Use of EMDS in Conservation and Management Planning for Watersheds

Sean N. Gordon

Abstract Some of the earliest applications of the Ecosystem Management Decision Support (EMDS) system were in the field of watershed assessment and planning. This chapter reviews nine cases in which EMDS has been applied to watershed management and three additional cases of the application of similar multi-criteria evaluation approaches that were at least partially inspired by EMDS. These cases are compared using the following major themes: participation, objectives, definition of watershed condition, temporal and spatial aspects, indicators and evaluation criteria, and model structuring. The cases show the model complexity and variability that is possible when trying to operationalize an ambiguous concept, such as watershed condition. EMDS has been quite successful in helping organizations structure the concept of watershed condition, but all efforts faced significant challenges with obtaining the desired data and setting evaluation criteria. Some possible areas for future software development are suggested, but many difficulties in building good models are more conceptual in nature, and thus, would likely be best addressed though improved information sharing among practitioners.

Keywords Conservation · Planning · Watershed analysis · Habitat · Fish populations · Population viability

1 Introduction

The importance of water for human uses and ecological processes has led to a variety of methods for assessment and planning based on watersheds (aka catchments). Historically, the singular focus of calculating water yields for human uses

S. N. Gordon (✉)
Institute for Sustainable Solutions, Portland State University, P.O. Box 751,
SUST, Portland, OR 97207-0751, USA
e-mail: sean.gordon@pdx.edu

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made such assessments tractable to statistical methods; however, increasing interest in water's role in supporting natural ecosystems has made assessment more complex. For example, evaluating habitat conditions for fish populations has proven challenging. A wide variety of factors (e.g., availability of large wood, pools, riparian and upslope vegetation) at several scales of observation are thought to influence habitat, but the data needed to correlate these indicators with fish populations are generally unavailable over large landscapes. Furthermore, the species of concern in the Northwest, where most of the applications of EMDS discussed in this chapter have taken place, are primarily anadromous, introducing ocean habitat conditions and migration barriers as confounding variables. As a result, few studies have attempted such correlations at landscape scales (but see Kaufmann and Hughes 2006; Pess et al. 2002).

Land managers and regulatory agencies need ways to evaluate current aquatic habitat conditions and the likely future effects of proposed commodity extraction and restoration activities on water quality and fish populations. In the USA, such evaluations are required by federal laws, particularly the Clean Water (CWA 1977) and Endangered Species Acts (ESA 1973). A variety of methods have been developed to address this need. The US Environmental Protection Agency (EPA) and associated state agencies (e.g., Oregon Department of Environmental Quality) have developed and applied water quality regulatory standards under the CWA (Hayslip et al. 2004; Hubler et al. 2009). Similarly, the national regulatory agency for fisheries has developed standards for evaluating habitat attributes (NOAA Fisheries 1996).

This chapter reviews nine cases in which the EMDS software has been applied to watershed management, and an additional three cases that have used conceptually similar approaches. The objectives are to compare these cases along a few key dimensions, as well as to summarize lessons learned about the use of such models and suggest areas for possible software development.

2 Motivation for Using EMDS in this Context

Use of EMDS for watershed assessment was precipitated by two weaknesses in previous approaches. First, for regulatory clarity, assessors used absolute thresholds to evaluate each stream or watershed metric (e.g., a watershed temperature of 17 °C would pass, but 18° would fail), even though biological effects are graduated along gradients. Second, they did not go beyond the independent evaluation of each parameter, so it was unclear how several parameters might be integrated to determine overall condition or status. EMDS provided a solution framework to both of these problems with its use of gradient-based evaluation criteria and integration of multiple measures, using a variety of logic functions. Additionally, EMDS can easily combine quantitative information and more qualitative expert knowledge, when explicit measures or relationships are not available.

3 EMDS Applications in this Problem Domain

3.1 Northwest Forest Plan

Some of the earliest EMDS applications were developed for watershed assessment and planning on federal forest lands in the Pacific Northwest of the United States. In particular, the initial development period of EMDS coincided with development of the Northwest Forest Plan (NWFP), one of the earliest and largest ($\sim$10 million hectares) applications of ecosystem management principles in the US. It consists of a coordinated set of guidelines for federal lands in the continental northwestern United States (USDA and USDI 1994). The area covered by the NWFP was principally determined by the range of the northern spotted owl (*Strix occidentalis caurina*), which was listed as a threatened species in 1990 under the national Endangered Species Act (USFWS 1990). The planning process also developed an aquatic conservation strategy to protect aquatic ecosystems in anticipation of possible listings of a number of fish species.

Early on, EMDS was proposed to meet the need for watershed assessment and planning for the NWFP (Reynolds et al. 1996). However, the involvement of numerous federal agencies in the NWFP, each with a different concept of watershed monitoring, led to a drawn-out process of finalizing the aquatic monitoring strategy (Reeves et al. 2003). Despite this delay, the watershed monitoring program was established in 2000 and an initial assessment using EMDS was completed in 2001. The first major report on NWFP monitoring (Gallo et al. 2005) addressed the first 10 years of the plan (1994–2003). To cover the large, diverse area, the watershed monitoring team worked with local experts and created six subregional EMDS assessment models (Gordon and Gallo 2011). NWFP monitoring reports are planned for every five years, and a second iteration of the modeling and assessment process using EMDS was recently completed (Lanigan et al. 2012).

3.2 National Forest Planning

National forests managed by the US Department of Agriculture Forest Service (USFS) make up the largest portion of the NWFP area, and development of EMDS in the Pacific Northwest research branch of the USFS (Reynolds et al. 2002), along with adoption for the NWFP, has led to a number of applications developed at the national forest scale. One of the first was an assessment of the Chewaucan watershed in south central Oregon USA (Reynolds and Peets 2001). The assessment demonstrated how multiple scales of data (subwatersheds and stream reaches) could be integrated, and users of EMDS will recognize it as the tutorial case.

Under federal law, national forests are required to create a comprehensive management plan and update this plan every 15 years (NFMA 1976). The actual rules for defining these plans have changed numerous times in the past decade due to attempted updates and court challenges (http://www.fs.usda.gov/main/planningrule/history), but all versions have included language on the protection of species. A few national forests in the Pacific Northwest are engaged in plan revision and have been using EMDS to help assess and plan for "aquatic ecological sustainability." This approach was piloted on the Okanogan-Wenatchee National Forest, which is documented in Reiss et al. (2010).

3.3 California North Coast Watershed Assessment Program

Government agencies at the state level also share responsibility for the protection of water quality and conservation of aquatic species. In 2001, the state of California initiated the North Coast Watershed Assessment Program to evaluate the status of coastal watersheds that historically supported anadromous fish. Through connections to the Northwest Forest Plan process, the California program decided to use EMDS to assess overall watershed and in-stream conditions for fish. They produced models for instream habitat and sediment delivery, a key component of watershed condition, as determined by the EPA (Dai et al. 2004; Walker et al. 2007).

3.4 Other Northwest Agencies and Nonprofits

In Oregon, an EMDS-based watershed assessment process has been applied to at least two other major efforts for which publications are available. First, a broad partnership between federal and state agencies and nonprofits used EMDS to develop restoration priorities for the Sandy River, a major Columbia River tributary, near Portland, Oregon (SRBWG 2006, 2007). Second, the Portland-based nonprofit Wild Salmon Center undertook an evaluation of 5,500 km^2 of watersheds in northwestern Oregon to evaluate and influence the implementation of a "Salmon Anchor Habitats" strategy being implemented by the state's forestry department (Miewald et al. 2008).

