Prioritizing riparian corridors for ecosystem restoration in urbanizing watersheds

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Background: Riparian corridors can affect nutrient, organic matter, and sediment transport, all of which shape water quality in streams and connected downstream waters. When functioning riparian corridors remain intact, they provide highly valued water quality ecosystem services. However, in rapidly urbanizing watersheds, riparian corridors are susceptible to development modifications that adversely affect those ecosystem services. Protecting high quality riparian corridors or restoring low quality corridors are widely advocated as watershed level water quality management options for protecting those ecosystem services. The two approaches, protection or restoration, should be viewed as complementary by watershed managers and provide a foundation for targeting highly functioning riparian corridors for protection or for identifying poorly functioning corridors for restoration. Ascertaining which strategy to use is often motivated by a specific ecosystem service, for example water quality, upon which watershed management is focused. We have previously reported on a spatially explicit model that focused on identifying riparian corridors that have specific characteristics that make them well suited for purposes of preservation and protection focused on water quality. Here we hypothesize that focusing on restoration, rather than protection, can be the basis for developing a watershed level strategy for improving water quality in urbanizing watersheds.

Methods: The model described here represents a geographic information system (GIS) based approach that utilizes riparian characteristics extracted from 20-meter wide corridors centered on streams and rivers. The model focuses on drinking water reservoir watersheds that can be analyzed at the sub-watershed level. Sub-watershed riparian data (vegetation, soil erodibility and surface slope) are scaled and weighted based on watershed management theories for water quality, and riparian restoration scores are assigned. Those scores are used to rank order riparian zones – the lower the score the higher the priority for riparian restoration.

Results: The model was applied to 90 sub-watersheds in the watershed of an important drinking water reservoir in north central Texas, USA. Results from this study area suggest that corridor scores were found to be most correlated to the amount of: forested vegetation, residential land use, soils in the highest erodibility class, and highest surface slope ($r^2 = 0.92$, p<0.0001). Scores allow watershed managers to rapidly focus on riparian corridors most in need of restoration. A beneficial feature of the model is that it also allows investigation of multiple scenarios of restoration strategies (e.g. revegetation, soil stabilization, flood plain leveling), giving watershed managers a tool to compare and contrast watershed level management plans.

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15 Abstract

16 **Background**: Riparian corridors can affect nutrient, organic matter, and sediment transport, all
17 of which shape water quality in streams and connected downstream waters. When functioning
18 riparian corridors remain intact, they provide highly valued water quality ecosystem services.
19 However, in rapidly urbanizing watersheds, riparian corridors are susceptible to development
20 modifications that adversely affect those ecosystem services. Protecting high quality riparian
21 corridors or restoring low quality corridors are widely advocated as watershed level water quality
22 management options for protecting those ecosystem services. The two approaches, protection or
23 restoration, should be viewed as complementary by watershed managers and provide a
24 foundation for targeting highly functioning riparian corridors for protection or for identifying
25 poorly functioning corridors for restoration. Ascertaining which strategy to use is often
26 motivated by a specific ecosystem service, for example water quality, upon which watershed
27 management is focused. We have previously reported on a spatially explicit model that focused
28 on identifying riparian corridors that have specific characteristics that make them well suited for
29 purposes of preservation and protection focused on water quality. Here we hypothesize that
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31 strategy for improving water quality in urbanizing watersheds.
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33 approach that utilizes riparian characteristics extracted from 20-meter wide corridors centered on
34 streams and rivers. The model focuses on drinking water reservoir watersheds that can be
35 analyzed at the sub-watershed level. Sub-watershed riparian data (vegetation, soil erodibility and
36 surface slope) are scaled and weighted based on watershed management theories for water
37 quality, and riparian restoration scores are assigned. Those scores are used to rank order riparian
38 zones – the lower the score the higher the priority for riparian restoration.

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46 managers a tool to compare and contrast watershed level management plans.
47

48 ## Introduction

49 Many areas across the globe are rapidly urbanizing, resulting in land use and land cover changes
50 that can adversely affect the natural resources upon which the growing population relies
51 (Melchiorri, Florczyk et al. 2018). When urban growth is substantial, riparian corridors are often
52 modified by human development activities. Modification of riparian corridors can alter
53 vegetation, hydrology, channel morphology and water chemistry, including nutrients and
54 pollutants ((Walsh, Roy et al. 2005, Ramírez, Engman et al. 2012). In north central Texas the
55 four counties that form the core of the Dallas-Fort Worth urban area (Collin, Dallas, Denton, and
56 Tarrant Counties) are projected to grow to approximately 7.4 million by 2030, from its 2010
57 population of about 5.6 million, or a 30.9% increase in 20 years (U.S. Bureau of the Census 2010
58 data, Texas Water Development Board 2030 projections). By 2070 the population is projected to
59 increase to approximately 11 million. The watershed that was used as the test site for the study
60 reported here, a 240,000 hectare watershed in the Dallas-Fort Worth area, has seen substantial
61 growth in urban lands that accompanies the population growth in north central Texas. Lands
62 classified as urban (i.e. residential, commercial, industrial and transportation) in this watershed
63 have grown from 15,300 hectares in 2001 (6.4% of total land) to 29,800 hectares (12.4%) in
64 2014. These types of projections can be found for many large urban areas throughout the world.
65 This growth puts pressure on all natural and infrastructure resources, including the freshwater
66 resources that supply drinking water to these areas. Illegal refuse dumping, chemical runoff,
67 clear-cutting, grazing, and other human influences are just a few of the detrimental factors
68 affecting the dynamic balance between rivers and streams, their surrounding riparian corridors,
69 and their encompassing catchments upon which these rapidly growing urban areas rely.
70

71 **Riparian Corridors**
72 As one of the most diverse of habitat types, riparian corridors influence water quality, flood
73 prevention, wildlife habitat, economics, and various other ecological, physical, biological, and
74 chemical processes (Wagner, 2004). Riparian corridors reduce erosion (Castelle and Johnson
75 2000), filter sediments and pollutants out of overland runoff (Staddon, Locke et al. 2001,
76 Dabney, Moore et al. 2006, Bongard, Wyatt et al. 2010), block solar radiation to moderate water
77 temperature (Sweeney 1992), provide habitat (Jones III, Helfman et al. 1999), and store water
78 thereby moderate flooding (Cooper, Hiscock et al. 2019). However, on a global basis more than

79   32,000 large dams (defined by the International Commission on Large Dams as a dam with a
80   height of 15 meters or greater, or a dam between 5 meters and 15 meters impounding more than
81   3 million cubic meters (ICOLD 2011)), and upwards of 1,000,000 total dams have fragmented
82   systems of streams and rivers (Jackson, Carpenter et al. 2001), leading Dudgeon, Arthington et
83   al. (2006) to state that freshwater ecosystems "… may well be the most endangered ecosystems
84   in the world". The U.S. Geological Survey's John Wesley Powell Center for Analysis and
85   Synthesis further suggests that "fresh water is arguably the most valuable resource on the planet,
86   but human activities threaten freshwater ecosystems" (USGS 2019). Effective assessment and
87   management techniques are necessary to protect the diversity of the ecosystem services found
88   within these ecosystems, and to mitigate current and future conditions of environmental stressors
89   amplified by rapid urban development.
90
91   Scientists have long studied riparian corridors as ecosystems of forested and/or vegetative
92   transition zones that link aquatic and terrestrial environments (see, for example Karr and
93   Schlosser (1978)). Studies show that healthy riparian stream corridors perform a multitude of
94   valuable services for their adjacent waterways, including: their overall influence on water quality
95   (e.g. Connolly, Pearson et al. 2015); biological diversity (e.g. Mlambo, Paavola et al. 2015);
96   ecosystem maintenance (e.g. Montgomery 2001); and protection of intermittent streams and the
97   residual pools that they provide as refuges for multiple species during dry periods (e.g.
98   Wigington Jr, Ebersole et al. 2006). Nutrient cycling, contaminant filtration, water purification,
99   bank stabilization, stream temperature maintenance, flow stabilization, flood attenuation, and
100 habitat preservation are some of the numerous functions carried out by riparian zones (National
101 Research Council 2002). In a recent review of riparian restoration literature (Feld, Fernandes et
102 al. 2018) it was stated that riparian restoration provides "a no-regrets management option to
103 improve and sustain lotic ecosystem functioning and biodiversity".
104
105 Riparian corridors exhibit a wide variety of geomorphic characteristics across a continuum of
106 scales. Studies that need to define the lateral extent of those corridors for research purposes have
107 used a range of approaches, from defining each riparian corridor on an individualized case-by-
108 case basis, to defining all corridors simultaneously in a study area based upon more generalized
109 definitional basis. An example that is nearer the individualized end of the spectrum, a recent
110 study that developed a model to measure departures of current riparian conditions from historic
111 conditions (defined as pre-European settlement in the north-western United States) used a stream
112 segment's valley bottom width as the lateral riparian extent because that represents the maximum
113 possible extent of riparian vegetation (Macfarlane, Gilbert et al. 2017). Using Thiessen polygons
114 with centroids located at the midpoint of each stream segment, they defined the individual lateral
115 extent of each steam segment's riparian corridor across an irregular planform of geometries and
116 valley bottoms. Nearer the other end of the spectrum Gilbert, Macfarlane et al. (2016) developed
117 a tool that set the maximum valley bottom (defined as the stream or river channel and the
118 associated low-lying floodplain) as the maximum possible extent of a riparian area. That tool set

