Nonpoint Source Pollution Modeling in the North Coast of CaliforniaNonpoint Source Pollution Modeling in the North Coast of California Within a GIS: A Predictive Screening Tool for Watershed Management

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Introduction

The Navarro River watershed hosts one of the last extant populations of coho salmon (Oncorhynchus kisutch) in the Central California Evolutionarily Significant Unit. As such, the identification and restoration of riparian habitats in the Navarro River watershed is paramount to the continued survival of this coho salmon population. This study utilizes a modeling procedure to identify priority locations in the Navarro River watershed using a geographic information system (GIS). This riparian habitat modeling method was used to identify priority restoration sites in the Navarro River watershed. The modeling structure emphasizes a hydrological metric, wetness index, and several landuse - land cover parameters. This GIS based model of the Navarro River was used for selecting potential riparian restoration sites, and used to demonstrate the utility of the model for selection of potential salmonid habitat. The results of analyzing the similarity between two model runs, one emphasizing habitat potential and the other anthropogenic degradation, indicate that riverine-riparian habitats have been disproportionately affected. This effort is offered as a potential tool to aid resource managers and local stakeholders with a method in which to initiate protection of aquatic ecological systems and coho salmon habitat in particular.

Background

The need for a systematic, comprehensive approach to the identification and conservation of aquatic habitats in California is evident and pressing. The documented and continuing decline of native fishes and amphibians in California, in addition to the destruction of critical aquatic habitats, warrants a change in current management strategies. Although efforts have been made to identify gaps in the conservation of biologically diverse areas for terrestrial systems, such a systematic approach to aquatic systems has been limited. Owing to the cyclical and fluvial nature of aquatic ecosystems, it is understandable that current management techniques, such as parks and reserves, have failed to conserve aquatic biota and habitats. A method of identifying, cataloguing, and prioritizing within watershed aquatic habitats, in regards to biodiversity and associated risk, is essential and necessary to provide resource managers and public stakeholders with the best information for decision making. In addition to conservation of habitats, restoration of degraded landscapes is becoming an important land management tool. The success of ecological restoration is often dependent on the site that is selected; whether it is the restoration of riparian vegetation or instream habitat, the hydrology, current landuse, and vegetation are important factors in the selection process. As restoration ecologists and the public attempt to restore and manage entire watersheds, it is increasingly important to have tools to help in the site selection process. Biodiversity is declining faster in aquatic environments than terrestrial ones (Moyle and Williams 1990); moreover, efforts by conservation scientists to preserve biodiversity have rarely addressed aquatic systems (Hughes and Noss 1992). At the beginning of the 1990's, it was said that there would be a greater emphasis on aquatic biodiversity conservation (Cairns and Lackey 1992) and rightfully so. The numbers of declining, threatened, and endangered fish taxa are staggering. Numerically, 314 native naturally spawning anadromous salmonids in the northern Pacific Ocean are on the decline (Nehlsen et al. 1991, FEMAT 1996). This decline is further evidenced by recent listings of fishes as Threatened or Endangered species under the Endangered Species Act; in California alone, this includes Delta smelt, Sacramento splittail, and several runs of anadromous salmonids. Although fishes are good indicators of aquatic ecosystem integrity because they are generally top-level trophic consumers, declines of other aquatic biota are also well documented. In California, 70% of all anuran taxa and 46% of all salamander taxa are considered a species of special concern, if not threatened or endangered with extinction (Jennings and Hayes 1994). The degree of degradation and elimination of aquatic ecosystems is directly bound to the anthropogenic manipulation of these systems.