3.5 Environmental Protection Agency

The Pacific Northwest Research Station (USDA Forest Service) and EPA cooperatively developed one of the earliest EMDS applications for watershed assessment and monitoring of ecological states and processes (Reynolds et al. 2000).

Much of this application was concerned with assessment of stream characteristics to provide decision support for managing nonpoint source (NPS) pollutants under the EPA's Total Maximum Daily Load (TMDL) program. TMDLs specify the maximum daily amount of pollutants allowed meeting state water quality standards, and the TMDL program allocates pollution control responsibilities among pollution sources in a watershed. NPS TMDL parameters considered critical to aquatic ecosystems include streamflow, stream temperature, nutrients, stream sediment, and in-channel stream habitat. Given the objectives of the EPA water quality assessment program, the primary logic topics included in design were watershed processes, watershed patterns, general effects of human influence, and specific effects of human influences on aquatic species.

3.6 Other Regions

While most applications of EMDS to watersheds have taken place in the Pacific Northwest, there has also been an extensive application to planning in Region 1 of the USDA Forest Service (Montana, North Dakota, and northern Idaho), and similar multi-criteria techniques have been adopted by two national efforts. The USFS Region 1 application was initiated as part of the forest planning process to evaluate ecosystem sustainability across a number of national forests and adjacent lands, and then to help prioritize restoration activities. Aquatic integrity was one of five submodels built for this effort (the others being terrestrial integrity, fire danger, social opportunity, and economic integrity) (Jensen et al. 2009).

One Oregon and two national watershed assessment initiatives have also been implemented using similar multi-criteria techniques, which appear to have drawn from the EMDS applications, although they do not use the software specifically. I have included these cases because of their national significance and similarity in methods. In 2007, the nonprofit, Trout Unlimited, launched its Conservation Success Index, which is a multi-criteria approach to evaluating the status of a variety of coldwater fish species to facilitate protection, restoration, reintroduction, and monitoring efforts. The index includes 20 indicators grouped into four categories. To date, assessments of numerous species have been carried out in five broad regions of the USA (California Salmon, Sierras, Intermountain West, Desert Southwest, Midwest, and East) (Williams et al. 2007; Trout Unlimited 2007). The second national effort is the USDA Forest Service National Watershed Condition Classification (WCC, USDA Forest Service 2010), which was begun in 2006 in response to a federal oversight agency (Office of Management and Budget, OMB) criticism that the Forest Service lacked a nationally consistent method for assessing and prioritizing watershed restoration actions even though it was a major strategic emphasis (US OMB 2006). Each national forest is now required to assess each of their watersheds using a standard set of 12 indicators, which are combined into an overall index score. EMDS was used for a pilot national assessment, but the

FS established a national database system to store and calculate the first full assessment in 2010. Finally, a recent feasibility study for the reintroduction of threatened bull trout (*Salvelinus confluentus*) into the Clackamas River, Oregon used a multi-criteria framework built on earlier experiences with EMDS (Dunham et al. 2011).

4 Experiences Using EMDS for Watershed Assessment

This section reviews the positive and negative aspects of the application of EMDS in the cases mentioned above. It is organized according to a number of major issues involved in preparing and applying such models to structured problem solving. To more compactly reference the cases, bracketed case numbers from Table 1 are used in the following discussion.

4.1 Participation

Problem framing depends on who is involved and the processes used to gather input. Relatively little has been written about this aspect of the cases, beyond providing a brief mention of general types of participants or occasionally a more specific list. The summary of model-building efforts in Table 1 shows that involvement has largely been limited to technical experts in the various aspects of watershed functioning. Participation has ranged from a team of two (a fish biologist and a modeling specialist [case 2]) to a case involving 12 organizations, including nonprofits and local/state/federal government agencies [8]. In fact, many of the cases involve multiple organizations [1, 7, 8, 9, 10], demonstrating that the EMDS framework has been simple and flexible enough to span such organizational boundaries. Even when used within one organization, it has served to integrate multiple disciplinary perspectives [4, 5, 6] and bridge multiple hierarchical levels. As reported in Gordon and Gallo (2011), the concepts involved in multi-criteria modeling did not appear difficult for the experts to grasp, and the modeling process provided a much-needed framework for expressing and combining their knowledge. The EMDS framework was also easy to understand and helped increase the transparency of the assessment process. As one user put it,

> It's a great tool for that [watershed assessment] and everyone sees right there on paper but this is how you did it, whereas some of the other models that I'm aware of, you go into a black box approach and you don't really know what happened with the data. It just spits out a number in the end. (Gordon 2006).

However, Gordon and Gallo (2011) also identified some core challenges related to broader involvement in model-building:

Table 1 Summary of key factors in 12 applied cases of EMDS and related multicriteria methods to watershed assessment and planning

#	Application	References	Participation	Objectives	Definition of watershed condition	Temporal extent	Spatial extent
1	Northwest forest plan watershed condition	Gallo et al. (2005) Gordon and Gallo (2011) Lanigan et al. (2012)	Aquatic experts from federal and state agencies	Monitor status and trends under a regional forest policy	Supports a high diversity and abundance of aquatic and riparian species, particularly salmonids	Historical condition at start of plan (1994) then current conditions at 5-year reporting interval (2005-ongoing)	NWFP area (98,000 km^2)
2	Nestucca Basin, OR	Reynolds and Reeves (2003)	USFS research fish biologist and EMDS specialist	Evaluate salmon habitat suitability	suitable biophysical condition for salmon habitat	Current condition only	Nestucca Basin (5th field hydrologic unit, 664 km^2)
3	Upper chewaucan watershed (Oregon)	Reynolds and Peets (2001)	USFS watershed assessment lead and EMDS specialist	Identify priority restoration areas in a national forest watershed	Assessment: Salmonid habitat suitability Prioritization: Protect the best, then restore the rest	Current condition only	Upper Chewaucan watershed (5th field HUC, 694 km^2)
4	USFS region 6 National forest planning	Reiss et al. (2010)	Team of 4 agency aquatics specialists + consultations with ~20 agency resource specialists and scientists	Support national forest planning requirement to assess contributions to the sustainability of ecosystems and species	Focal species populations in sub-basins are sustainable	Current and historical reference condition	2 pilot 4th-field watersheds (2,800 and 5,500 km^2)
5	USFS region 1 National forest planning	Jensen et al. (2009)	USFS staff specialists representing various disciplines, including landscape ecology, fish biology, and hydrology	Support national forest planning requirement to assess contributions to the sustainability of ecosystems and species	Evaluating ecosystem sustainability (desired conditions) and prioritizing areas for integrated landscape restoration (objectives)	Current condition only	3 Forest Service planning zones (58,000 km^2)
6	USEPA TMDL Analysis	Reynolds et al. (2000)	EPA scientists	Evaluate watershed condition under EPA framework of total maximum daily loads (TMDLs)	Watershed patterns and processes relative to unmanaged conditions and organizational standards	Current condition only	4th-field watershed

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Table 1 (continued)

