical capabilities in five countries represents a small subsample of countries worldwide. However, our sample reflects a collection of major countries that to greater and lesser degrees practice modern land use planning and conservation. Hence, we suggest that our sample, although obtained opportunistically by available projects, reflects on the condition of many countries worldwide, including those with lesser developed environmental science and technology programs. Thus, many more countries likely have national hydrography that is incomplete (lacking headwaters if not larger portions of their river networks), lack analytical capabilities (consistent with our description of virtual watersheds) or both. However, the building of synthetic river networks, coupling them to DEMs and adding analytical components in each project indicates how new technologies can be applied in each country to enhance resource management and conservation objectives. Thus, we believe an opportunity exists, globally, to achieve similar improvements in other countries.

4.2 Building Virtual Watersheds in Support of Resource Management and Conservation

Combining as complete as possible synthetic hydrography with DEMs (of the highest resolution available) and adding to them analytical capabilities (e.g., routing, landforms, connecting, discretizing and attributing) provides a robust basis for supporting resource management and conservation. We refer to the computer-based geospatial simulation of riverine landscapes as a “virtual watershed” (Figures 7 and 8).

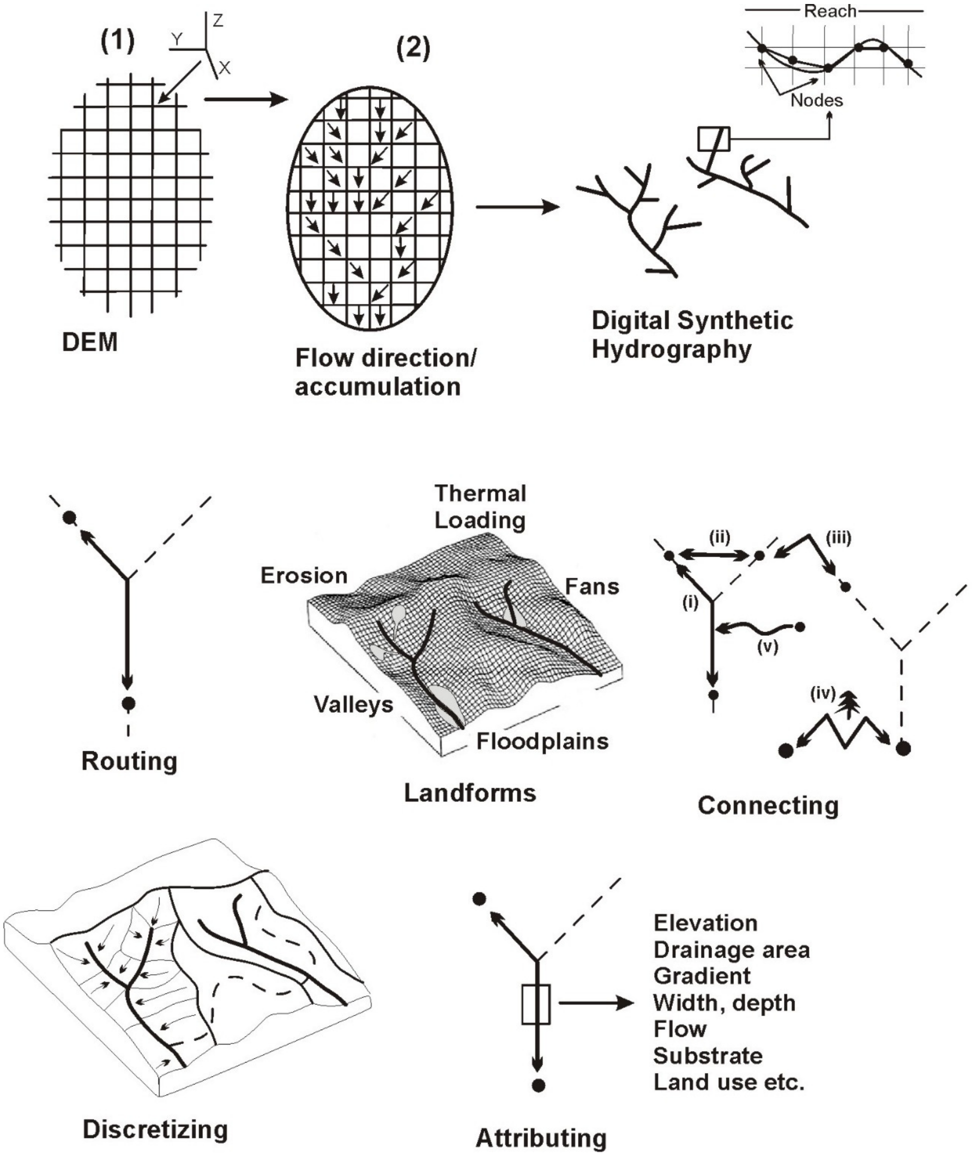

Figure 7. The coupling of the DEM with synthetic hydrography contains a numerical data structure that support five types of analytical capabilities within a virtual watershed. Multiple connectivity pathways, include i) river connected, ii) Euclidean distance, iii) slope distance, iv) gravity driven flow paths and v) modified slope distance.

