Designing a regional trail network of high conservation value using principles of green infrastructure

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Abstract

Conservation and recreation planning potentially share many common goals, including the desire to increase landscape connectivity. Trail networks, however, typically develop independently of ecological corridors, with emphasis placed solely on their human services. The failure to align conservation and human use values results in missed opportunities to maximize the benefits of new trail development. This study uses concepts of green infrastructure and tools of connectivity modeling to identify priority locations for a regional trail network in the James River watershed, Virginia USA. The approach uses methods derived from circuit theory to identify potential pathways that meet basic trail design criteria but are also deemed to be of high conservation value. Results are discussed with respect to three separate regions within the watershed, each with distinct planning challenges. The relatively undeveloped headwaters region allows for the greatest flexibility of trail design. In contrast, the narrow watershed boundary in the coastal zone, along with high levels of development, permit limited options for trail placement. As funding for conservation and recreation development is often limited, multi-purpose trails located strategically within densely settled watersheds provide an opportunity for integrated recreation and conservation planning.

Key Words: Circuitscape; James River; landscape connectivity; morphological spatial pattern analysis

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1   **Introduction**

2   As the population of the United States struggles with issues of obesity, diabetes, and

3   other health concerns related to an increasingly sedentary lifestyle, health professionals have

4   placed greater emphasis on creating a recreational infrastructure to increase physical activity

5   (Cordell 2008; VA DCR 2011; Thomsen et al. 2013). Recreational hiking, biking, and running

6   trails offer an effective strategy to promote community building, exercise, and active

7   transportation (Sandström 2002; Brownson et al. 2006; Tzoulas et al. 2007; Eyler et al. 2008).

8   Relatively small expenditures on new trails systems can fundamentally change the dynamics of a

9   region. In the Portland/Vancouver metropolitan area, for example, an initial investment in a 64-

10   kilometer loop trail (Oregon Metro 1992) stimulated the development of a system of over 480

11   kilometers of trails used by millions of people each year (Oregon Metro 2013).

12   The health benefits of regional trail systems to quality of life in local communities have

13   been well documented (Schasberger et al. 2009). A study assessing user demographics,

14   preferences, and economics of the Washington & Old Dominion Trail, a regional trail in northern

15   Virginia (Table 1), found that most users ranked health, recreation, and fitness as their top

16   reasons for trail use (Bowker et al. 2004). Trails encourage healthy lifestyles through physical

17   recreation and transportation (Payne et al. 1998; de Vries et al. 2003; Fenton 2005). Outdoor

18   experiences also support mental health through reduced stress and crime rates, greater

19   community support systems, opportunities for psychological relaxation and renewal, and

20   improved mental focus (Forsyth and Musacchio 2005; Schmalz et al. 2013). A recent cost-

21   benefit analysis estimated direct medical benefits of $2.94 for every $1.00 investment in trail

22   development (Wang et al. 2005).

23   New trails provide additional benefits to communities beyond promoting physical and

24   mental health. For example, active transportation on trail systems reduces air pollution and

25   transportation costs (Shafer et al. 2000). Trails also attract tourists and bring money to local

26   businesses through increased visitor traffic (Bowker et al. 2004). These benefits often translate

27   into increased property values (Campbell & Munroe 2007; Beeton 2010). Educational benefits

28   associated with trails include greater access to and understanding of the environment, and trails

29   offer the opportunity for interpretative signage and exhibits (Schasberger et al. 2009; Thomsen et

30   al. 2013).

31   Trails offer relatively untapped potential benefits for conservation. On one hand, new

32   trails can attract new visitors, which in turn can degrade natural resources, especially when

33   providing visitor access to unique habitats that are home to endangered species (Manning 2001).

34   However, new approaches to managing protected lands have focused on how outdoor recreation

35   can be used to promote conservation. As one example, the National Park Service's Healthy Parks

36   Healthy People program is examining ways in which park resources can be better leveraged to

37   encourage multiple objectives of conservation, education, and physical activity (Thomsen et al.

38   2013). The boom in interest in development of recreational trails creates an opportunity to couple

39   recreation and conservation planning.

40   The traditional paradigm of conservation planning has been to separate and exclude

41   humans from ecologically important areas (Miller & Hobbes 2002). Isolating people from

42   conservation activities can be counter-productive. Combining recreational trail and park planning

43   can increase community awareness of and ownership in environmental conservation (Miller &

44   Hobbes 2002). At Minute Man National Historical Park, for example, a multi-use trail

45   connecting two historical sites has greatly increased community use of the park and exposed

46 visitors to its diverse natural, cultural, and educational resources (Thomsen et al. 2013). Through

47 increased awareness of natural surroundings, a conservation ethos can be formed (Forsyth et al.

48 2004). In Baltimore, Maryland, it was found that the Gwynn Falls watershed trail was

49 instrumental to catalyzing local citizen support of riparian restoration projects (Groffman et al.