#	Application	References	Participation	Objectives	Definition of watershed condition	Temporal extent	Spatial extent
7	California North Coast watershed assessment program	Bleier et al. (2003) Dai et al. (2004) Walker et al. (2007)	5 state agencies and EPA Scientific peer reviews Public input solicited on draft assessment manual	Assist prioritization of both in-stream and upland area watershed restoration and recovery efforts	The overall condition of the stream reach is suitable for maintaining healthy populations of native coho and Chinook salmon and steelhead trout	Current condition only	50,000 km^2, approximately 26,000 km^2 of which are private lands
8	Oregon Sandy River Basin Anchor habitats project	Sandy River Basin Working Group (2006, 2007)	12 organizations, including nonprofits and local/state/federal government agencies	Support maintenance and restoration of salmon and steelhead populations and the habitat that supports them	Best habitats for 4 specific fish species	Current condition only	Sandy River basin (1,316 km^2)
9	NW Oregon salmon anchor habitats	Miewald, van Dyk and Reeves (2008)	Nonprofit-organized, 4-person core science team (ODF, ODFW, USFS, TNC) Consultations with ~10 additional experts	Assess status of watersheds for supporting salmon species and relationships between conditions and management protections	watersheds in "good" condition in areas of high intrinsic potential for multiple species	Current condition only	Oregon North Coast (5,500 km^2)
10	Reintroduction decision framework for Bull Trout, Clackamas River, OR	Dunham et al. (2011)	Clackamas River Bull Trout Working Group (local, state, federal, tribal, utility)	A simple and transparent system for assessing the feasibility of bull trout reintroduction	Combination of current/historical presence, good current habitat conditions, and low future threats	Historical presence Current conditions Future threats	Upper Clackamas River (area not specified)
11	Trout unlimited conservation Success index	Williams et al. (2007)	Trout Unlimited staff and external expert reviewers	Characterization and synthesis of native salmonid status and prioritization of conservation areas Communicate complex assessment data and conservation opportunities to the public	Good distribution, population, and habitat conditions, and security from future threats	Mostly current conditions, but including % historic habitat occupied and future security indicators	Individual species ranges (areas not specified)
12	USDA forest service national watershed condition classification	USDA FS (2011)	USFS Watershed Condition Advisory Team (specification) USFS national forest staff (implementation)	Report on watershed conditions and trends at the national level for all national forests	Assess the state of the physical and biological characteristics and processes within a watershed that affect the hydrologic and soil functions supporting aquatic ecosystems	Current condition only	National forests (45–67,000 km^2)

Table 1 (continued)

#	Analysis units	Types of indicators	Assessment model structure	Prioritization model structure	Criteria source(s)	Weighting	Sensitivity/uncertainty	Tools used
1	1379 Subwatersheds (40–120 km^2) 193 stream reaches	- watershed-level: vegetation, roads, landslide risk - stream reach level: physical and biological factors	Upslope and Riparian Inchannel	NA	Expert knowledge elicitation workshops	Some provinces Roads versus vegetation Riparian versus upslope	Gallo et al. (2005) reported sensitivity of results to individual indicators	Netweaver
2	45 sub watersheds	Upslope: mature vegetation, road crossings, land use Riparian: NFBveg, FBveg Inchannel (low gradient): wood, pools, water temperature, substrate, off-channel habitat	Riparian Upslope Inchannel (low gradient)	NA	Expert knowledge and interpretation of the literature	Capacity to read in structure, but weights not mentioned in text	None	Netweaver
3	6 subwatersheds 104 stream reaches	- watershed-level: upland vegetation cover, road density, fish access, spawning fines, water temperature, reach condition - stream reach level: riparian vegetation (composition, seral stage), bank stability, W-D, large wood, pools Prioritization: efficacy, feasibility, access, watershed and reach conditions	Upland condition Habitat accessibility Stream condition	Protection watershed condition reach condition access efficacy feasibility Restoration watershed condition reach condition feasibility vegetation similarity	Previously published assessment	None described	None	Netweaver DecisionPlus (AHP and SMART)

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Table 1 (continued)

#	Analysis units	Types of indicators	Assessment model structure	Prioritization model structure	Criteria source(s)	Weighting	Sensitivity/ uncertainty	Tools used
4	13/13/28 subwatersheds (6th field), 3 subbasins (4th field)	- HUC6 habitat: road density (riparian, upland), riparian vegetation, fire risk - HUC6 focal species population: distribution, status, connectivity, nonnatives - HUC4 condition: distribution, patch sizes, HUC6 condition - HUC4 connectivity: population connectivity, habitat connectivity	Condition Distribution Patch HUC6 population HUC6 habitat Connectivity	Used in subsequent prioritization process (ACS key watersheds)	Expert knowledge and interpretation of the literature	Roads along low-gradient streams Road density by sensitive soils	Potential influence of each indicator (−1/+1 boundary analysis)	Netweaver
5	Subwatersheds (6th field, 40–120 km^2)	Watershed condition: water quality, roads, vegetation, stream habitat Fish species status: 7 species Threats: fire, flow, grazing, mining, population, recreation, roads	Watershed condition, Fish species status Threats	value (incl. watershed condition) risk feasibility	Relative to dataset (25/75th percentiles)	Prioritization model weighted for 3 different possible objectives	3 different prioritization objectives	Netweaver CriteriumDecisionPlus

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Table 1 (continued)

#	Analysis units	Types of indicators	Assessment model structure	Prioritization model structure	Criteria source(s)	Weighting	Sensitivity/ uncertainty	Tools used
6	Subwatersheds (6th field, 40–120 km^2)	processes: streamflow, erosion, fire patterns: upland, valley bottom, channel human influences: roads, dams, diversions, channelization, groundwater extraction, mines, grazing, recreation habitat: baseflow, substrate, temperature, cover	watershed processes watershed patterns human influence aquatic species habitat	NA	(1) reference conditions from unmanaged watersheds (2) standards set by resource management agencies (3) standards set by regulatory agencies	None	None	Netweaver
7	stream reaches CA planning watersheds (10–30 k acres)	Reach condition: water temperature, riparian vegetation, inchannel habitat (pools, substrate), stream flow Upland condition (sediment): roads, land use, land cover, and slope instability	Salmonid habitat Sediment production	Assessment results used to help identify limiting factors in broader prioritization process	Salmonid habitat: Science assessment team Sediment: 10/90th percentiles of dataset	None described	Data quality control procedures	Netweaver

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Table 1 (continued)

#	Analysis units	Types of indicators	Assessment model structure	Prioritization model structure	Criteria source(s)	Weighting	Sensitivity/ uncertainty	Tools used
8	Stream reaches (then summarized to 5/6th field HUCs)	Fish/redd counts Expert rating EDT habitat score	Fish/redd counts Expert rating EDT habitat score	Assessment model used to determine high priority restoration areas	high performing reaches (relative to dataset)	None	None	Netweaver
9	Subwatersheds (6th field, 40–120 km^2)	Upslope: native vegetation, hydrologic maturity, landslide risk Floodplain: shade, wood recruitment, native vegetation, channel containment Stream: dissolved oxygen, temperature, flow, connectivity, pool and wood frequency, fines, shade Fish: juvenile and spawning surveys Intrinsic potential: flow, valley width, gradient	Upslope Floodplain Stream Fish Intrinsic potential	Assessment results used in broader qualitative process to help identify priority watersheds for protection	Watershed condition: mainly previous modeling efforts + expert knowledge Fish: relative to area average Intrinsic potential: IP model	Yes, by indicator group (Table A1, p. 37)	None	Netweaver

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Table 1 (continued)

#	Analysis units	Types of indicators	Assessment model structure	Prioritization model structure	Criteria source(s)	Weighting	Sensitivity/ uncertainty	Tools used
10	Analysis area as a whole	Recipient habitat Historical presence Contemporary presence Habitat suitability (temperature) Threats Recolonization potential Donor population Suitability Threats to donor	Feasibility Recipient habitat Donor population	NA	Expert knowledge and interpretation of the literature	All equal	averaged the absolute values of scores for each component to derive a second index of uncertainty. In this case, scores closer to zero would indicate less certainty, whereas scores closer to 1 would indicate greater certainty	Excel?