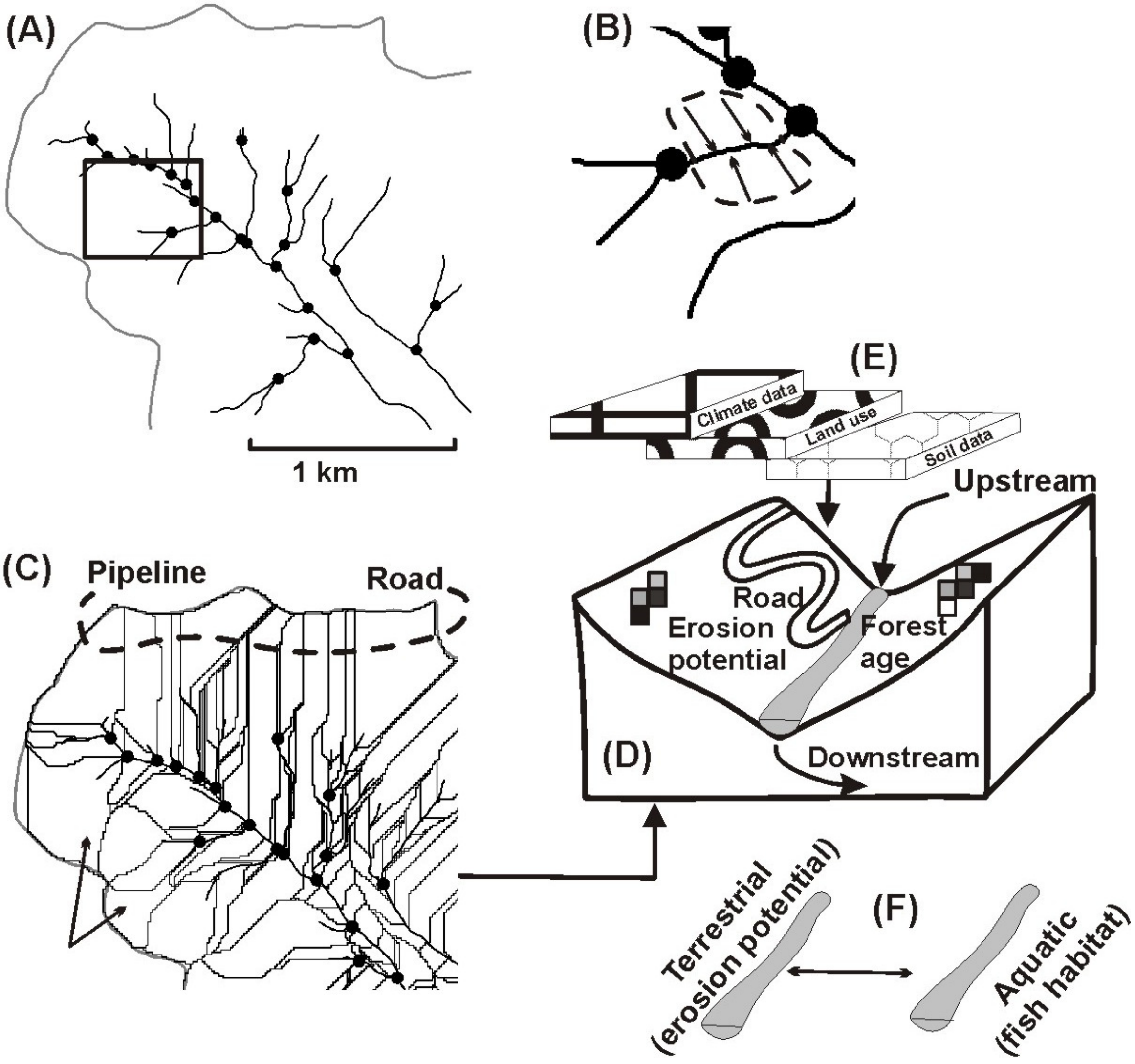

Figure 8. (A) A virtual watershed contains a synthetic, attributed and routed river network with individual river segments delineated (black dots denote tributary confluences). (B) Each river segment delineates a local contributing area (LCA) on both sides of the channel. (C) The virtual watershed is discretized into LCAs of appropriate scale; river segments of 100 to 200 m create LCAs of approximately 0.1 km^2. Linear features such as roads and pipelines are discretized at pixel scales and associated with similarly scaled indices of other attributes such as erosion. (D) Each LCA creates similarly scaled terrestrial information including roads, erosion potential, wildfire risk and climate change attributes etc. depending on the models and tools linked to the virtual watershed. (E) Other data layers can be added such as water bodies, basin boundaries, lithology, soils, vegetation and climate and treated as landscape features to be discretized, routed, and analyzed via connectivity pathways (Figure 7). (F) Terrestrial attributes are mapped as channel data and overlaid onto stream attributes such as sensitive habitats. All types of data can be routed downstream (or upstream) revealing patterns at any spatial scale defined by the network.

The capacity to build virtual watersheds exists in any country. Three components are required. The first are digital elevation models and the resolution of DEMs is an important consideration. For example, the most widely available DEM across the contiguous U.S. is the National Elevation Dataset (NED) with a resolution of 0.3 arc-second (approximately 10 m, but somewhat variable based on latitude); sub meter LiDAR DEMs are becoming increasingly common, greatly expanding on the potential uses and accuracy of virtual watersheds. Many regions and countries have their own locally derived DEMs, such as China's 12 m or Alberta's 20 m. Globally available DEMs include the Space Shuttle Radar Topography Mission (SRTM) in 1 arc-second resolutions (approximately 30 m at the equator). Other global scale DEMs include Interferometric Synthetic Aperture Radar (IfSAR ~5 m) and TanDEM-X 0.4 arc second (approximately 12 m). The suitability of DEMs within a virtual watershed for specific project applications depends on their resolution and the questions asked. In some applications, 20 m resolution may suffice while in others, sub 10 meter would be more suitable. Although high resolution LiDAR DEMs (1 - 2 m) are of limited availability, they have the potential to greatly advance the utility of virtual watersheds for site specific resource planning and conservation worldwide.

The second component is digital hydrography. As determined from our review of available hydrography in five countries (Tables 2 and 3, and Figures 1 through 5), synthetic hydrography, particular those delineated using higher resolution DEMs (10 m or LiDAR), offers the best choice, and in addition, is most suitable for developing analytical capabilities. Various methods can be used to derive synthetic hydrography from DEMs including 'ArcHydro' (Maidment 2002), 'TauDEM' (Tarboton 1997) and 'HEC-GeoHMS' (USACE 2000). However, as mentioned earlier, simply delineating synthetic hydrography from DEMs (using the models above) is not the same as building synthetic hydrography from DEMs and integrating them together with a numerical data structure to create the five analytical capabilities (routing, landforms, connecting, discretizing and attributing). In other words, a stream layer is not a virtual watershed.

In our analyses covering actual resource management and conservation projects in five countries, we employed the watershed modeling platform ‘NetMap’ (Miller et al. 2002, Benda et al. 2007) to create the synthetic hydrography. NetMap’s utilizes a robust channel delineation technology that includes drainage area per unit contour length (Montgomery and Dietrich 1989), hillslope gradient, planform curvature and channel-initiation criteria (Clarke et al. 2008). The channel network contains a data structure comprised of a set of linked nodes, with node spacing maintained at the finest scale of the DEM. Smoothing algorithms are used to create discreet (but routed) channel segments with adjustable length scales.