119   the lateral extent of riparian areas for a given size of a drainage area (classified as either
120   "confined", "transition" or "large" based on km^2) based on a buffer around the stream channel
121   set to the maximum valley width in the drainage area.
122
123   Watershed managers concerned with water quality find that suggesting restrictions on
124   development in high quality riparian corridors, or restoring degraded riparian corridors, is
125   particularly challenging in Texas. Water law in Texas has evolved from conflicts between private
126   landowners and the needs of Texas citizens. Privately owned lands dominate the landscape of
127   Texas; less than 2% are federal lands (Vincent, Hanson et al. 2017). Additionally, two legal
128   doctrines of surface water law are recognized in Texas today: the riparian doctrine, and the prior
129   appropriation doctrine (Sansom 2008). The fundamental concept of prior appropriation is based
130   on pre-statehood Spanish law that evolved to control water use in irrigation intensive settlements
131   in Texas and the southwest. Those Spanish law concepts have today evolved such that Texas
132   owns most surface water, holding it in trust for the public, and allocates use of that resource
133   through a permitting process. Permits are issued on a "first in time, first in right" for a given
134   allocation of water. The riparian doctrine is based on an older English common law approach to
135   water use. The basic concept is that private water rights are tied to the ownership of the land
136   bordering a natural river or stream. Thus, surface water rights in Texas are tied to both state
137   permitted appropriations and by land ownership (Wurbs 2004), effectively restricting watershed
138   managers' options, and for all practical purposes limits the lateral extent of a riparian corridor
139   that a watershed manager can consider for water quality purposes.
140
141   Here, we offer a strategy for prioritizing riparian corridors for potential ecosystem restoration
142   focused on water quality. Fortunately, efforts focused on a specific ecosystem service can also
143   enhance other ecosystem service. For example, Fremier, Kiparsky et al. (2015) focus on riparian
144   restoration as a means for improving connectivity between protected habitats as a means to
145   increase the ecological resilience of those protected habitats. Their work was motivated in part
146   much the same as ours; increasing a system's ability to respond to natural and human induced
147   perturbations. Although their focus was for enhancing biodiversity while ours was for improving
148   water quality, the net result of either focus would likely yield benefits to the other. Other
149   beneficial synergistic restoration outcomes could include aesthetics, in-stream habitat, fish
150   passage and bank stabilization (see, e.g. Bernhardt, Palmer et al. 2005).
151
152   **Effects of Urbanization**
153   Urbanization and its subsequent activities, without proper planning, often leads to the
154   degradation of streams and their riparian corridors. This degradation may affect the natural
155   cycles of biological and physical activities normally carried out within riparian ecosystems
156   (Tanaka, de Souza et al. 2016), and also cause social and economic problems at both local and
157   regional levels. For example, Withers and Jarvie (2008) state that the problems can influence
158   human health (e.g. algal toxins), species abundance and diversity, amenity value and costs of

159 water treatment for drinking. Streams and rivers on the periphery of urbanizing areas are
160 particularly vulnerable due to population density, sensitivity to land use change and ubiquitous
161 exploitation (Walsh, Roy et al. 2005).   Furthermore, many of those aquatic systems at the urban
162 periphery have already been exposed to agricultural practices, such as grazing and the direct
163 access of cattle to streams. This has resulted in increased erosion of stream banks due to
164 trampling, as well as direct deposition and indirect flow of animal waste into waterways, a
165 principal component of nonpoint source pollution (Hamilton and Miller 2002). Ultimately, the
166 dynamic equilibrium of stream ecosystems can be altered by the cumulative effects of
167 channelization, clear-cutting, illegal dumping, and increased chemical usage, all consequences of
168 urbanization of surrounding riparian corridors.

170 Many places throughout the world are experiencing the same pattern of land use change that can
171 be seen in north central Texas, the application site for this model. Former rural areas are
172 becoming a part of an ever increasing urban landscape. As residential developments,
173 commercial properties, and industrial facilities increase, they cover the natural landscape with
174 roads, buildings, parking lots, and other impervious surfaces (Wang, Chen et al. 2019). Stream
175 health can be directly linked to urbanization, the effects of which simultaneously decrease bank
176 stability and increase pollutant presence and transfer. Healthy riparian buffer zones have been
177 shown to filter out up to 97% of soil sediment prior to stream entrance (Lee, Isenhart et al. 2003).
178 However, removing trees in riparian zones is often one of the first activities associated with
179 urban and suburban development, leading to increased soil erosion. Increased erodibility results
180 in a decrease in the depth of fertile topsoil and an increase of sediment within streams. These
181 sediments often contain metals such as lead, chromium or zinc, pesticides such as DDT, other
182 organics such as polychlorinated biphenyls (PCBs) or polycyclic aromatic hydrocarbons (PAHs),
183 or various other synthetic chemicals that may be toxic to aquatic and terrestrial species, and may
184 also be linked to human health via the food chain (see, for example: Pavlović, Mitrović et al.
185 2016, Walters, Otter et al. 2018, Bing, Wu et al. 2019).

187 The 2000 National Water Quality Inventory (U.S. Environmental Protection Agency 2000)
188 indicated that 39% of the river and stream miles in the United States were listed as impaired or
189 polluted, but the updated 2017 report indicated that the number increased to 46% (U.S.
190 Environmental Protection Agency 2017). River and stream conditions were assessed with
191 measures of biological quality, chemical stress, physical habitat stress, or human health
192 indicators. Aquatic conditions have led to extinction rates of freshwater fauna that are five times
193 that for terrestrial biota (Ricciardi and Rasmussen 1999, Sand-Jensen 2001). Fortunately, aquatic
194 ecosystem restoration can lead to improved biological, chemical and physical conditions,
195 resulting in both improved wildlife habitat and water quality.

197 **Objectives of This Study**

198   In an earlier study focused on prioritizing and protecting the highest quality riparian corridors, a
199   spatially explicit modeling and mapping technique was developed; the Water Quality Corridor
200   Management (WQCM) model (Atkinson, Hunter et al. 2007, Atkinson, Hunter et al. 2010),
201   originally referred to as the "wick 'em" model because of the acronym. We now call that model
202   the WQCM-P model, because it is focused on "protection" strategies. The model involves a
203   geospatial database that utilizes GIS and remote sensing techniques to assess and prioritize
204   stream reaches according to their overall health and sustainability. That model was developed
205   and then assessed for its ability to document stream corridor quality, and ultimately, establish a
206   ranking system for developing management strategies for protecting the highest quality stream
207   corridors for drinking water quality purposes.
208
209   The model's application area for this research consists of an important watershed in north central
210   Texas, USA. The overall watershed is 240,000 hectares in size (593,000 acres) and drains to a
211   relatively large drinking water reservoir (12,000 hectares; 29,600 acres), Lewisville Lake, which
212   serves the Dallas /Ft. Worth area (current population approximately 6 million). The watershed
213   was divided into 90 sub-watersheds based on U.S. Geological Survey Hydrologic Unit Codes,
214   ranging in size from 230 to 12,000 hectares (570 to 29,000 acres). Atkinson, Hunter et al. (2010)
215   provides a map that shows the results of the original WQCM-P modeling applied to that
216   watershed. That map illustrates to watershed managers which sub-watersheds contain the highest
217   priority stream corridors that should receive the initial focus for an overall watershed riparian
218   protection program.
219
220
221   Because high quality riparian corridor protection is only one strategy available for water quality
222   purposes, it became apparent after the release of the WQCM-P model that a tool was also needed
223   to rank riparian corridors in terms of potential aquatic ecosystem restoration . A re-working of
224   the original model was hypothesized to potentially provide that new focus. The new work
225   described in this paper turns the riparian protection question around, and asks the model to
226   prioritize riparian corridors for potential restoration activities in order to improve water quality in
227   the reservoir. The objective of the research reported here was to modify the original model, using
228   the same spatial databases, to one focused on potential "restoration" opportunities, or the
229   WQCM-R model. Using the same databases to reframe the question asked in this research
230   allowed an analysis of the effects of the reframing of the question, without a confounding effect
231   of also changing databases. Therefore, the new model described in this paper used the same sub-
232   watershed delineations, stream network, land use, soils, and topography data as was used the
233   original model.
234
235   A subsequent benefit of this new model is that not only will it indicate which sub-watersheds
236   contain riparian corridors that have the greatest restoration needs, it also allows targeting of sub-
237   watersheds that would receive the largest increases in riparian corridor quality based on specified

238 restoration strategies (e.g. revegetation with native plants, soil stabilization, etc.). As Nilsson,
239 Polvi et al. (2015) state, natural river ecosystems are both self-sustaining and dynamic, one of
240 their stated goals for successful river restoration. Our goal is that WQCM-R will assist watershed
241 managers in choosing not only the riparian areas most in need of restoration, but also help them
242 identify the most appropriate restoration strategy. Using both the WQCM-R and the WQCM-P
243 models, watershed managers should have access to a broad range of riparian corridor options for
244 assisting in water quality considerations in rapidly urbanizing watersheds.
245

246 ## Materials & Methods
247 The WQCM-R model, reported on here, was designed to (1) utilize easily accessible data for the
248 purpose of identifying and assessing potential water quality issues and (2) to classify stream
249 segments in order of riparian quality in order to prioritize potential restoration activities as a
250 component of an overall watershed management plan. The model generates scores for each sub-
251 watershed based on riparian zone characteristics for each of the spatial variables considered by
252 the model – lower scores imply higher restoration priority. While results are listed for each sub-
253 watershed for purposes of clarity, in actuality the results are limited to data extracted from only
254 the corridors.
255

256 **GIS Materials**
257 The following spatial data layers were utilized in the generation of the WQCM-R model:
258

259 Sub-watershed and its Corridor Component: U.S. Geological Survey (USGS) Hydrologic
260 Unit Codes were used to define 90 sub-watersheds in the overall Lewisville Lake drainage.
261 These sub-watersheds ranged in size from 230 to 12,000 hectares (570 to 29,000 acres).
262 ESRI ArcInfo's buffer tool was used to generate a 20 meter (66-foot) wide buffer zone
263 around a stream shapefile (40 meter total width) obtained from the USGS National
264 Hydrography Dataset (NHD[1]), which is provided at a scale of 1:24,000. The stream buffer
265 was then exported as a separate shapefile to be used as the extent from which the land use,
266 soil erodibility,and surface slope were clipped. Because sub-watershed varied substantially in
267 area, all subsequent data were transformed with a scaling factor: the ratio of total riparian
268 area within a sub-watershed to total sub-watershed area.
269

270 Land Use Parameter: Using the same land use classifications from our previous modeling
271 effort (Atkinson, Hunter et al. 2007, Atkinson, Hunter et al. 2010), surface area of eight
272 classes of land use were extracted for each riparian corridor in the study area: barren,
273 cropland/pasture, forested, residential, shrub/brush rangeland, urban, water, and unclassified.
274 The land use classes were derived from 30-meter resolution LANDSAT 8 ETM satellite

[1] NHD stream hydrography and sub-watershed topology is 99.98% identical to NHDPlus topology for the
Lewisville Lake watershed (8,615 segments out of 8,617 segments were identical). Because NHD data
were used in the original WQCM-P model, we continued to use the same dataset for WQCM-R.