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Table 1 (continued)

#	Analysis units	Types of indicators	Assessment model structure	Prioritization model structure	Criteria source(s)	Weighting	Sensitivity/ uncertainty	Tools used
11	Subwatersheds (6th field, 40–120 km^2) Also rangewide and subbasin indicators	Range-wide condition: % historic habitat occupied by subbasin, subwatershed, stream order, lakes Population integrity: density, extent, purity, disease vulnerability, life history diversity Habitat integrity: land stewardship, connectivity, physical (roads), water quality, flow Future security: land conversion, resource extraction, climate change, introduced species	Range-wide condition Population integrity Habitat integrity Future security	Uses different combinations of indices to prioritize 4 management actions: - Protection: high population and habitat integrity, low future security - Restoration: moderate to high for population and habitat integrity, high future security - Reintroduction: low population, high habitat integrity and future security - Monitoring: all qualifying for 3 actions above	Expert knowledge and interpretation of the literature	All equal		Google Maps Google Earth

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Table 1 (continued)

#	Analysis units	Types of indicators	Assessment model structure	Prioritization model structure	Criteria source(s)	Weighting	Sensitivity/ uncertainty	Tools used
12	Subwatersheds (6th field, 40–120 km^2)	Aquatic physical: 303d listed, flow, habitat fragmentation, large wood Aquatic biological: life form presence, native versus exotic species, riparian vegetation condition Terrestrial physical: road density and maintenance, proximity to water, soil productivity, soil erosion Terrestrial biological: fire condition class, loss of forest cover, invasive species, insects and disease, ozone	Aquatic Physical Aquatic Biological Terrestrial Physical Terrestrial Biological	Suggests using assessment results used in broader qualitative process to help identify priority watersheds for protection	Expert knowledge and interpretation of the literature	All equal		Excel Oracle database

> The downside of flexibility and incorporation of local knowledge is the generation of multiple, possibly inconsistent, models. In hindsight, one of the decisions with the most profound impacts turned out to be the geographic scale at which we engaged the experts. We expected some model differences between physiographic provinces due to ecological differences, but holding multiple knowledge elicitation workshops also introduced an unknown amount of variation based on the mental models of the different experts attending each session.

The USFS anticipated this potential problem in implementing their national watershed condition assessment over their 175 management units, and they chose to implement a strict, standardized structure to help achieve consistency. The cost of this "controlled" approach is that a generic model structure may not fit local conditions well. Gordon and Gallo (2011) hypothesized two other approaches: (1) an informational approach, which would provide participants with detailed information on the other models and encourage them to use similar structures as appropriate; and, (2) a post-processing approach, in which, after the workshops, the project team or a small group of regional experts (preferably who are able to attend all the workshops) would review all the models and propose changes to harmonize them, perhaps followed by an additional validation workshop. Given high interest in assessment compatibility, both horizontally and vertically in the organizational sphere, further documentation of this aspect and research in this area is needed.

4.2 Objectives

EMDS has been used to meet the objectives of a number of different watershed-related organizational programs (see Table 1, Objective column). One fundamental difference in the scope of applications is whether they involve only assessment or both assessment and prioritization. Four of the cases focus exclusively on assessment [1, 2, 6, 10]. Five cases occupy a "middle ground", where assessment results are either used directly for prioritization [8], or they are used in a broader, qualitative prioritization process [4, 7, 9, 12]. For example, the USFS National Watershed Condition Framework [12] suggests prioritizing the protection of watersheds with high condition scores that also fall into certain land use categories, such as designated wilderness or municipal water supplies.

Only three cases include formal prioritization models implemented using the multi-criteria approach [3, 5, 11]. The details of these cases are discussed further in the **Model structure** section below. Clearly, EMDS has been seen as a useful tool for both types of objectives; however, it is interesting that only three of the 12 cases have used the multi-criteria methods for prioritization as well as assessment. For the first three cases mentioned immediately above, prioritization appears to simply be outside their scope. The five "middle ground" cases, however, clearly state prioritization as a key objective, so why was the multi-criteria method not used? This question is not answered directly by the texts, but reading between the lines,

I hypothesize two reasons: (1) the factors were deemed too complex or idiosyncratic for formal analysis, and/or (2) it was desired to maintain flexibility for local decision makers. A third possibility is technical: the integration of different software programs for assessment (" Netweaver", Chap. 2) and prioritization (" Criterium Decision Plus", Chap. 3) creates a steeper learning curve for users and adds costs for obtaining versions of both programs needed for model development.

4.3 Definition of Watershed Condition

Despite the shared focus on watershed condition, there are considerable differences among the cases in how this concept is operationalized (Table 1, Definition of watershed condition). In a case study of the NWFP, Gordon and Gallo (2011) identified framing the initial approach to watershed assessment as one of the most challenging aspects of the modeling effort. Multiple federal agencies were involved, each of which had previously developed their own approach.

Notable in the objectives across cases is the degree of emphasis on maintaining native fish species; many of the applications were developed in the Pacific Northwest, USA, where a number of salmonid populations have been listed under the federal Endangered Species Act (ESA). Because the ESA mandates a number of protection measures, these species are important foci for management and policymaking. A major framing decision for planning is whether to focus on fish populations, habitat, or both.

The importance of maintaining fish species is emphasized in all the cases, yet some include abundance metrics in their models, while others do not. The NWFP assessment [1] does not include any abundance indicators because the USFS, as a land management agency, is primarily responsible for habitat rather than population management, the province of regulatory agencies, and habitat is what is most directly affected by management. Additionally, no consistent population data are available over this large area, and the emphasis of the program is on consistent, repeatable trend metrics. The Chewaucan, EPA, and CA North Coast assessments [3, 6, 7] also do not include population data, although it is not stated whether this is for lack of data, or an intentional focus on habitat. In contrast, the USFS aquatic sustainability [4], Oregon anchor habitats [9], and USFS Region 1 [5] models all include fish population metrics. The more limited spatial scale of the first two makes this more tractable. Also, in the case of the USFS aquatic sustainability effort, the governing law requires assessment of the viability of species.

A second broad consideration in the definition of watershed condition is the relative emphasis on ecosystem processes versus ecosystem states. Emphasizing processes acknowledges the dynamic nature of aquatic ecosystems, an area where aquatic assessments have generally lagged behind their terrestrial counterparts (Reeves et al. 1995). A number of the cases frame the problem in terms of

processes, but at the same time they still rely on state-based indicators. As Reiss et al. (2010, p. 25) explain,

> The habitat condition component of the HUC [hydrologic unit code] 6 AEC [aquatic ecological condition] model was designed to assess ecological processes, rather than evaluate the habitat needs of any particular species. Upslope and riparian road and vegetation attributes were selected as surrogates for the processes that affect stream habitat[,] and to act as indicators of anthropogenic influence on ecological processes.

A process-based approach also acknowledges that even in "pristine" environments, not all watersheds can be expected to be in a state supporting good fish habitat all of the time. Natural disturbances will change conditions over time, such as landslides or debris flows that may disrupt habitat in the short-term, but provide necessary inputs to in-stream habitats over the longer term. The common solution to these dynamics is to focus on the distribution of watershed scores in an area rather than the score of each individual watershed. These actual distributions are then compared to a reference distribution, for example the start of the NWFP [1] or pre-European settlement [4].