The third component is the analytical capabilities that take advantage of a synthetic hydrography that is derived directly from a DEM. Five analytical components were identified in our analysis (Figures 6 and 7), perhaps others can be added. Within a virtual watershed, the numerical data structure that is required to create the five analytical capabilities also support the integration of various models. For example, resource management and conservation applications may require models to evaluate or predict stream power and channel substrate (Buffington et al. 2004), radiation loading and water temperature (Boyd and Kasper 2003), in-stream wood recruitment and aquatic habitat formation (Benda and Sias 2003), landslide sources and risk mapping (Miller and Burnett 2007), landslide runout corridors and hazard delineation (Burnett and Miller 2008), wildfire (Agar et al. 2011), surface erosion (Elliot et al. 2001), and riparian zone delineation (Fernandez et al. 2012a) among others.

The NetMap watershed modeling system used in each of the in-country projects contains all five of the analytical capabilities because it was molded by numerous project objectives that required those capabilities (Miller et al. 2002, Benda et al. 2007, Clarke et al. 2008, Miller and Burnett et al. 2007, 2008, Benda et al. 2007, 2009, Penas et al. 2011, Barquin et al. 2011, McCleary et al. 2011, Fernandez et al. 2012a, Pickard 2013, Ji et al. 2013, Bidlack et al. 2014, Reeves et al. in press). However, other virtual watershed platforms could be built using other science and technology within individual countries in need of analytical capabilities associated with modern land use planning and conservation. It is likely that models will be built opportunistically for smaller scale, high profile projects that contain the five analytical capabilities described herein by universities, agencies and consultancies. However, there is a difference between building one-off models for local projects in specific geographic areas and building a system of regional to national scale virtual watersheds for wide use among diverse stakeholders (sensu Benda et al. 2009).

Modern land use planning and conservation activities at the scale of landscapes, states, provinces and entire countries are requiring more extensive use of computer aided modeling and analysis. Although field investigations have informed numerous models that will be incorporated into virtual watersheds, additional field analysis may be warranted, including to parametrize existing models, build new models and validate model predictions.

Conclusions

Our study focused on the ability of readily available DEMs and national to regional scale hydrography (cartographic or synthetic), including their analytical capabilities, to address a wide range of resource management and conservation questions (e.g., Table 1) in five countries involving 12 university, agency and NGO organizations. Based on our analysis, we conclude that the majority of the regional, national and global scale digital river networks in our sample lack in network completeness, analytical capabilities or both. This work also suggests that other countries may also lack access to readily available analysis and decision support capabilities in the form of national to regional databases encompassing DEMs and hydrography (e.g., in the numerical format of virtual watersheds). Hence, there is a growing need to develop and disseminate analysis capabilities, inclusive of complete synthetic river networks with analytical capabilities, to a wider group of agency, NGO and private sector stakeholders in countries worldwide.

There are likely consequences for the lack of readily available analysis capabilities in resource management and conservation in the form of national to regional scale databases (e.g., DEMs coupled to hydrography). The lack of adequate analysis and planning capabilities risks increasing inefficiencies in resource use and increasing environmental degradation. Wider use of robust analysis technologies, such as the virtual watershed technology described herein, in both developed and developing countries could contribute to increase efficiency in resource use, limit environmental degradation and enhance conservation. In this paper we demonstrated the NetMap form of the virtual watershed (www.terrainworks.com), a technology that could be transferred (and tailored) to other areas and countries. New types of virtual watersheds can also be built in-country using local expertise and knowledge. We believe this presents a global opportunity for in-country agencies, or international actors, to support creation of virtual watersheds to increase environmental problem solving, broaden access to the watershed sciences, and strengthen resource management and conservation in countries worldwide.

Gore (1998) articulated a vision for a virtual earth (“Digital Earth”), one that would host vast quantities of data, including geospatial information, and analysis and visualization technologies to evaluate numerous aspects of our environment and human’s relationships to it, at a global scale (but down to individual watersheds and neighborhoods). The Digital Earth concept has been proposed to address global climate change, natural disaster prevention, new energy development, agricultural and food scarcity, and urban planning (Chinese National Academy of Sciences 1999, 2008). The expansive concept of a top-down global digital earth, however, has given way, for practical reasons, to a more bottom up approach involving multiple connected systems across multiple technology platforms (Goodchild et al. 2012). Our proposed building of virtual watersheds at regional to national scales in many countries of the world to strengthen resource use and conservation is in accordance with Gore’s (1998) concept of a Digital Earth and its evolution at more local (region, country) scales.

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