275   imagery using Definiens eCognition object-based image classification software. The native
276   scale of 30 meter raster cells were utilized for all raster data.

277

278   Soil Erodibility Parameter: Using the same erodibility data from our previous model, theSoil
279   Survey Geographic (SSURGO) data from the National Resource Conservation Service was
280   used to create a soil erosion potential shapefile. There were eight erodibility 'kffact'
281   categories in the study area, where higher numbers indicate higher potential erosion: Kw = 0,
282   Kw = 0.17, Kw = 0.20, Kw = 0.24, Kw = 0.28, Kw = 0.32, Kw = 0.37, and Kw = 0.43. Soil
283   erodibility classes were extracted for each riparian corridor in the study area.

284

285   Surface Slope Parameter: The same Digital Elevation Model (DEM) from our previous
286   model was used for developing surface slope in the study area. Thirty meter raster data were
287   obtained from the USGS National Elevation Dataset (NED) to create a percent slope raster
288   file. Those data were categorized into five potential surface slope categories: <1%, 1% to
289   <2%, 2% to <3%, 3% to <4%, and 4% to 5% (no riparian corridors had areas with slopes
290   greater than 5%).

291

292   **Methods Used in Original Water Quality Corridor Model for Protection – WQCM-P**
293   The original WQCM-P model utilized the same four geospatial variables listed above, but also
294   included a "floodplain parameter" which accounted for the percent of a riparian zone that fell
295   within a Federal Emergency Management Agency (FEMA) 100-year floodplain. This was
296   included in the WQCM-P model because it helped account for some "protective" measures
297   already in place (e.g. restrictions on certain types of developments within the floodplain).

298

299   Each of the spatial variables consists of an importance weight and a scaling function (details
300   provided in Atkinson, Hunter et al. (2007) and (Atkinson, Hunter et al. 2010)). Importance
301   weights and scaling functions assigned to each variable range from 1 to 5, with 5 indicating a
302   greater need for protection. For example, land use class was considered the most important
303   variable in the model, receiving 5 importance points, and the scaling function for land use
304   indicates that forested areas within the riparian buffer receive 5 points while residential areas
305   within the riparian buffer receive 2 points. Each variable's scaling function was based on the
306   same concept: what conditions are more relevant to protect via preservation? Two of the
307   variables are specific to preservation goals. First, the FEMA 100 year Floodplain variable was
308   considered because areas designated to be inside these floodplains already receive some amount
309   of preservation protection (e.g. certain types of activities require flood insurance which often
310   discourages that activity). Second, the Corridor Ratio variable is the ratio of stream's corridor
311   area to its sub-watershed area. The Corridor Ratio and was considered because larger corridor
312   ratios suggest less room for development in the sub-watershed and therefore more pressure to
313   develop inside a stream's corridor area. In the WQCM-P model, higher scores represent higher
314   quality and therefore should be targeted for riparian corridor protection.

315
316   **Changes in Methods for the Water Quality Corridor Model for Restoration – WQCM-R**
317   The newly developed WQCM-R, established for restoration potential modeling, eliminated the
318   floodplain variable and the corridor ratio variables used in WQCM-P because they were
319   specifically focused on preservation strategies. Because floodplain development restrictions
320   typically do not affect "restoration" of riparian zones, these parameters were eliminated from the
321   WQCM-R model. The remaining four variables were retained for WQCM-R but importance and
322   scaling functions were altered to reflect a focus on restoration potential. Final scores were
323   calculated for each corridor in each sub-watershed's riparian area based on characteristics of
324   three variables: land use (L), erodibility (E) and slope (S). Values were calculated for the forth
325   variable, the area of the 20 meter wide corridor on each side of the stream segments in the study
326   area, generating an overall WQCM-R score for the riparian corridors of each sub-watershed.
327
328   The underpinning model is presented in equation 1:
329
330   WQCM-R Score = $L_iL_f + E_iE_f + S_iS_f$ (equation 1)
331
332   Where the subscripts "i" and "f" represent "importance" and "functional scale" (Table 1).
333
334   Table 1 approximately here (importance and scaling functions for each variable)
335
336   WQCM-R scores were generated for each sub-watershed's riparian corridors based on equation
337   1. Each riparian corridor's score was associated and mapped onto the appropriate sub-watershed,
338   and all sub-watersheds were then placed into one of four priority quartiles: low, moderate, high,
339   and highest restoration priority. Scores can theoretically range from a low of 10 (a sub-watershed
340   whose riparian zones are comprised of 100% barren land, 100% highly erodible soil, and 100%
341   steep surface slope), to a high of 50 (riparian zones comprised of 100% forest or water, 100%
342   low erodibility soil, and 100% negligible surface slope). This model intends watershed
343   managers to focus riparian restoration efforts on lower scores, those that represent the best
344   opportunities for watershed level water quality management.
345
346   **Statistical Analyses**
347
348   Principal component analyses. Data for 20 variables characterized each sub-watershed's riparian
349   corridor: area of each of 7 land use classes; area of each of 8 soil erodibility classes, and; area of
350   each of 5 surface slope classes. Principal component analyses were used to examine the sources
351   of variation in the 20 variables and determine how many principal components were needed to
352   explain at least 50% of the total variation, as well as determine if the variables that formed the
353   largest eigenvectors of the first principal component corresponded with the variables that formed
354   the best multivariate linear regression model.

355
356 Least squares regression. Least squares multivariate linear regression analysis was also applied
357 to the WQCM-R results, seeking the best regression model using a maximum r-squared
358 approach. Regression modeling set a sub-watershed's riparian area WQCM-R score as the
359 dependent variable, and each of the 20 riparian characteristics for the sub-watershed's riparian
360 area as the independent variables. The criteria for "best" included:
361   1. each variable must be logically consistent in terms of the sign of its coefficient
362   2. each variable must be statistically significant
363   3. the addition of each variable must increase the adjusted r^2 by a minimum of 0.05
364   4. the overall model must be statistically significant.
365
366

367 **Results**
368 Each sub-watershed's environmental data were entered into a GIS database, and the
369 corresponding 20-meter wide riparian corridor data were extracted. For each corridor up to seven
370 land use classes were identified and mapped, up to eight soil erodibility classes were mapped,
371 and up to five surface slope classes were mapped. Due to varying sizes of the sub-watersheds
372 and their riparian corridors, each mapped class was also normalized by the ratio of riparian area
373 to sub-watershed area to allow comparisons across all sub-watersheds. Normalization allows
374 comparisons to be based on the percent of each environmental class in a riparian zone as opposed
375 to the absolute area of each class.
376
377 Principal component analyses of the normalized data (20 variables) found that the first three
378 principal components explained more than 50% of the variance of the data (Figure 1). The five
379 largest eigenvectors of the first principal component were derived from: surface slope between
380 4% and 5%, Kw28 and Kw32 erodibility soils, forested vegetation and surface slope less than
381 1%.
382
383   Figure 1 approximately here (variance explained by principal components)
384
385 The WQCM-R algorithm was next applied to the riparian zones in each of the 90 sub-watersheds
386 in the study area. Based on the resultant score, each sub-watershed was placed into a
387 corresponding WQCM-R restoration priority quartile (low, moderate, high, or highest). Figure 2
388 provides a restoration priority map, where sub-watersheds with the darkest color represents the
389 highest priority (lowest scores) for stream corridor restoration, while the riparian corridors
390 themselves are mapped using colors associated with each pixels actual WQCM-R score. This
391 mapping technique allows watershed managers to visualize where stream corridor restoration
392 activities will generally be most beneficial based on a sub-watershed's quartile, and more
393 specifically where to target restoration activities within the smaller riparian area of the sub-
394 watershed.
395
396   Figure 2 approximately here (WQCM-R quartiles map)
397

398   Least squares linear regression analysis was also applied to the WQCM-R results, seeking the
399   best regression model using a maximum r-squared approach.

400

401   Using the criteria established to define the best multivariate regression model, the best model
402   identified included four variables (r^2=0.922, adjusted r^2=0.919, p<0.0001): percent of riparian
403   area with forested vegetation, percent of riparian area with residential land, percent of riparian
404   area with soils in the highest erodibility class, and percent of riparian area with highest surface
405   slope class. As would be expected for an algorithm that yields lower scores for areas more in
406   need of restoration, Table 2 shows that forested land has a positive coefficient (increasing forest
407   area results in higher WQCM-R scores and less potential need for restoration), while residential
408   land, high erodibility soil and high surface slope all have negative coefficients (increasing area
409   results in lower WQCM-R scores and more potential need for restoration).

410

411   Figure 3 illustrates a comparison of predicted restoration scores based on the best four variable
412   linear regression modeling versus the twenty variable WQCM-R scores. The data in the Figure 3
413   represent the 90 sub-watersheds sorted from highest to lowest WQCM-R restoration priority,
414   illustrating the close correlation between the twenty variable weighted-scaled WQCM-R
415   approach and the four variable regression modeling approach, suggesting the simpler approach
416   may be preferred. However, the WQCM-R approach allows exploration of multiple restoration
417   strategy scenarios, as will be described below, which the regression modeling approach does not.