Reasons for these declines are many, but they have been best qualified for anadromous salmonids and, thus, provide only a subset of the many issues related to declining populations of aquatic vertebrates in California. Specifically, Nehlson et al. (1991), Brown et al. (1994), and Yoshiyama et al. (1998) discuss the reasons contributing to the decline of anadromous salmonids, both natural and anthropogenic. These anthropogenic factors are many, but primarily reflect unsustainable economies of natural resource exploitation: over-fishing and habitat destruction. Habitat destruction comes in many forms: migration route blocking and spawning area inundation by dams; spawning area sedimentation by road-building and timber harvest practices; increased water temperatures due to reduced canopy cover and sedimentation by timber harvesting and riparian grazing; and the reduction in coarse woody debris used for juvenile cover due to timber removal (Nehlson et al. 1991, Brown et al. 1994, Yoshiyama et al.1998). The natural factors contributing to the population decline of anadromous salmonids are climate conditions, such as abnormally warm sea surface temperatures and droughts. These factors, as Brown et al. (1994) point out, are catastrophic events that salmon have experienced throughout their evolutionary existence. Therefore, it is the concerted and or cumulative effect of these factors that are responsible for the decline in salmonid populations. Furthermore, it is the anthropogenic stress on the aquatic systems that make salmonids and other aquatic and riparian dependent organisms more susceptible to perturbations by natural disturbance regimes.

The development of an aquatic habitat conservation strategy, and thus a worthwhile modeling effort, requires an understanding of existing theory and practice directed toward this endeavor. Principally, the two methods used to prioritize aquatic systems on a watershed basis in California are the use of Aquatic Diversity Management Areas (ADMAs) and Watershed Indices of Biotic Integrity (W-IBI). A review of their tenets are provided to show 1) the methods used in developing the Navarro River watershed model are consistent with their aim and 2) the Navarro River watershed model provides a dynamic tool that can be parameterized and scaled. The essence of these two strategies are: 1) the importance of a watershed scale perspective; 2) the inter-connectedness of riparian-lotic systems; and 3) the need for systematic assessments of both biotic and abiotic factors when determining management activities.

ADMAs

The five tiered approach to aquatic habitat conservation by Moyle and Yoshiyama (1992, 1994) advocates the use of the Endangered Species Act for conservation of a single species at the most discrete tier. This tier offers the best protection, in terms of political mandate and budget, for a species in peril. Often, the ESA listing can serve as both a signal to ecosystem stress and also as protection for other species dependent on the same habitat. However, there are instances where management for one species is at the detriment to other species, therefore assemblages or clusters of species can be a useful unit of conservation and is the second tier (Moyle and Yoshiyama 1994). This combination of using of existing policy, such as the Endangered Species Act, and the clustering of species assemblages can protect the critical habitat for other taxa as well. It is important to note that species clusters or assemblages are an ecologically more appropriate approach to ecosystem monitoring; habitat requirements vary among taxa and it is the heterogeneity in habitat composition that supports them all.

This strategy of assemblages or clusters of species allows for long-term management oriented toward conserving critical habitat. The prioritization of watersheds, and thus the identification of clustered critical habitats, is facilitated by the development of Aquatic Diversity Management Areas (ADMAs). ADMAs are watersheds that meet well-defined criteria and are specifically recognized for the maintenance of aquatic biodiversity (Moyle and Yoshiyama 1994). ADMAs are large enough to preserve natural processes and buffet against local species extirpation; maintained by a natural hydrologic regime; composed of native fauna; comprised of a heterogeneous mix of habitats; determined to be of high biotic integrity; and unique in character (Moyle 1996).

W-IBI

The contemporary methods for assessing the health, or biotic integrity, of aquatic systems, are indices of biotic integrity (Karr 1981). A watershed model described in detail by Moyle and Randall (1998) can be used to systematically prioritize conservation efforts at a coarser scale than the original method developed by Karr (1981). The Watershed Index of Biotic Integrity (W - IBI) was developed with the use of watershed scores, as opposed to in-stream measurements, for the presence and relative abundance of variables such as native fish, native ranids, and anadromous fishes (Moyle and Randall 1998). Also, landscape scale variables, such as number of dams and road densities, were compared to the W-IBI scores to give a further comparative measure (Moyle and Randall 1998). Programatically, these scores indicate watersheds with high conservation potential, in that they contain desirable biotic qualities. The W - IBI units of analysis are relatively large in scale, additionally managers and stakeholders are localized in their activities, thus an array of metrics are needed to identify smaller watersheds nested within the larger ones. These are identified areas of high potential for conservation / restoration or are at high risk from anthropogenic activities. An outstanding need is the facilitation of local management activities within watersheds, as opposed to landscape conservation efforts across watersheds.