EMDS was flexible enough to accommodate this range of definitions and had the benefit of making definitions of an ambiguous concept more explicit. Users in this domain should be aware, however, of the complexity of this task, as revealed by the attempt of Lanigan et al. (2012) to provide a clear definition:

> The condition of a watershed is defined as "good" if the state of these attributes support a high diversity and abundance of aquatic and riparian species. Many of the physical indicators are chosen for their relevance to native or desired fish species because of these species' roles in driving management policies (including the NWFP itself) and the availability of research related to their habitat needs. However, we attempt to assess indicators relative to the natural potential of the site to provide biotic habitat. A watershed that naturally does not support fish populations (because of elevation or other natural conditions) but has little vegetation disturbance, few roads, good pools, and wood should be evaluated positively. If this watershed loses significant vegetation, even from natural causes (e.g., fire), then the condition rating will go down (it is below its potential).

4.4 Temporal Aspects

Another aspect of problem framing is the temporal extent of interest. Most of the cases focus on the present–current conditions and priorities based on these conditions. A few cases, however, use historical data in different ways. The NWFP assessment [1] is tasked with evaluating changes since the inception of the plan, and so has created a historical baseline assessment of conditions in 1994 as a comparison point for trend. The ability of EMDS to provide a consistent and repeatable metric was a major reason it was chosen. However, it does not currently have utilities that support calculating such score changes over time. In a similar vein, the USFS Region 6 national forest planning model [4] uses a simulated historical condition at watershed scale for a comparison baseline. At the subwatershed level, it includes a few individual indicators that are based on comparisons

with historical conditions (focal species status and distribution). The Trout Unlimited Conservation Success Index (CSI) [11] also includes an indicator of fish distributions relative to historical conditions. The NW Oregon Salmon Anchor Habitats assessment [9] discusses potential differences in priorities over time (although the report only provides a single set of priorities):

> First, any conservation strategy must include a short-term plan to protect the watershed processes that maintain current core areas or anchor habitats (Reeves et al. 1995). Second, for longer term conservation it is useful to consider the concept of the "intrinsic potential" (IP) of a stream to provide high quality habitat.

Some models also look to the future. The Trout Unlimited CSI [11] includes a whole branch of the model related to "future threats." These future threats have been drawn from a variety of sources, such as land development and climate change models. In summary, looking at multiple time periods is an important aspect of most natural resource problems. Many cases have figured out ways to integrate temporal aspects into EMDS analyses, but the inclusion of temporal tools would be a useful area for future EMDS development.

4.5 Spatial Aspects

Another fundamental consideration in the development of EMDS models are spatial aspects, including spatial extent, analysis units, and spatial relationships. The spatial extents of the cases range from the 98,000 km^2 of the NWFP [1] to the $\sim$600 km^2 of two single watershed studies [2, 3]. Broader-scale applications appear to have been typically defined by administrative boundaries, such as USFS planning units [1, 5, 12] and a state planning region [7]. Mid-scale assessments seem more tied to particular ecological or hydrologic units, such as one or more major river basins [8, 9, 10] or species ranges [11]. Studies in the smaller size range were generally intended as pilot efforts that could be scaled up to larger regions [2, 3, 4, 6]. The USFS assessments limited their evaluation coverage to federally managed lands, although their new national effort [12] includes qualitative ratings of other lands in shared ownership watersheds. Other assessments included all ownerships but faced the associated challenge of variable data coverage and data quality evenness.

While spatial extents of the studies varied widely, there has been considerably more congruence on the analytical/modeling units used: all cases used either stream reaches (segments) and/or subwatersheds (12-digit hydrologic unit, HUC12). The convergence to the HUC12 is likely due to it being the smallest available hydrologic unit in the watershed boundary component (WBD, Seaber et al. 1987; USDA NRCS 2012) of the national hydrologic dataset (NHD, USGS 2012).

The US government has sponsored development of the NHD to facilitate consistency in hydrologic modeling across agencies and jurisdictions. The NHD provides considerable potential for the compatibility of different watershed

assessments. However, it is also subject to continuing updates by state data stewards, so the polygons used for one assessment at one point in time may not be congruent with those produced from a different time period. These changes present a challenge for sampling designs intended for trend analysis, such as in the NWFP [1]. Furthermore, there appears to be little attention to date on clear versioning of the WBD; there have been no version labels (e.g., version 1.4) applied and update dates are rather deep in the metadata.

The spatial unit of "reaches" appeared to be used in four of the twelve studies [1, 3, 7, 8]. Stream reaches have been defined in many different ways, which are exemplified in these cases. Two [1, 7] based reaches on stratified random point samples, with measurements extending a variable length along the channel based on stream width (e.g., 20 bankfull stream widths), but usually limited by fixed minimum and maximum lengths (150–500 m). The Chewaucan case [3] did not specify what the reach represented, but it can be assumed to be based on the USFS Level II survey protocol, which defines reaches by physical characteristics, such as valley width, channel gradient, and sinuosity (USDA FS R6 2009). These reaches tend to be longer (generally 1200 m minimum), and whole streams within the ownership are typically sampled, resulting in a segmented line feature. The Sandy River case [8] also created a segmented stream network for the entire study area, based principally on geomorphic considerations used in one of their submodels (EDT, although details are not provided in the main report). Within this master structure they integrated diverse datasets with original reach lengths varying from $<$200 m to $>$10 km. Interestingly, none of the studies mentioned the NHD and its standardized reach segmentation. This lack of standardization presents a problem for the reuse and integration of reach-level datasets.

Many of the studies acknowledge the importance of integrating multiple scales of analysis. All of the studies employing reach-level metrics, except [8], also aggregate these up to HUC12-level summaries using reach length-weighted averaging.

The USFS Region 6 analysis [4] summarized from the HUC12 to the HUC8 (subbasin) level. Their rationale was that subbasins are more consistent with species recovery plans and the size of their administrative ranger districts. Similar to the reach-to-subwatershed integration, the HUC12 assessments were combined with a number of analyses done at the broader HUC8 level, including fish distributions, habitat patch sizes, and population and habitat connectivity. Trout Unlimited's CSI [11] is unique in that it takes data from broader scales (populations, subbasins), and applies these (common) ratings as part of their individual watershed scores. Aggregating data and linking to other scales is a common function in watershed assessment (as well as other natural resource assessments), and therefore a task which EMDS may wish to consider providing specific functions to support in the future. This capability might be accomplished by a tool which allows users to identify different scales of analysis and then enables the selection of their outputs as inputs to other scales. There also appears to have been little investigation or reporting on the accuracy of such aggregation procedures. It would be helpful to create some measure of the statistical uncertainty based on the

sampling design. However, such a function broaches the much larger topic of the integration of statistical and fuzzy uncertainties, for which more user education would be most helpful but unfortunately is beyond what this author can provide.

A final spatial aspect that deserves consideration is the use of indicators involving spatial relationships. All of the cases include indicators based on spatial location, and the most common are those assessing vegetation and road conditions in proximity to streams (e.g., riparian vegetation). What is largely absent in these models are indicators involving spatial relationships between individual reaches or watersheds. These second order spatial relationships are important given the connected nature of the stream network between reaches and watersheds (Naiman et al. 1992). Only two indicators along these lines were found in the cases: 1) the USFS region 6 model [4] includes a genetic connectivity metric, which measures degree of connectivity between the HUC6 and other populations within the HUC4, and 2) the Trout Unlimited CSI [11] includes a watershed connectivity indicator, which is based on a count of fish passage barriers downstream from the subwatershed. Such network or neighborhood relationships are common in other natural resource topics as well, and so may be another consideration for future EMDS development.