418

419   Table 2 approximately here ("best" regression models with variables' coefficients)
420   Figure 3 approximately here ("best" regression modeled score versus WQCM-R score)

421

422   A valuable aspect of the WQCM-R model, as opposed to the simpler regression model, is that in
423   addition to an overall restoration potential score, specific landuse, soil erodibility, and surface
424   slope data are also available for each corridor. This additional information allows watershed
425   managers to glean insight as to why and how a particular corridor should be restored, and
426   explore the overall watershed implications for various restoration strategies. For example, if a
427   restoration strategy was focused on re-vegetation of crop/pasture land in a riparian zone with
428   native tree species, it is straightforward to determine how effective that strategy would be in
429   terms of improving overall riparian scores. It is a simple matter within the model to reclassify
430   crop and pasture lands within riparian corridors to forested land and recalculate WQCM-R
431   scores. For the 90 sub-watersheds in this analysis, this restoration strategy (re-vegetation of
432   crop/pasture lands with native trees) would result in an increase of average WQCM-R score from
433   36.68 to 37.11 (1.18%), a positive outcome. The resultant change is shown in Figure 4, where the
434   90 sub-watersheds are ordered from lowest to highest original score on the x-axis and displayed
435   with a solid black line (lower scores have higher restoration priority). New scores for a given
436   riparian corridor based on a revegetation restoration strategy are shown with green data points.
437   As can be seen in the graph however, very little of the improvement would occur in the riparian
438   corridors with the lowest original scores, the sub-watersheds most in need of restoration. This
439   information would be very useful for a watershed manager whose intent is to focus on improving
440   the lowest scoring sub-watersheds.

441
442 A second restoration strategy might be to focus on stabilizing the most erodible soils using the
443 same approach as above, and reclassifying highly erodible soils into a lower Kw class to
444 represent soil stabilization. A restoration scenario focused on the most erodible soils would
445 increase scores from 36.68 to 37.63 (2.60%). Figure 4 represents this scenario with orange data
446 points, and it is clear that much of the improvement would occur in sub-watersheds in the lowest
447 quartile scores. A watershed manager might prefer this strategy because it is more closely
448 aligned with the conceptual design of the WQCM-R model – improving the most problematic
449 riparian corridors first. This type of scenario analysis is a useful benefit of a spatially-based
450 riparian restoration model such as WQCM-R.
451
452   Figure 4 approximately here (improvement in scores based on restoration strategy)
453

Discussion

455
456 WQCM-R was developed to be generally applicable to any rapidly urbanizing watershed. The
457 model was applied to a major drinking water reservoir in north central Texas, because the region
458 is one of the fastest growing regions in the country. Of the top 6 fastest growth rates in large
459 cities between 2017 and 2018, two are in this region: Frisco and McKinney, and Fort Worth
460 experienced the third largest overall population increase in the United States during the same
461 time (U.S. Census Bureau 2019). Rapid urbanization in the north central Texas area has been
462 occurring for several decades. An analysis of the U.S. Department of Agriculture/U.S.
463 Department of Interior's LANDFIRE data base for north Texas land use indicates the degree of
464 urbanization in the sub-watersheds in the study area indicates a substantial increase in
465 urbanization between 2001 and 2014 (U.S. Geological Survey 2014). Of the 90 sub-watersheds
466 analyzed, 32 experienced more than 10% increases in urban lands during that time, five of which
467 increased by over 100% increases. Of the 90 associated riparian corridors, exactly 30 had
468 increases in urban lands of over 10% four of which experienced more than 100% increases of
469 urbanization. Figure 5 shows the relationship between the percent change in urban lands of a
470 riparian corridor and the percent change in urban lands in the associated sub-watershed. This
471 relationship ($r2=0.83$, $p<0.01$) indicates why watershed planners are concerned with urbanization
472 pressures on riparian corridors – urban development in a sub-watershed will almost certainly
473 encroach on nearby riparian corridors.
474
475   Figure 5 approximately here (sub-watershed urban change vs corridor change regression)
476
477 A visual examination of urban growth in the northern Dallas/Fort Worth metropolitan area over
478 the past 3 decades is also revealing. Figure 6 shows three snapshots in time of satellite imagery
479 of the area, spanning 32 years, (A) a graphic that labels dominant features in the imagery; (B)
480 1984; (C) 2000; (D) 2016. Urban land use is quite distinct (brighter pixel values seen
481 predominantly in the southeast sectors of the imagery) and the expansion of urban land use is
482 obvious. In 1984 Lewisville Lake (in center of satellite images) has some urban lands
483 immediately to the southwest, and some to the northwest. Ray Roberts Lake (top center) did not

484 exist in 1984, and Grapevine Lake (lower left corner) had very little urban land immediately
485 surrounding the lake. DFW International Airport, one of the more dominant features in the
486 imagery (bottom center) was completed in 1974, and by 1984 there is only moderate amounts of
487 urban land use near the airport. However, by 2000 there is substantial urban development around
488 the airport and noticeable urbanization around both Grapevine and Lewisville Lakes, and Ray
489 Roberts Lake has been completed, but there is little urban land use around the new lake. By
490 2016, urbanization has almost completely surrounded both Grapevine and Lewisville Lakes, and
491 there are hints of urban land use near Ray Roberts Lake. This trend is likely to continue, with
492 more and more urban development occurring as the Dallas Fort/Worth metropolitan area
493 continues its rapid growth to the north. The Lewisville Lake watershed has experienced a high
494 degree of urbanization in the southern half of its watershed over these 3 decades, and the
495 northern portions are likely to urbanize if pressure for development around Ray Roberts Lake
496 follows a similar pattern as that which occurred around Grapevine and Lewisville Lakes.
497
498   Figure 6 approximately here (orientation graphic and 3 satellite images)
499
500 The rapid urbanization of Dallas/Fort Worth region, along with its associated population growth,
501 has alerted watershed planners of the need to focus on potential ways to safeguard water quality
502 in the sources of drinking water for more than 6 million people currently living in the area. One
503 of the first things these planners considered was targeting riparian corridors that were highly
504 functioning in terms of water quality services for potential protection from development
505 pressures that tend to reduce water quality services. This initially led to the development of the
506 WQCM-P model that has been described above, which was applied initially to the Lewisville
507 Lake watershed. That effort ranked 90 sub-watersheds in terms of priority for protective actions
508 (e.g. a Water Authority might purchase corridors, might offer incentives to land owners for
509 limiting development). Next, watershed managers wanted to consider targeting riparian corridors
510 that were poorly functioning in terms of water quality for potential restoration projects that
511 improve water quality services.
512
513 Initially, it seemed reasonable to assume that riparian corridors which were ranked low for
514 protection actions would be those that were most appropriate for restoration. However, multiple
515 discussions with local watershed managers lead to the realization that two variables used in
516 WQCM-P to identify riparian corridors for protection, FEMA floodplain designation and riparian
517 area to sub-watershed area, were not the most appropriate considerations for identifying
518 corridors for restoration. Additionally, the importance weighting and scaling that had been
519 applied to riparian corridor variables under protection strategies needed adjustment under
520 restoration strategies. After the development of the WQCM-R model, a rational question to
521 explore was whether WQCM-P scores and WQCM-R scores were highly correlated.
522 Conceptually, there should be a negative relationship: the higher the potential for protection
523 based on water quality services, the lower the need for restoration. If they were highly negatively
524 correlated, the WQCM-R would not be necessary, and watershed managers could simply target
525 riparian corridors that had low scores for protection as those that had high potential for
526 restoration. Figure 7 shows the relationship between the WQCM-P and the WQCM-R scores for

527   the 90 sub-watersheds under review. The data show a negative correlation, but the variation in
528   WQCM-P that explains WQCM-R is very low (r^2=0.052). However, the trend is statistically
529   significant (p=0.03) confirming the conceptual assumption that there is a statistically significant
530   negative relation between the protection and the restoration models, but not one that can be used
531   to predict the other.
532
533   Figure 7 approximately here (WQCM-P v WQCM-R regression)
534
535   WQCM-R priority scores of each sub-watershed's riparian corridors are the primary tool that
536   watershed managers use to develop a targeted restoration strategy. For visual simplicity, a map is
537   produced that divides the sub-watershed into restoration priority quartiles (for example, see the
538   WQCM-R sub-watershed quartile map above), and is the product that guides a watershed
539   manager to find actual corridors suitable for restoration. In practice, a watershed manager will
540   examine each sub-watershed in the highest priority quartile, using the detail of high resolution
541   aerial imagery to locate candidate restoration opportunities. For example, in the Lewisville Lake
542   watershed, Figure 8 shows (A) an orientation map that depicts the location of a high restoration
543   potential sub-watershed and (B) a corresponding 2106 National Agriculture Imagery Program
544   (NAIP) image with the 40 meter wide riparian corridor boundary highlighted. Figure 9 shows
545   (A) an orientation map that depicts the location of a low restoration potential sub-watershed and
546   (B) a corresponding 2016 NAIP image with its 40 meter wide riparian corridor boundary
547   highlighted. These two examples represent how WQCM-R would be used in practice; the
548   quartiles map focuses attention on where the watershed manager should look more closely to
549   identify restoration opportunities.
550
551   Figure 8 approximately here – NAIP imagery of a highest restoration priority riparian
552   corridor.
553
554   Figure 9 approximately here – NAIP imagery of a lowest restoration priority riparian
555   corridor.
556
557
558

Conclusions

560   It has been estimated that riparian ecosystems once covered 75 to 100 million acres (30 to 40
561   million hectares) in the contiguous United States, and that by the mid 1980's two-thirds of that
562   land had been converted to other non-native land-uses (Swift 1984). Recognition of the loss of
563   ecosystem services accompanying those changes, for example the loss of water quality
564   protection, led to conservation efforts focused on riparian areas. Because it is typically less
565   expensive to preclude conversion of existing native riparian areas than it is to restore riparian
566   areas that have already been converted, initial conservation efforts normally focus on
567   preservation. However, riparian corridor restoration, especially in rapidly urbanizing watersheds,
568   is likely to become more prevalent as water quality managers seek watershed based management

569 approaches to protect and enhance water quality. This is becoming more evident in light of
570 increasing benefit/cost studies that show the value of restored riparian ecosystem services
571 exceeds the costs of those restoration efforts (e.g. (Holmes, Bergstrom et al. 2004, Benayas,
572 Newton et al. 2009, Costanza, de Groot et al. 2014, Daigneault, Eppink et al. 2017, Uggeldahl
573 and Olsen 2019), even though restoration is typically more costly than preservation.