Rationale

An element of these conservation strategies that is missing, however, is the development of a criteria based mechanism for resource managers and local stakeholders to help prioritize conservation efforts in watersheds. These efforts may not be in areas of high biotic value at a macro watershed scale, but do contain remnant areas of extant high quality habitat or areas worthy of restoration activities at a finer scale, a meso watershed scale. This meso level attribution would help predict vulnerable habitat within ADMAs, and also identify high quality sites in more degraded watersheds (low W-IBI scores). These are akin to "Priority 3" riparian areas, as defined by Moyle et al. (1996), which contain some high quality habitat that is extant, but fragmented. Such an analysis would utilize spatial relationships to determine if this extant zone also serves as refugia for vulnerable native fishes or amphibians. This modeling mechanism would also allow for prioritization of restoration efforts. An example of one such approach, is the use of a geographic information system (GIS) by Russell et al. (1997) to select sites for wetland restoration in the San Luis Rey River watershed based on land use, relative wetness, and proximity to existing riparian vegetation. A similar set of criteria was compiled for the Navarro River watershed model.

Management goals for riparian - aquatic systems center largely on the identification of elements and processes that promote ecosystem function in riparian zones. In particular, rare and/or endemic species, native species, and late seral stage species are advocated for special consideration. Additionally, maintenance of factors such as vegetative connectivity, in-channel geomorphology, subsurface water flow, and water quality parameters are offered as general goals, especially when they represent the native elements for ideal conditions (Moyle et al. 1996a). Thus, the Navarro River watershed assessment, integrates much of what Moyle et al. (1996a) identified as elements in need of collection for site specific management of riparian zones. Specifically, it is a priority ranking system which evaluates the overall condition of riparian and aquatic habitats.

Successful long-term restoration efforts require consideration of hydrology and land use (Russell et al. 1997). Russell et al. (1997) use a GIS to identify restoration sites from an index of several parameters: land use - land cover, patch size, patch proximity, and wetness values. The use of the topographic index, from hereto referred to as wetness index, by Russell et al. (1997) and O'Neill et al. (1997) for aiding in the identification and prioritization of riparian sites is an outcome of recent acknowledgements from restoration ecologists to the importance of disturbance in ecosystems. Particularly, the effects of flood hydrology, sedimentation, and stream channel morphology are innate factors to riparian habitat formation and structure in both spatial and temporal dimensions. The spatial modeling procedures provided in a GIS are advocated for several reasons. Namely, the data sources used are commonly available, the computing algorithms are easily employed, and the multi-factorial dimension allows for individual parameterization (O'Neill et al. 1997, Russell et al. 1997). Thus, the GIS model is delivered as a tool for identifying and evaluating riparian restoration sites, which can be employed in other watersheds (Russell et al. 1997).

In light the recent listing of the Central California Ecological Significant Unit of coho salmon as a Threatened species, the issues presented by Brown et al. (1994) concerning the decline of coho salmon populations and their remediation are complex; however, there are a few salient points that are still applicable. As Brown et al. (1994) stress, many of the problems contributing to declines have been well recognized for years. Namely, the status of many streams is still unknown. A systematic inventory of these streams is still needed in order fully implement any conservation management activity. Watersheds with intact habitat and coho salmon populations should be a high priority for continued conservation. Other watersheds need to be prioritized based on their potential for improvement; habitat restoration is not only expensive and time consuming, but also does not necessarily succeed.