4.6 Data and Indicators

At the base of a multi-criteria approach, such as EMDS, is the choice of indicators to include in the model. Efforts often begin by mapping out all types of data thought to influence watershed condition, and then paring these down to those with available data. A fundamental modeling decision is the extent to which one leaves in indicators with missing data. One of the strengths of EMDS-Netweaver is that it handles missing data by assigning a neutral value for the indicator (e.g., 0 on the standardized −1 to +1 scale). However, if a number of indicators with missing data are left in, they push the model results to an undetermined, neutral value. The California Coastal Assessment [7] sediment model is an example in which there are more indicators without than with data. More discussion of this issue would be helpful. However, later versions of the EMDS-NetWeaver component include an option to turn off indicators with no data (i.e., do not count them rather than assign a zero value).

One strategy for incorporating key indicators that lack empirical data is through the reliance on expert knowledge. Two cases [4, 12], in particular, incorporate a large number of indictors based on expert assessment. Experts may be able to provide accurate assessments for some attributes, and EMDS can at least capture and preserve these results. However, the EMDS framework does not provide a mechanism for capturing the rationale or uncertainty associated with an individual expert's knowledge or opinion. As a result, the challenge of achieving consistency between experts and assessments over time becomes even more difficult. Modelers should create processes and data structures necessary to capture such expert judgment metadata. The EMDS Netweaver and CDP components already have some capacity

to store such metadata; possible improvements include further consistency between components and their abilities to export these data in structured formats.

While the use of empirical data for indicators is more transparent and repeatable, it is still subject to a number of potential problems. For one, preparing the raw data for model input is likely to be the most time consuming piece of the assessment. EMDS models can be built relatively rapidly, but the compilation of empirical datasets can be quite time consuming, accounting for as much as 80 % of the time and money used to develop a model. Even when working with existing data, the necessary transformations and concatenations to format data for EMDS inputs can take time. This formatting and transformation is also a large potential source of errors. Special care should be taken with indicator metrics. The units involved in environmental assessment are often complex (e.g., is the measure "miles of riparian road per square mile riparian area" or "miles of riparian road per mile of stream"?). Some metrics can simply be poor choices. For example, the USFS national watershed assessment [12] uses the following riparian road indicator: "percent of road/trail length is located within 300 feet of a stream." Using this measure, a watershed with 100 m of road, all of it along a stream, will be evaluated worse than a watershed with 10 km of roads, where only half are located next to streams. In general, density metrics are preferable (e.g., per stream km or per km^2).

A final issue related to data and indicators relates back to the earlier discussion of process- versus indicator-based models. Conceptually, the preference of watershed experts seems to be for process-based thinking; however, most of the models to date have been structured more around available data using an indicator-based approach. A central reason behind this inconsistency is the apparent redundancy that occurs in process-based structures. A process-based model looking at mass wasting, sedimentation, wood delivery, and shading would likely include potentially quite similar vegetation indicators under each of these processes. This apparent redundancy is unsettling for those trained in statistics, where the problem of multicollinearity requires the elimination of highly correlated independent variables. I argue that indicators should be re-used if they are proxies for different processes. Multicollinearity is not an issue because in an EMDS knowledgebase one is not statistically estimating the influence (i.e., coefficients) of explanatory factors on a dependent or response variable; rather, one is assigning weights that are used to calculate a dependent index (no actual values of "watershed condition" are independently measurable). This is not an issue of EMDS as a software system, but one that needs to be addressed through scientific communication from the EMDS community.

4.7 Evaluation Criteria

Under the multi-criteria approach, each indicator chosen must be evaluated or normalized to a common scale to facilitate their combination. The choice of evaluation criteria is often one of the most difficult and subjective aspects of model

building. Three basic approaches are found in the watershed cases. First, expert opinion-based indicators are typically expressed directly using a standardized (e.g., −1 to +1) continuous scale, or through the application of a categorical ruleset. For example, in the USFS R6 "distribution" indicator [4] asks for an expert judgment of the percent of potential habitat occupied, with 0–100 % judgment transformed in a continuous linear fashion to the −1 to +1 scale. Their "population status" indicator asks for categorical judgments, which have standardized values (e.g., Strong population = +1, Depressed population = +0.5, and so on).

A second approach to setting criteria uses an external standard. Specific thresholds are set based on measured or estimated levels of impact, e.g., the −1 threshold is >2.4 road mi·mi^{-2} of watershed, and the +1 threshold is 0 mi·mi^{-2}. Sometimes management or regulatory standards already exist and can be applied. For example, the EPA study [6] makes use of numerous existing water quality regulatory standards. Often, however, no such standards exist: rarely is a definitive, specific impact study available to set these standards, and so the modelers must rely on some combination of expert judgment and synthesis of the literature. As discussed in Gordon and Gallo (2011), tracking this interpretive process is a major challenge, but one that is crucial for the replicability and validity of the model.

Another source of external criteria is called reference conditions, which are usually derived from the range of values found in undisturbed watersheds or historical estimates of site condition. Several cases [4, 6, 11] use this approach for multiple indicators. Given the natural variability of watershed attributes and reasonable management expectations, reference distributions still require some interpretation to set evaluation criteria. For example, Trout Unlimited's CSI indicator "percent of historic[al] watersheds occupied by populations" uses thresholds of 20 %/80 % to define the −1/+1 thresholds. Grey literature reports for some cases [4, 11] provide details on how reference conditions were chosen and established. Such details are not provided for the EPA model [6], likely due to the space constraints of the journal format, which points to the challenge in communicating models through traditional scientific publications.

The third major approach to setting criteria found in these cases is an internal approach, which sets levels relative to the range of values encountered in the analysis area. For example, the USFS R6 analysis [4] used the 25th/75th percentile values to set the −1/+1 thresholds for riparian vegetation, while California North Coast assessment [7] used the 10th/90th percentiles for attributes in its sediment model. The Oregon North Coast assessment [9] used the average spawning fish count for the region as their +1 threshold and zero spawners as the −1 threshold. Walker et al. (2007) refer to it as "a more empirically-based approach to defining reference curves"; however, "empirical" should not be confused with "objective" here, as the thresholds were subjectively derived. Reiss et al. (2010, p. 31) note the potentially hazardous assumption that is inherent in this approach, "By selecting these percentile values, we assumed that 25 % of all of the HUC6s on each forest were in good condition and 25 % were in poor condition with the rest distributed in between."

4.8 Model Structure

After individual indicators are evaluated, they are then combined into an overall model structure, which includes the hierarchical arrangement, aggregation functions, and weights (e.g., see Fig. 1 and Table 1). Model hierarchies are presented in all the cases reviewed here, but the rationale behind them is typically not documented. However, the underlying logic is generally evident in the structures. Most of the assessment model indicators are grouped by watershed process location (upslope, riparian, in-channel) and then indicator domain (roads, vegetation, etc); exceptions are the EPA model [6], which takes a more explicitly process-based approach, and the Sandy River case [8], whose overall structure is determined by the three different major data sources (see Table 1, Assessment Model Structure column).

As mentioned above, three of the cases include explicit prioritization models, which integrate additional indicators to the assessment model results. The Upper Chewaucan case [3] had separate models for protection and restoration goals, both of which included factors relating to feasibility and efficacy of possible actions. The USFS Region 1 prioritization model [5] similarly included feasibility metrics, but also included a section on risk: risk of severe fires (from vegetation attributes) and risk of sedimentation (based on road density).