574

575 Based on the approach utilized in the development of the original WQCM-P model to identify
576 high quality riparian systems for potential preservation purposes, it was hypothesized that the
577 model could be re-worked into a different tool that could be used to prioritize riparian corridors
578 in terms of potential riparian restoration. The new goal was to develop WQCM-R to assist
579 watershed managers in rank ordering riparian areas most in need of restoration from a water
580 quality ecosystem service perspective, and to also help them identify the most appropriate
581 restoration strategy for those riparian corridors. It was conceived of as being a straightforward
582 and uncomplicated tool that could be applied to urbanizing watersheds that drain into drinking
583 water reservoirs, allowing prioritization of the sub-watersheds in terms of riparian corridor
584 restoration potential. An additional benefit of WQCM-R would be that it allows exploration of
585 multiple riparian restoration strategies prior to expending resources to implement a watershed
586 management plan.

587

588 The development of WQCM-R was based on watershed management theories that suggest which
589 environmental variables should be included in an examination of riparian zones, as well as how
590 important each variable would be for prioritizing a riparian zone for potential restoration for
591 water quality purposes. The model was developed based on commonly available information and
592 applied to an important watershed in north central Texas, USA. The results confirmed that high
593 surface slope, high soil erodibility and lack of forested vegetation (in that order) were the driving
594 factors in restoration potential. Because WQCM-R is a spatially explicit model, the results allow
595 mapping of the rank order of restoration potential, providing watershed managers an overall view
596 of where restoration efforts are needed first. Finally, the model allows watershed managers to
597 examine multiple restoration strategies to determine the most effective approach for improving a
598 riparian zone's score. Future applications could include economic benefit/cost analysis, such as
599 those recently conducted by Daigneault, Eppink et al. (2017), in the WQCM-R rankings. This
600 addition would allow further prioritization of restoration efforts, focusing on those that provide
601 the highest benefit/cost potential as well as ecosystem services improvement, and provide
602 incremental analysis insights when watershed managers are working with limited budgets under
603 improved water quality goals.

604

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608 in terms of preserving high quality riparian zones and the underlying foundation that those
609 efforts had in the development of the model focused on restoration reported here.
610

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755

Figure 1

Principal components (90 observations, 20 variables): first three principal components explains 54.3% of total variance.

Proportion of total variance explained by each eigenvalue (solid line) and cumulative proportion of total variance (dashed line).

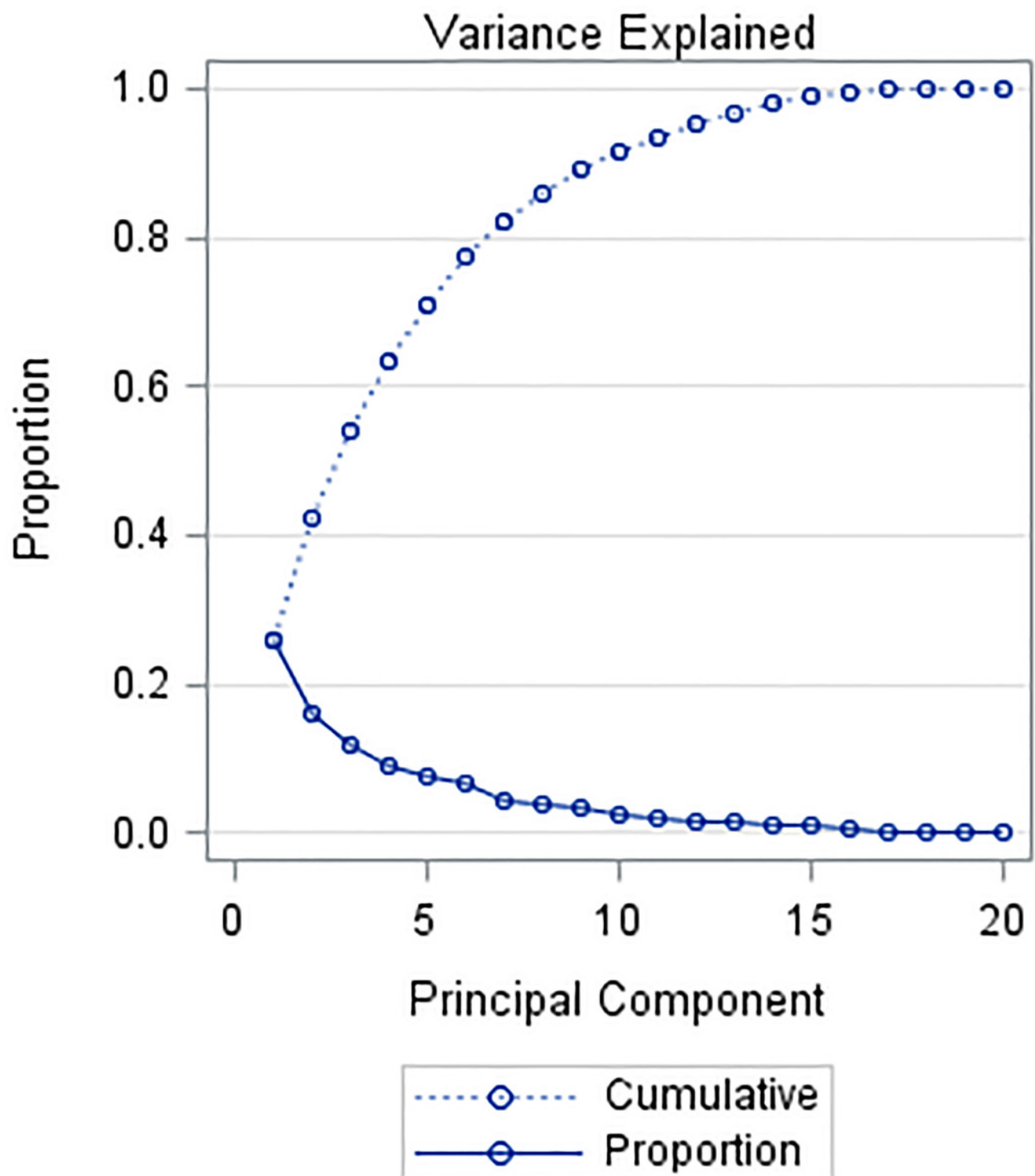



Figure 2

WQCM-R: priority for riparian restoration.

Darkest color represents highest priority for restoration quartile, lightest color represents lowest priority quartile for restoration.

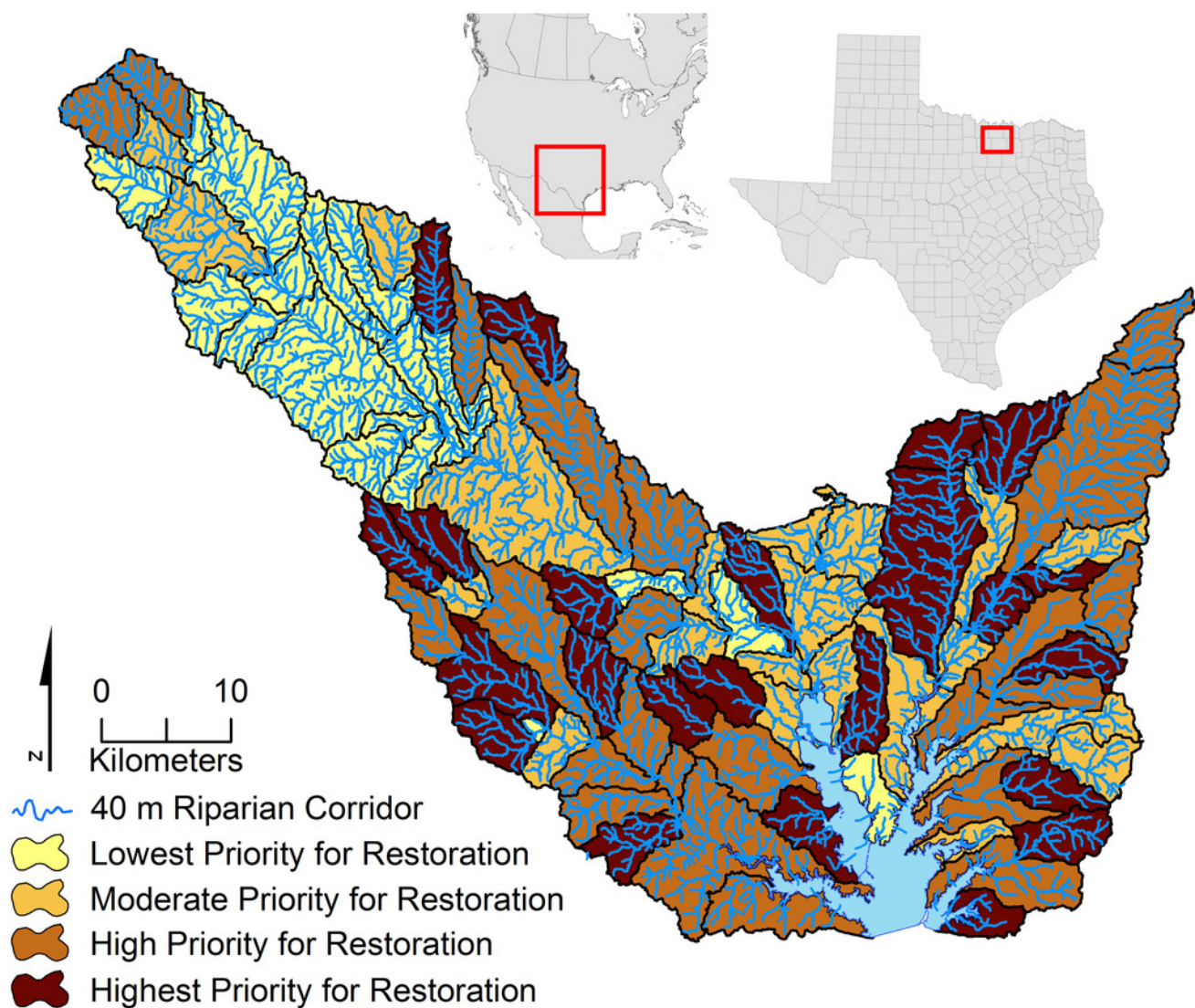



Figure 3

Multivariate regression prediction of restoration priority compared to WQCM-R modeled restoration priority for 90 sub-watersheds, ordered from highest to lowest WQCM-R restoration priority (left to right).