Navarro River Watershed Model

The Navarro River watershed in located in southern Mendocino County in the Coast Range abutting the Pacific Ocean. Historically, the Navarro River watershed used for a resource based economy; namely, timbering, grazing, and limited cropping are the primary land use activities in the watershed. However, recent changes in the California economy have resulted in increased viticultural activities and an increased local human population (ca. 3500). The Navarro River watershed, 820 square kilometers in size, drains to the Pacific Ocean. Its proximity to the Pacific Ocean gives it a temperate climate, warm in the summer and cool in the winter, receiving an average of 1,203 millimeters of precipitation per year.

Two models were generated for the Navarro River, one a restoration matrix used several GIS data sources, in addition to a derived wetness index, includes riparian - forest canopy density, aspect, distance from existing riverine habitat, and precipitation. A preservation matrix was run to incorporate anthropogenic manipulation; a composite of data layers were used to indicate habitat quality, in addition to a proximity to roads layer.

All data sources were processed in ESRI's ARC/INFO GRID module. The use of Digital Elevation Models (DEMs) required additional manipulation and was done uniformly according to accepted practice and internal algorithms; namely, adjacent tiles were mosaiced and all elevational sinks were filled. Accumulated areas were generated from the FLOWACCUMULATION command as dependent on the output of the FLOWDIRECTION command. Accumulated areas (a) were also adjusted to provide areal values to cells without inflow. The use of slope (b) in the development of the wetness indices were generated from the SLOPE command with the DEGREE option and converted to radians; furthermore, adjustment was made for slopes of zero degrees to prevent indeterminacy.

The use of wetness values is derived, on a theoretical basis, from other hydrologic modeling efforts. TOPMODEL (TOPography based hydrological MODEL), a model using DEMs, has been used in a wide array of hydrological applications for over twenty years (Beven 1996). The primary topographic metric used in TOPMODEL is a topographic index which takes the form k = a / tan b , where a is the area draining through a point from upslope and tan b is the local slope angle (Beven 1997). The index responds hydrologically in that index values indicate a spatial pattern of expansion and contraction of wetted areas (Beven 1997). The postulated form of the topographic index uses a multiple flow algorithm to determine accumulated flow, with the accumulated area adjusted by the contour interval. The preferred algorithm in ARC/INFO GRID is "single flow direction" and does not require the contour interval adjustment; this method was employed by Russell et al. (1997) in their development of a wetness index.

The identification of riparian habitat for the Navarro River watershed was tailored specifically to the needs of coho salmon. These parameters are based largely on the distribution of Redwood (Sequoia sempervirens) forests, the optimal habitat for coho salmon (Brown et al. 1994). Streams of moderate (<3%) gradient with cool water and clean gravels are also required for coho salmon spawning. Notably, coho salmon, an anadromous fish species, rely upon the cool waters of streams shaded by dense canopy cover and northerly aspect, relatively low sloped streams for spawning gravels, and a complex instream structure of rootwads and boulders for juvenile cover (Brown et al. 1994). The modeling parameters used were chosen to best approximate these needs. Specifically, the wetness index identifies priority areas in two respects: one, areas of low slope are emphasized; and two, riparian vegetation, and thus rootwads, etc., require hydric conditions. The use of an aspect index indicates the cooler northerly facing subbasins, which coupled with the ameliorating effect of a precipitation index, identifies naturally cool and continuous water sources. The riparian - canopy cover index prioritizes existing riparian habitats and also the dense canopy cover provided by late successional forests preferred by coho salmon (Brown et al. 1994). Lastly, the proximity to riverine habitat can be taken as a weighting factor; namely, the farther the habitat is from the river, the less useful it is to coho salmon.