Environmental context switches also play an important part in some of the watershed model hierarchies. Such switches select different evaluation pathways in the model depending on the value of an environmental attribute. One of the most common examples is the use of stream gradient. In reach-level models, some cases [1, 2] only evaluate certain indicators on low gradient streams ($\leq$3 %), and in some watershed models [1, 4] roads along low gradient streams are evaluated differently from high gradient (>3 %) streams. Scores for roads in areas deemed geologically sensitive also receive from 50 to 100 % higher weighting in some models [1, 4]. Vegetation attributes naturally vary by a number of environmental factors, and elevation and precipitation are used as context switches in a few models [1, 4]. The USFS national model [12] simply allows a few indicators to be designated "not applicable": forest cover, rangeland vegetation, large woody debris, mass wasting. Given the strong spatial patterning in many landscape attributes, it is surprising that more models do not include such context factors. Explanations may include the limited scale of some cases (a relatively homogenous area), or it is an acceptable simplifying factor based on the overall distribution within a watershed. In support of the scale argument, the NWFP [1], as the largest application case, actually developed separate models for six subregions. This complete division allowed considerable variability between regions, however, and it became difficult to discern which differences were truly due to ecological factors versus involvement of different panels of experts. The team is now planning to consolidate the models into one using context switches based on explicit ecological factors.

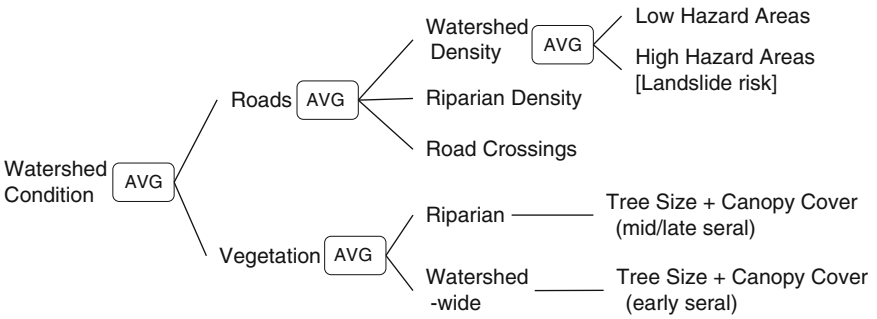


Fig. 1 Example model structure for assessing watershed condition ('AVG' represents use of an averaging aggregation function)

EMDS-Netweaver provides a wide variety of mathematical and logic operators for combining the standardized indicator scores. The most prevalent ones in the watershed models are the UNION and AND operators, which correspond to a partially-compensatory (i.e., average) or non-compensatory (minimum, limiting factor) functions, respectively. As users of Netweaver know, the AND function is rather ingenious and more complex than a simple minimum, but can be difficult to explain. However, NetWeaver also includes a true minimum math operator. The choice between these operators typically has significant consequences for model results. An early draft of the NWFP model [1] used primary ANDs, but the results were judged by experts to be unrealistically poor. The California North Coast assessment [7] found that using non-compensatory operators seemed more appropriate when considering certain low-level indicators, but that partially-compensatory performed better in higher levels of the model hierarchy.

Weighting is a third factor in the model structure. Five out of the twelve cases appear to have implemented some type of weighting (beyond the default weighting inherent in the model structure) [1, 2, 4, 5, 9]. The USFS R6 case [4] included weighting at the indicator level that was tied to their use of context variables: roads along low gradient streams and on sensitive soils received higher weights. The NWFP and NW Anchor Habitats cases [1, 9] included weighting at the indicator level and also further up in the hierarchy. Major differences between assessments of the same watersheds by the NWFP and USFS national [12] assessments were traced back to differences in the weighting of roads, both explicitly and through its averaging with a generally highly rated "soils" attribute in the latter. Clearly, care must be taken in the effects of model weighting and structuring. Steele et al. (2009) make the further point that relationships between criteria weights and evaluation criteria should also be considered. Few of the cases used the Priority Analyst portion of EMDS, but the USFS R1 case [5] demonstrated how models with different weightings can be used to prioritize for different objectives (improve watershed condition, reduce hazardous fuels in wildland urban interface, protect developed recreation values).

5 Conclusion

Watershed assessment is one of the oldest and most frequent application areas for EMDS. Watershed condition is a complex concept, and cases have struggled with representing dynamic processes with indicators based on ecosystem states. Structuring models more according to processes has faced the additional hurdle of overcoming flawed assumptions about multi-collinearity from standard statistical training.

The models built in the cases reviewed here varied considerably, depending on the purposes of the study (e.g., assessment versus prioritization), but also on available data (particularly fish habitat versus fish populations). In contrast, broad consistency in the basic unit of analysis (HUC6) is a benefit for data sharing and comparison of results, although more attention is needed to the versioning of these boundaries. Various efforts have come up with differing assessments for the same watersheds (e.g., cases 1 and 12), apparently more due to unintentional model structuring differences than divergent purpose. Care must be taken in the effects of model weighting and structuring, down to the bottom level of indicators and their evaluation criteria.

The complexity of the contributions to watershed condition means that data for key attributes are often not available. A number of the cases filled in these gaps with expert knowledge., EMDS is well-suited to integration of qualitative and quantitative data sources. Development of key sets of evaluation criteria is always a major challenge, and most models rely heavily on expert knowledge and literature assessments. For reliability and replicability, good documentation of these judgments is essential. While I have suggested a few areas where EMDS might provide further support in terms of software functionality, such as with temporal and spatial relations, many challenges lie in the broader domains of conceptual development and use of the results. Such needs may be best addressed through better sharing of information among a community of practitioners, and I would suggest that facilitating such ongoing dialog is a high priority for the future of the software.

References

Bleier C, Downie S, Cannata S, Henly R, Walker R, Keithley C, Scruggs M, Custis K, Clements J, Klamt R (2003) North coast watershed assessment program methods manual. California Resources Agency and California Environmental Protection Agency, Sacramento

CWA [Clean Water Act] (1977) 33 U.S.C. s/s 1251 et seq

Dai JJ, Lorenzato S, Rocke DM (2004) A knowledge-based model of watershed assessment for sediment. Environ Model Software 19(4):423–433

Dunham J, Gallo K, Shively D, Allen C, Goehring B (2011) Assessing the feasibility of native fish reintroductions: a framework applied to threatened bull trout. N Am J Fish Manage 31(1):106–115

ESA [Endangered Species Act] (1973) 16 U.S.C. 1531–1536, 1538–1540

Gallo K, Lanigan SH, Eldred P, Gordon SN, Moyer C (2005) Northwest Forest Plan—the first 10 years (1994–2003): preliminary assessment of the condition of watersheds. PNW-GTR-647. USDA Forest Service Pacific Northwest Research Station, Portland

Gordon SN (2006) Decision support systems for forest biodiversity management. In: a review of tools and an analytical-deliberative framework for understanding their successful application. Dissertation, Oregon State University, Corvallis

Gordon SN, Gallo K (2011) Structuring expert input for a knowledge-based approach to watershed condition assessment for the Northwest Forest Plan. USA. Environ Monit Assess 172(1):643–661

Hayslip GA, Herger LG, Leinenbach PT (2004) Ecological condition of western cascades ecoregion streams. U.S. Environmental Protection Agency, Region 10, Seattle

Hubler S, Miller S, Merrick L, Leferink R, Borisenko A (2009) High level indicators of Oregon's forested streams. DEQ09-LAB-0041-TR. Oregon Dept. Environmental Quality, Laboratory and Environmental Assessment Division, Hillsboro

Jensen M, Reynolds K, Langner U, Hart M (2009) Application of logic and decision models in sustainable ecosystem management. Paper presented at the 42nd Hawaii international conference on system sciences, Hawaii, HI, 5–8 Jan 2009