Solid points represent WQCM-R modeled priority for a sub-watershed and open points represent multivariate regression prediction for the same sub-watershed.

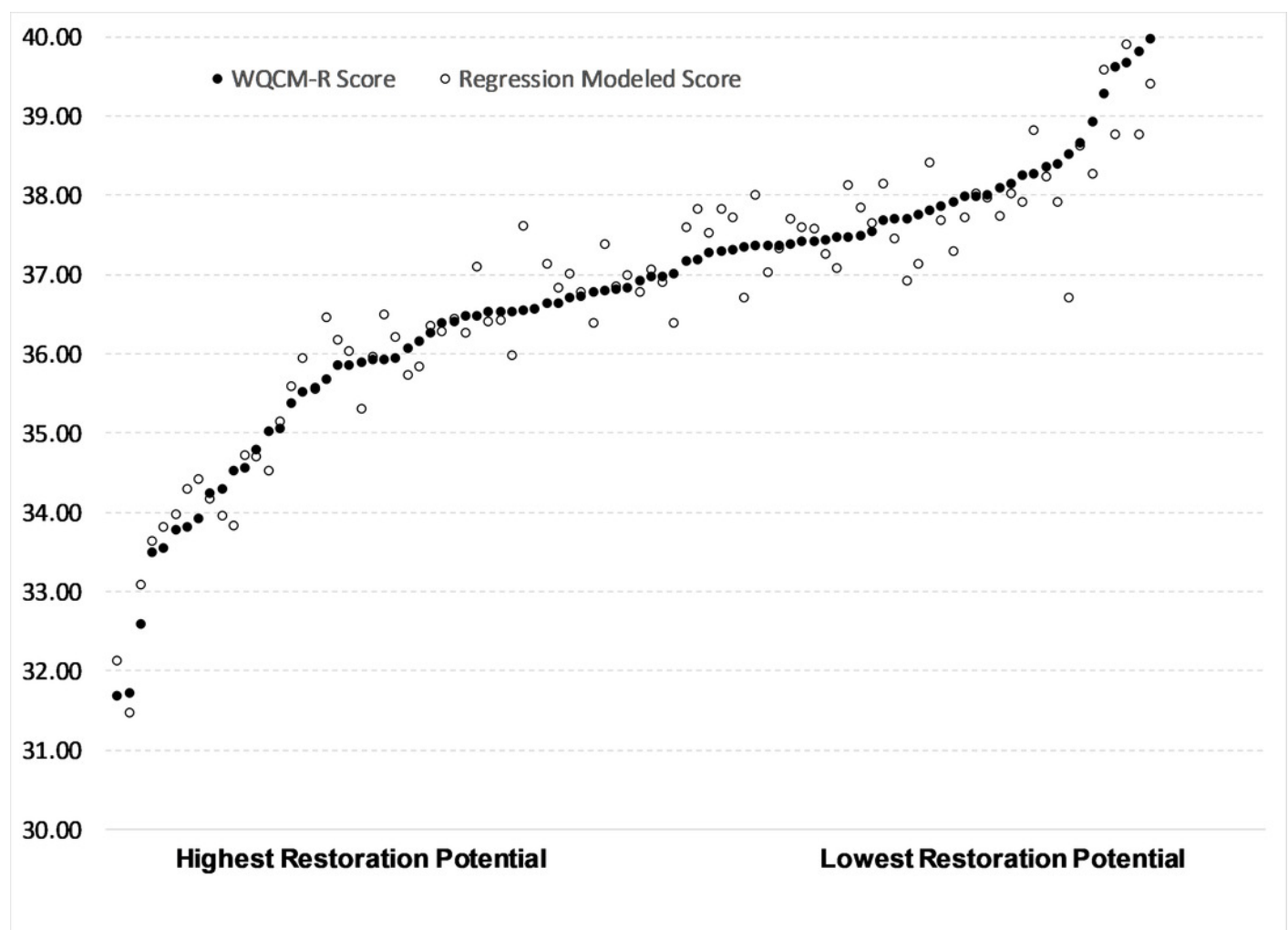



Figure 4

Improvement in WQCM-R scores based on two different restoration strategies (restore native riparian vegetation or stabilize soils).

Black line represents original restoration priority score, green points represent improvement in score under a re-vegetation restoration strategy and orange points represent improvement in score under a soil-stabilization restoration strategy.

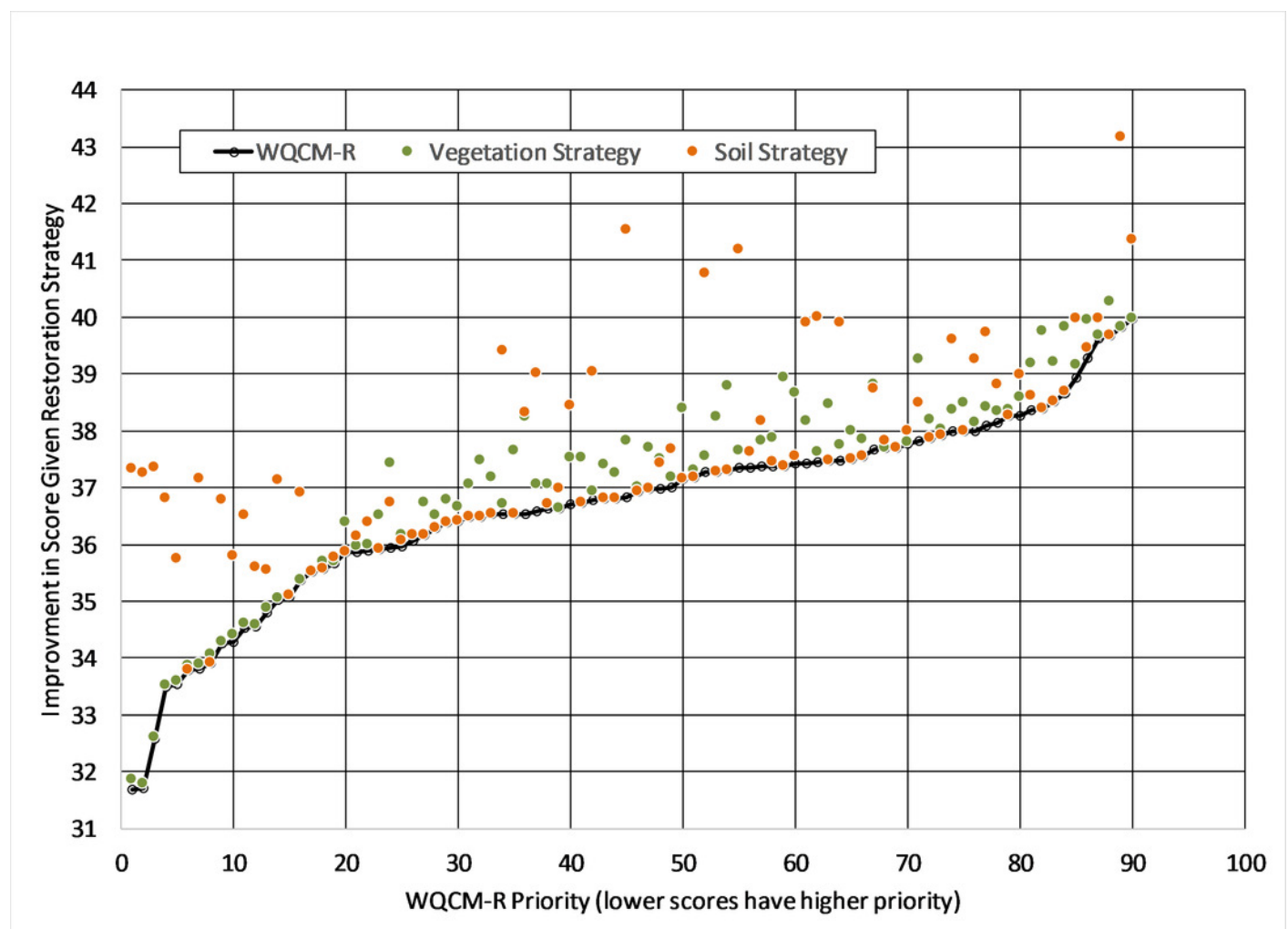



Figure 5

Percent change in urban lands in sub-watershed versus percent change in urban lands in the associated riparian corridors.

There is a high and statistically significant relationship between percent increase in urban land use in a sub-watershed and the percent increase in urban land use in the sub-watershed's riparian corridors.