The wetness index, created as described above, was scored by normalizing the values with the highest index value. Thus, the wettest area received a score of one and the driest areas a score of zero. The riparian - canopy cover density index was created by combining two existing data sources. Riparian areas identified by the California Department of Forestry and Fire Protection (CDF) were extracted, given a value of one hundred, and conditionally added to a grid of canopy density derived from satellite imagery by CDF whose values indicated percent canopy cover. This subsequent grid was then normalized by 100, to emphasize both riparian areas and areas with dense canopy cover. The aspect index was generated by using the ASPECT algorithm in GRID on the 30 meter USGS DEM. The resultant values were conditionally scored to value North, East, West, and South from 1 - 0, respectively (a 90 degree swath was used with the cardinal direction at the 45 degree mark); this index was additionally smoothed with a 60 meter radial kernel to discriminate ridges and valleys. A precipitation index was created by averaging two existing data sources and normalizing by the highest value; the CDF precipitation layer depicts the years 1900-1960 and the Oregon State layer the years 1960 - 1990 (Daly et al. 1997), thus the index emphasizes the last 30 years. Lastly, the riverine proximity index, was created by scoring the Euclidean distance from a 1:100000 hydrography layer as 1 - 0, near to far respectively.

The second modeling procedure, with the inclusion of anthropogenic features, attempts to emphasize both existing degradation and environmental risks. The habitat composite index uses the Redwood inventory to identify old growth forests; the GAP Vegetation data (Davis et al. 1991), emphasizing spectral interpretation of land use and logging in particular; and lastly, Land Use - Land Cover, as depicted by the United States Geological Survey (USGS). The Redwood inventory was valued with scores of 0 - 1 with high scores indicating old growth redwood stands and low scores conferring newly planted areas. The GAP vegetation index was scored 0 - 1 with lesser scores going to urban areas and areas depicted as having been recently logged. Lastly, the land use data was scored 0 - 1 with urban, commercial, and residential areas receiving the lowest score and Redwood and Douglas Fir forests getting high scores. The habitat composite index is an average of these three data sources, which was further smoothed with a 60 meter radial kernel to indicate ecotonal gradients. The other anthropogenic feature that was included in the second modeling run was proximity to roads. A roads index layer was created by appending both 1:100000 and 1:24000 scale derived roads data and scoring the Euclidean distance; the farthest cells received a score of one and cells containing roads were scored with a zero.

Navarro River Watershed Model Results and Discussion

The upper quartile of the restoration matrix resulted in 46,257 acres of high potential habitat; these are areas that provide for the best coho habitat based on physical parameters. When compared to the preservation matrix, there is a significant decrease in area. The preservation matrix identified 40,758 acres of habitat in the upper quartile of scores, a 12% reduction in total area. Furthermore, these two indices had a Jaccard similarity coefficient of 0.65, indicating that much naturally coho habitat has been degraded. When these indices are restricted to within 100 meters of existing riverine areas, the decrease from restoration to preservation is even more marked. Within the riverine buffer area, 12,049 acres were identified for their natural value as a result of being the upper quartile of scores. There were only 9,546 acres in the preservation matrix, a reduction of 21% in area with a Jaccard similarity coefficient of 0.68.

To what degree do the spatial patterns predicted by the wetness index coincide with existing riparian areas? As evidenced by the calculation of Jaccard's similarity coefficient, the spatial coincidence is minimal (Bonham-Carter 1994). This result could be misleading for a number of reasons, but the primary reason for this, in our estimation, is the anthropogenic reduction in naturally occurring riparian habitats. Additionally, the uniformly low similarities between predicted wetness indices and two dissimilar existing riparian data sources further underscores this anthropogenic induced change. The wetness index predicted 9,173 acres of potential riparian habitat when the breakpoint was set at a wetness index of 10. The riparian - canopy cover index predicted 4,467 acres of riparian associated habitat when the breakpoint was set at 90% canopy cover. The coincident measure of these two indices is 2,583 acres, with a Jaccard similarity coefficient of 0.16. The dissimilarity of these two parameters, although unexpected, indicates that no measure alone can be used to identify priority sites.