Kaufmann PR, Hughes RM (2006) Geomorphic and anthropogenic influences on fish and amphibians in Pacific Northwest coastal streams. In: Hughes RM, Wang L, Seelbach PW (eds) Landscape influences on stream habitats and biological assemblages, American Fisheries Society symposium 48, Bethesda, MD

Lanigan SH, Gordon SN, Eldred P, Isley M, Wilcox S, Moyer C, Andersen H (2012) Northwest Forest Plan—the first 15 years (1994–2008): status and trend of watershed condition. PNW-GTR-856 USDA Forest Service, Pacific Northwest Research Station, Portland, OR

Miewald T, Van Dyk B, Reeves G (2008) Oregon North Coast Salmon conservation assessment. Wild Salmon Center, Portland. http://www.wildsalmoncenter.org/pdf/WSC_OR_NCSalmonAssmnt08.pdf. Accessed 28 Aug 2013

Naiman RJ, Beechie TJ, Benda LE, Berg DR, Bisson PA, MacDonald LH, O'Connor MD, Olson PL, Steel EA (1992) Fundamental elements of ecologically healthy watersheds in the Pacific Northwest coastal ecoregion. In: Naiman RJ (ed) Watershed management: balancing sustainability and environmental change. Springer, New York

NFMA [National Forest Management Act] (1976) Act of October 22; 16 U.S.C. 1600

NOAA Fisheries (1996) Making endangered species act determinations of effect for individual or grouped actions at the watershed scale. National Oceanic and Atmospheric Agency, Fisheries Division. http://www.nwr.noaa.gov/publications/reference_documents/esa_refs/matrix_1996.pdf. Accessed 28 Aug 2013

Pess GR, Montgomery DR, Steel EA, Bilby RE, Feist BE, Greenberg HM (2002) Landscape characteristics, land use, and coho salmon (*Oncorhynchus kisutch*) abundance, Snohomish River, wash. USA Can J Fish Aquat Sci 59:613–623

Potyondy JP, Geier TW (2011) Forest Service watershed condition classification technical guide. USDA Forest Service, Washington. http://www.fs.fed.us/publications/watershed/watershed_classification_guide.pdf. Accessed 28 Aug 2013

Reeves GH, Benda LE, Burnett KM, Bisson PA, Sedell JR (1995) A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. In: Nielson JL, Powers DA (eds) Evolution and the aquatic ecosystem: defining unique units in population conservation, vol 17. American Fisheries Society, Bethesda, pp 334–349

Reeves GH, Hohler DB, Larsen DP, Busch DE, Kratz K, Reynolds K, Stein KF, Atzet T, Hays P, Tehan M (2004) Aquatic and riparian effectiveness monitoring plan for the Northwest Forest Plan. PNW-GTR-577 USDA Forest Service, Pacific Northwest Research Station, Portland

Reiss KY, Gallo K, Konnoff D, Dawson P (2010) Process for evaluating the contribution of national forest system lands to aquatic ecological sustainability: a regional pilot process conducted on the Okanogan-Wenatchee and Colville National Forests. USDA Forest Service, Region 6 (Unpublished draft)

Reynolds K, Peets S (2001) Integrated assessment and priorities for protection and restoration of watersheds. In: Proceedings of the IUFRO 4.11 conference on forest biometry, modeling and information science, Greenwich, 26–29 June 2001

Reynolds K, Reeves GH (2003) Role of knowledge-based systems in analysis and communication of monitoring data. In: Busch DE, Trexler JC (eds) Interdisciplinary approaches to ecological monitoring of ecosystem initiatives. Island Press, New York

Reynolds KM, Saunders MC, Foster M, Olson R, Schmoldt D, Latham D, Miller BJ, Steffenson J (1996) A knowledge-based information management system for watershed analysis in the Pacific Northwest US. AI Appl 10(2):9–22

Reynolds KM, Jensen ME, Andreasen J, Goodman I (2000) Knowledge-based assessment of watershed condition. Comput Electron Agric 27:315–333

Reynolds KM, Rodriguez S, Bevans K (2002) Ecosystem management decision support 3.0 user guide. USDA Forest Service, Pacific Northwest Research Station, Corvallis

SBRWG [Sandy River Basin Working Group] (2006) Salmon and steelhead conservation: an assessment of anchor habitat on the Sandy River, Oregon Trout, Portland. http://www.thefreshwatertrust.org/sites/fwt.ortrout.org/files/pdf/SandyHabRpt.pdf. Accessed 28 Aug 2013

SBRWG [Sandy River Basin Working Group] (2007) Sandy River basin aquatic habitat restoration strategy: an anchor habitat-based prioritization of restoration opportunities. Oregon Trout, Portland. http://www.sandyriverpartners.org/pdfs/SandRestStrategWEB.pdf. Accessed 28 Aug 2013

Seaber, Paul R, Paul Kapanos F, Knapp GL (1987) Hydrologic unit maps. United States Geological Survey Water-supply Papers 2294

Steele K, Carmel Y, Cross J, Wilcox C (2009) Uses and misuses of multi-criteria decision analysis (MCDA) in environmental decision making. Risk Anal 29(1):26–33

Trout Unlimited (2007) Trout unlimited's conservation success index user guide 3.0. http://www.tu.org/science/conservation-success-index. Accessed 28 Aug 2013

US OMB [U.S. Office of Management and Budget] (2006) Forest Service watershed program assessment. Washington. http://georgewbush-whitehouse.archives.gov/omb/expectmore/detail/10003029.2006.html. Accessed 8 Aug 2013

USDA FS [U.S. Department of Agriculture Forest Service] (2008) Aquatic and riparian conservation strategy. Pacific Northwest Region, Portland. http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5316591.pdf. Accessed 28 Aug 2013

USDA FS [U.S. Department of Agriculture Forest Service] (2011) Watershed condition framework: a framework for assessing and tracking changes to watershed condition. Report FS-977, U.S. Department of Agriculture, Forest Service, Washington

USDA FS [U.S. Department of Agriculture Forest Service] (2009) Stream inventory handbook: level I and II. USDA Forest Service, Region 6, Portland

USDA NRCS [U.S. Department of Agriculture, Natural Resource Conservation Service] (2012) What is the WBD? http://nhd.usgs.gov/wbd.html. Accessed 28 Aug 2013

USDA, USDI (1994) Record of decision for amendments to forest service and bureau of land management planning documents within the range of the northern spotted owl. U.S. Department of Agriculture Forest Service and U.S. Department of Interior Bureau of Land Management, Washington

USFWS [U.S. Fish and Wildlife Service] (1990) Endangered and threatened wildlife and plants: determination of threatened status for the northern spotted owl. Fed Reg 55:26114–26194

USGS [U.S. Geological Survey] (2012) National hydrography dataset. http://nhd.usgs.gov/index.html. Accessed 28 Aug 2013

Walker R, Keithley C, Henly R, Downie S, Cannata S (2007) Ecosystem Management Decision Support (EMDS) applied to watershed assessment on California's north coast. In: Standiford RB, Giusti GA, Valachovic Y, Zielinski WJ, Furniss MJ (eds) Proceedings of the Redwood Region Forest Science Symposium: What Does the Future Hold? PSW-GTR-194. USDA Forest Service Pacific Southwest Research Station, Albany CA

Williams JE, Haak AL, Gillespie NG, Colyer WT (2007) The Conservation Success Index: synthesizing and communicating salmonid condition and management needs. Fisheries 32(10):477–493