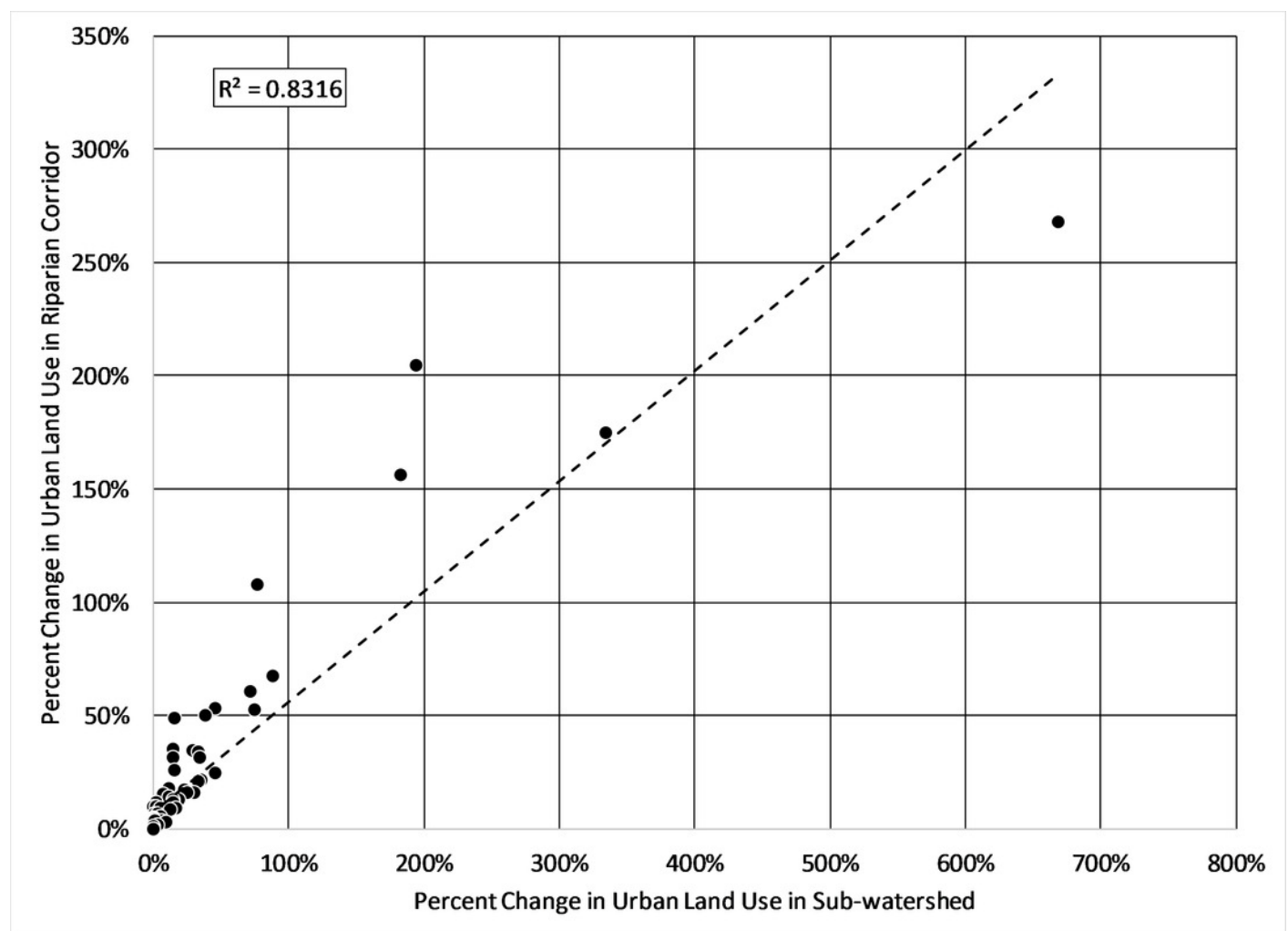



Figure 6

Urbanization in north central Texas observed from satellite imagery, ©2018 Google Earth: Images Landsat/Copernicus.

(A) represents major landmarks in the imagery for orientation; (B) satellite imagery acquired in 1984; (C) satellite imagery acquired in 2000; (D) satellite imagery acquired in 2016. Imagery shows rapid urban development (urban land use tends to be brighter that natural vegetation and agricultural lands). The expansion of brighter pixels from the lower right (southwest) corner of the images up and to the left coincides with population growth and coincident water demand in the Dallas/Fort Worth region.

Ray Roberts Lake

Denton

Lewisville Lake

Grapevine Lake

DFW International Airport

N

10 km

to Fort Worth

to Dallas

A

B

C

D

Images Landsat / Copernicus
© 2018 Google

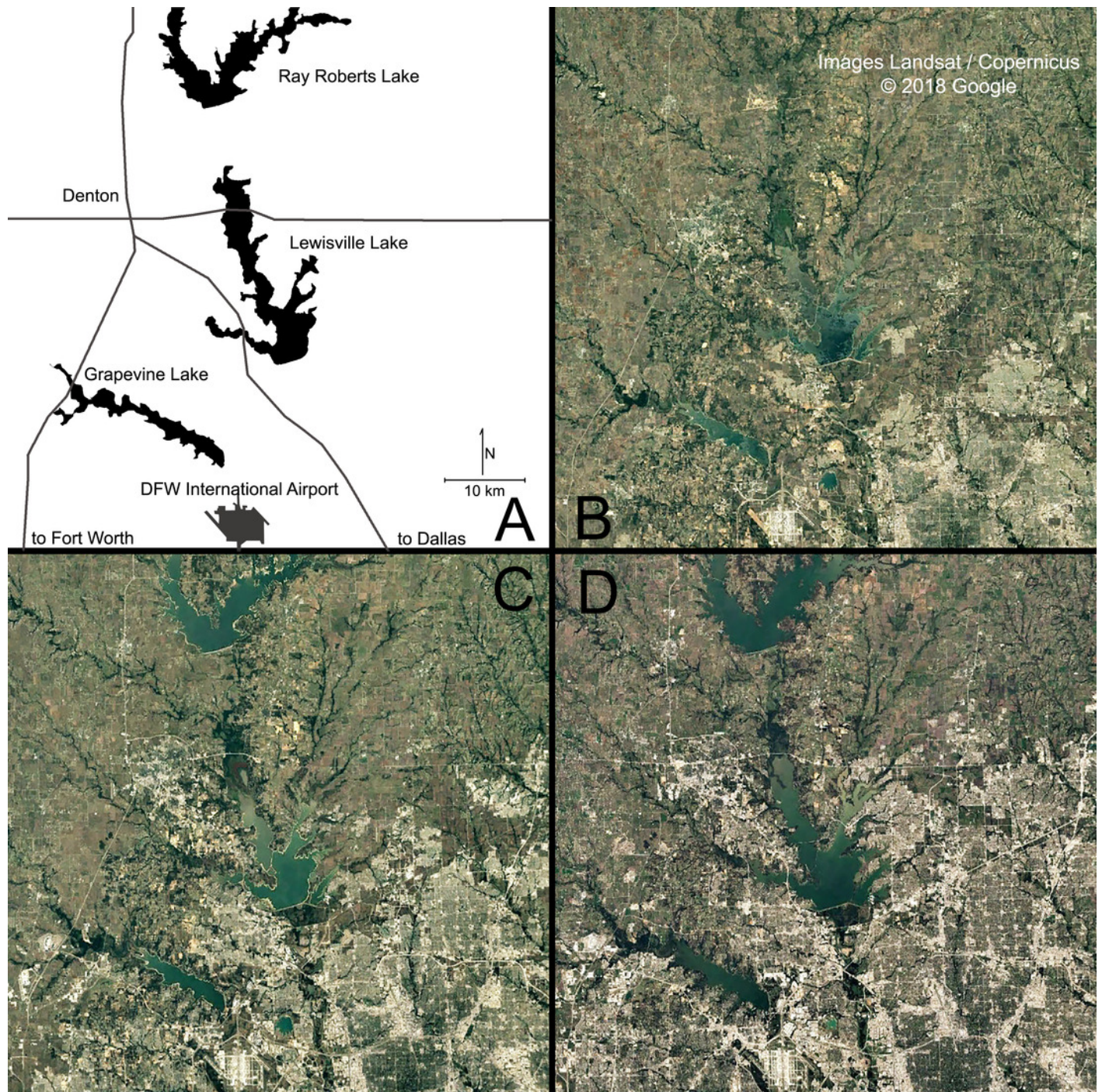



Figure 7

WQCM-P scores versus WQCM-R scores.

Regression line shows a statistically significant negative correlation between protection/preservation priority and restoration priority, as would be expected, but the coefficient of determination suggests that very little of the variability in WQCM-R can be explained by WQCM-P alone (r2=0.052, p=0.03).

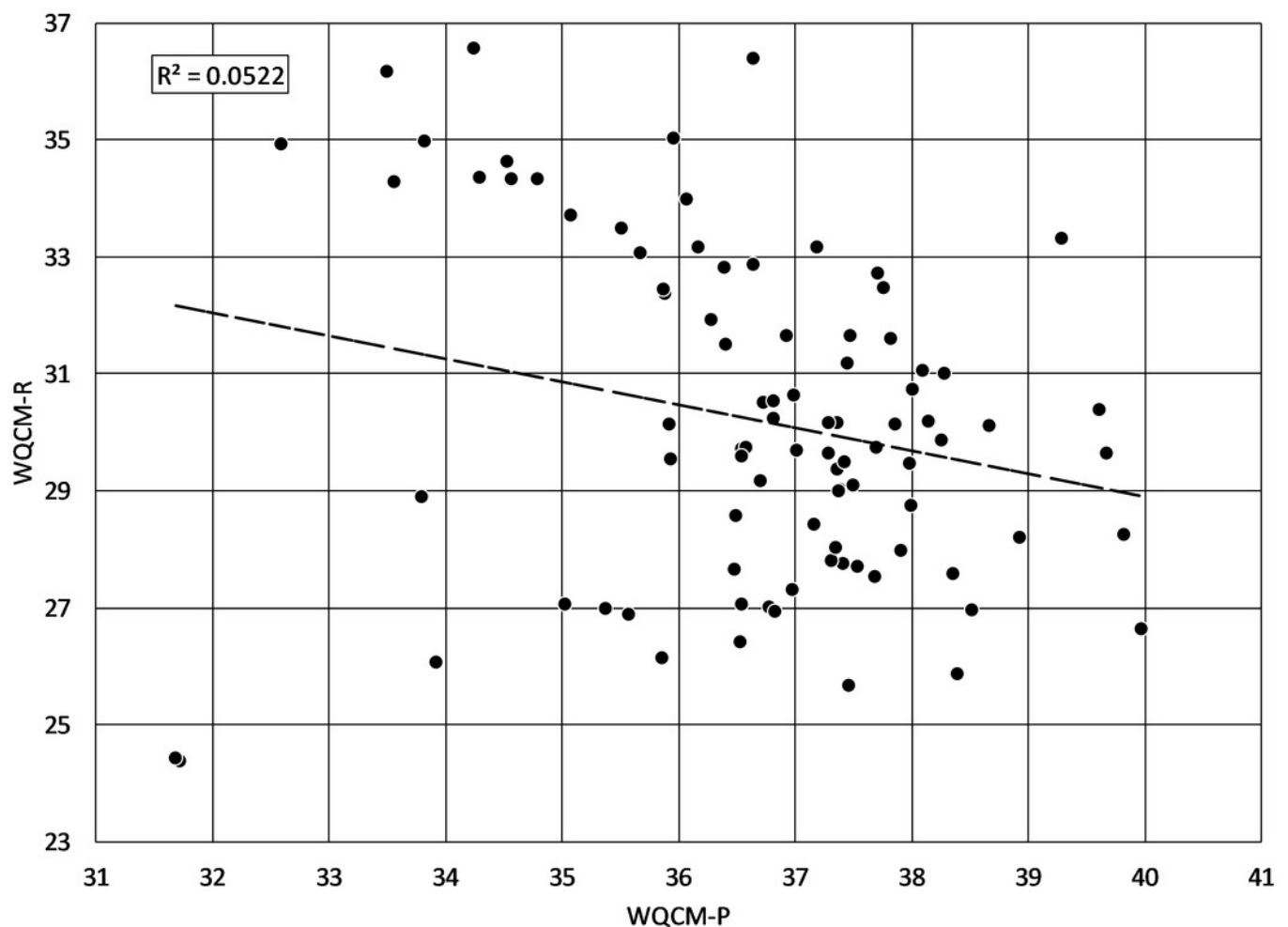



Figure 8

Visual examination of portions of a riparian corridor in a sub-watershed within the highest riparian corridor restoration quartile.