Table 1.

Wetness Index
Aspect
Riparian
Riverine Distance
Precipitation
Habitat
Road Distance

Elevation
Slope
NDVI
Preservation Matrix
Wetness Index
1
0.00398
-0.07321
0.13491
-0.12079
-0.09289
-0.08349
-0.21095
-0.4956
-0.0949
0.04355
Aspect
0.00398
1
0.25669
-0.06401
0.01375
0.25546
-0.02822
-0.02796
0.0395
0.29746
0.60476
Riparian
-0.07321
0.25669
1
0.05479
0.19007
0.49644
0.12498
-0.00835
0.27022
0.6961
0.80706
Riverine Distance
0.13491
-0.06401
0.05479
1
-0.06248
-0.03098
-0.02562
-0.31283
0.03434
-0.01328
0.19888
Precipitation
-0.12079
0.01375
0.19007
-0.06248

1
0.10597
0.22378
0.59218
0.27997
0.25217
0.29963
Habitat
-0.09289
0.25546
0.49644
-0.03098
0.10597
1
0.01425
-0.17395
0.26797
0.58062
0.65041
Road Distance
-0.08349
-0.02822
0.12498
-0.02562
0.22378
0.01425
1
0.17294
0.21002
0.15133
0.28572
Elevation
-0.21095
-0.02796
-0.00835
-0.31283
0.59218
-0.17395
0.17294
1
0.15509
-0.00636
-0.03155
Slope
-0.4956
0.0395
0.27022
0.03434
0.27997
0.26797
0.21002
0.15509
1
0.29903
0.26683
NDVI
-0.0949

0.29746
0.6961
-0.01328
0.25217
0.58062
0.15133
-0.00636
0.29903
1
0.69762
Preservation Matrix
0.04355
0.60476
0.80706
0.19888
0.29963
0.65041
0.28572
-0.03155
0.26683
0.69762
1

Coefficients of correlation were analyzed to determine 1) the driving variables of the preservation matrix and 2) if spatial autocorrelation existed for any of the used variables or other similar variables. As viewed in Table 1 (unused variables in italics), the preservation matrix was largely driven by the aspect and riparian - canopy cover indices. Furthermore, the riparian - canopy cover index was seriously correlated with an NDVI (Normalized Difference Vegetation Index) derived from satellite imagery. This determination, coupled with it also being a driving variable of the preservation matrix, lends a note of caution due the inconsistencies in satellite data and their interpretation.

Conclusion

In the Navarro River watershed, identification of restoration zones for coho habitat is important in several respects. Not only is this endeavor important for the sake of the salmon, but salmon also serve as ecological proxies in several respects. Namely, Bilby et al. (1996) convincingly show that nutrient uptake from decaying salmon takes place by riparian vegetation, in addition to salmonid juveniles, conferring ecological services beyond the aquatic realm. Also, Willson and Halupka (1994) detail the keystone stature of salmonids to other species in trophic linkages and spatial distributions. Thus, finding key watersheds for the protection and enhancement of coho salmon in the Navarro River watershed will provide for the desired effects of aquatic - riparian biodiversity protection outlined by Moyle and Yoshiyama (1994) and "a system... for regional landscape management with great benefits to human health and well-being" (Moyle and Yoshiyama 1994, p. 17).

It is the complementary actions of scaled strategies, accompanied by holistic integration of policy elements, that will ultimately give aquatic systems security. Protection for aquatic systems defies conventional land acquisition efforts. Aquatic organisms are the true bellwethers of ecosystem health; their life history and medium of existence, fluid and cyclical by nature, requires integrative and holistic approaches that span ecological scales and political boundaries. Watersheds provide the holistic scope and riparian habitats provide the integrative force between terrestrial and aquatic systems. The framework and implementation of the conservation strategies outlined above requires many elements, including humans. We can only hope that we are up to the task.

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