(A) orientation map that highlights which highest priority sub-watershed is considered and location of the NAIP imagery within the sub-watershed. (B) the corresponding 2016 NAIP imagery with the 40 meter riparian buffer highlighted. Public domain imagery: U.S. Department of Agriculture Farm Service Agency: National Agriculture Imagery Program, 2016.

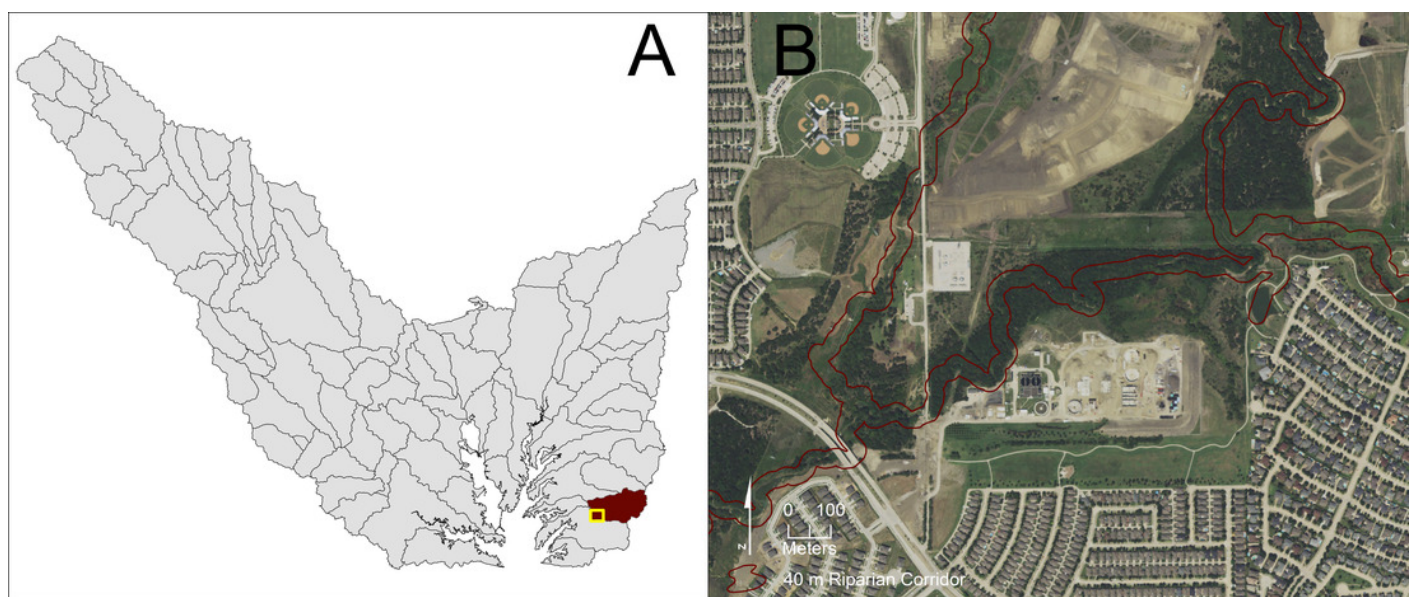
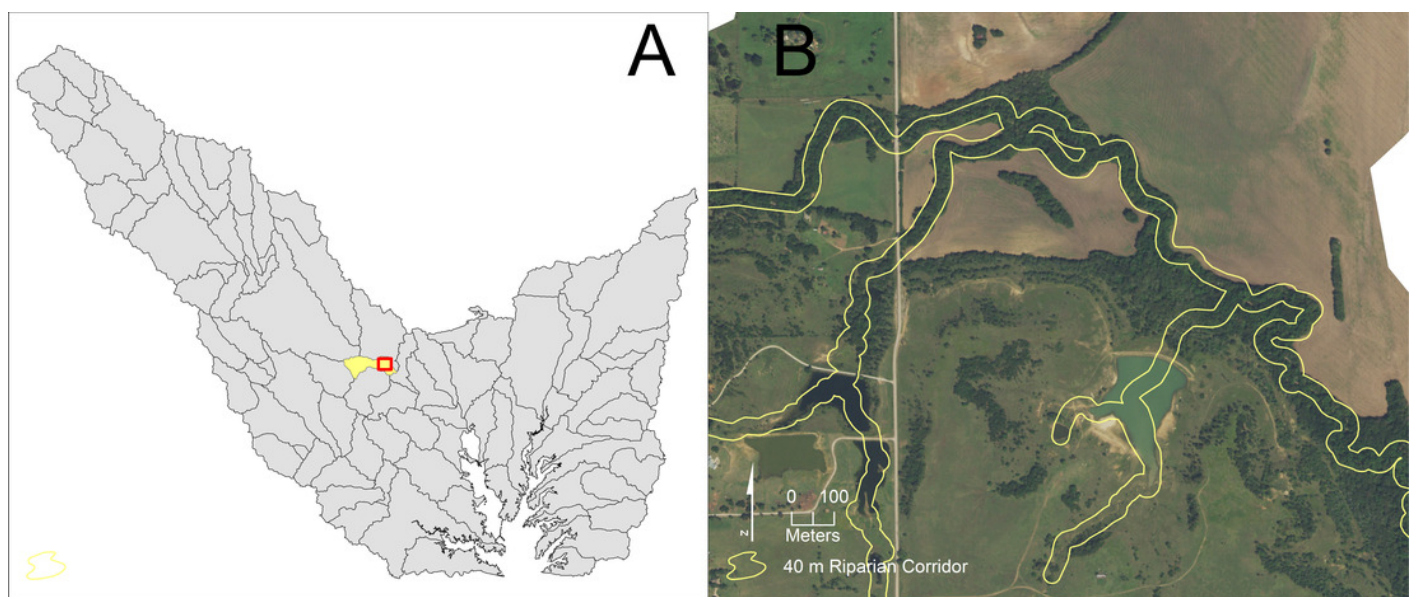



Figure 9

Visual examination of portions of a riparian corridor in a sub-watershed within the lowest riparian corridor restoration quartile.

(A) orientation map that highlights which lowest priority sub-watershed is considered and location of the NAIP imagery within the sub-watershed. (B) the corresponding 2016 NAIP imagery with the 40 meter riparian buffer highlighted. Public domain imagery: U.S. Department of Agriculture Farm Service Agency: National Agriculture Imagery Program, 2016.

Importance and weighting for each variable in WQCM-R model.

2
3

WQCM-R Variable	
Land Use (L) *Importance = 5*	Eight classes were generated. More the native the vegetative cover (forested riparian zones) within the stream corridor, are considered to have higher quality for drinking water purposes.
Class	**Class importance**
f = forest	5
w = water	5
s = shrub/brush	4
c = crop/pasture	3
b = urban	2
u = residential	2
r = barren	1
u = unclassified	5
$L_f = (c_f a_f + c_w a_w + c_s a_s + c_c a_c + c_c a_b + c_u a_u + c_r a_r + c_u a_u) / SWa$ *Where* L_f is the land use function, c_i is class importance, "a_i" represents area in acres of class c_i, and SWa is the sub-watershed area.
Erodibility (E) *Importance = 3*	Erodibility (Kw) in study area ranged from 0 to 0.43; lower Kw soils have less potential for erosion and are considered to have higher quality for drinking water quality purposes
Class	**Class importance**
Kw = 0.00	5
Kw = 0.17	5
Kw = 0.20	4
Kw = 0.24	4
Kw = 0.28	3
Kw = 0.32	3
Kw = 0.37	2
Kw = 0.43	1
$E_f = (c_f a_f + c_w a_w + c_s a_s + c_c a_c + c_c a_b + c_u a_u + c_r a_r + c_u a_u) / SWa$ *Where* E_f is the erodibility function, c_i is class importance, "a_i" represents area in acres of class c_i, and SWa is the sub-watershed area.
Slope (S) *Importance = 2*	Slope range from <1% to 5%; Gentler slopes soils have less potential for erosion and are considered to have higher quality for drinking water quality purposes.
Class	**Class importance**
slope < 1%	5
slope = 1% to <2%	4
slope = 2% to <2%	3
slope = 3% to <4%	2
slope = 4% to 5%	1
$S_f = (c_f a_f + c_w a_w + c_s a_s + c_c a_c + c_c a_b + c_u a_u + c_r a_r + c_u a_u) / SWa$ *Where* S_f is the slope function, c_i is class importance, "a_i" represents area in acres of class c_i, and SWa is the sub-watershed area.

Regression model variables' coefficients

WQCM-R score is dependent variable; independent variables found to best predict WQCM-R score in a riparian corridor were forested area, residential area, highest erodibility soil area and highest surface slope area are independent variables.

"Best" Regression Model to Predict WQCM-R score	Intercept	Independent Variables			
		Amount of Corridor with Forest	Amount of Corridor with Residential	Amount of Corridor with Highest Erodibility Soil	Amount of Corridor with Highest Surface Slope
Parameter Estimate	37.47442	6.01232	-10.60458	-5.51017	-8.55126
F-Value	99413.5	321.94	123.85	122.66	619.15
Pr > F	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
$r^2=0.9224$, p<0.0001, Adjusted $r^2=0.9187$					