50 2003). Giving citizens the chance to experience nature in their own communities exposes them to

51 the natural resources in their area, and makes them more likely to connect to, advocate for, and

52 take action to protect those resources (Miller & Hobbes 2002; Forsyth et al. 2004).

53   With limited funding for both recreation and conservation, linking these two goals can

54 provide a rich return on investment. The integration of regional trail networks with ecocorridors

55 is consistent with the overarching tenets of Green Infrastructure (GI) design to promote

56 ecosystem and human health, and the most successful implementations of GI networks often

57 incorporate multi-purpose corridors (Tzoulas et al. 2007). For example, the GI network

58 developed in Angelina County, Texas, was designed not only to preserve important ecosystem

59 processes and services, but also to help build the county's nature-based tourism industry

60 (Amundsen et al. 2009). Using GI networks as a basis for a recreational trail system offers the

61 opportunity to promote ecological conservation in a way that may be compatible with human use

62 (Tzoulas et al. 2007).

63   Broadly defined, GI consists of interconnected networks of core (large, intact areas of

64 natural habitat) and corridor (smaller, connecting bridges of habitat) green spaces that help to

65 enhance ecosystem services and conserve ecosystem functions (Benedict and McMahon 2001;

66 Tzoulas et al. 2007). The GI definition highlights the important dual role of GI networks:

67 providing ecosystem services to local communities, such as water filtration, stormwater control,

68 and air purification (de Groot et al. 2002; Tzoulas et al. 2007); and supporting critical ecological

69   processes, such as species migration, dispersal, and recolonization (Hargrove et al. 2000; Saura

70   and Pascual-Hortal 2007; Kong et al. 2010). Protection of core areas of mature, heterogeneous

71   habitat is a well-documented conservation tool in the battle to offset the many adverse effects of

72   habitat fragmentation (Tewksbury et al. 2002; Hooper, et al. 2005; Opdam et al. 2006; Tzoulas et

73   al. 2007). A recent meta-analysis indicates that corridors can enhance species movement between

74   core areas by as much as 50% compared to unconnected core areas (Gilbert-Norton et al. 2009).

75   The facilitated movement of plant and animal species through corridors potentially benefits

76   ecosystems in many ways, including increases in genetic diversity as species population sizes

77   increase (Bengtsson et al. 2002; Tewksbury et al. 2002; Haddad & Tewksbury 2005). Natural

78   corridors have been found to be more effective for species movement than created corridors,

79   suggesting that protecting existing habitat is more important than creating new habitat (Gilbert-

80   Norton et al. 2009). Thus, GI networks that target intact habitat corridors tend to best preserve

81   healthy ecosystem functions (Tzoulas et al. 2007).

82   There is, however, no uniform process for developing GI plans, which are highly

83   dependent on scale and geography (Benedict and McMahon 2001). In addition, there are

84   discouragingly few options for implementing those GI plans that have been developed. In the

85   current climate of budget cuts and funding shortfalls, leveraging the energy behind new trail

86   creation to maximize benefits for both community and ecosystem health seems a wise strategy.

87   The purpose of this study is to use principles of GI and the latest approaches in spatial pattern

88   analysis and connectivity modeling as a coarse filter to identify potential locations for new trails

89   in the James River watershed, Virginia, USA. The analysis yields general rules of thumb for trail

90   planning in different regions of the watershed and locates specific priority areas for more

91   detailed consideration of trail placement. Finally, existing trails being considered for inclusion in

92   the James River Heritage Trail system are assessed for their ecological value. The result is a

93   spatially explicit strategy for creating a connected trail network of high ecological value, in order

94   to facilitate the alignment of conservation and recreational planning.

95   **Methods**

96   *Study Area*

97   The James River watershed encompasses 16,473 square kilometers within three

98   physiographic provinces of the state of Virginia (Figure 1). Making up approximately a quarter

99   of the state, the James River watershed includes parts of 39 counties and 19 cities and is home to

100   one-third of all Virginia residents. At 547 kilometers, the James River is Virginia's longest river,

101   one of the nation's longest rivers contained entirely in one state, and Virginia's largest tributary

102   to the Chesapeake Bay (VA DCR 2005). The watershed is historically and ecologically

103   significant as the site of the first permanent English settlement in the Americas, one of the last

104   confirmed strongholds for the endangered Atlantic sturgeon, and one of the best examples of

105   bald eagle recovery on the continent (Watts et al. 2008; Balazik et al. 2012).

106   The James River Heritage Trail (JRHT) is envisioned as an interconnected network of

107   trails within the James River watershed (VA DCR 2011). Much of the JRHT will comprise

108   existing trails, including some paved, on-road bike lanes located near the banks of the James

109   River. Currently in the conceptual planning stages, the Virginia Department of Conservation and

110   Recreation is leading a coordinated approach among dozens of interested parties in the James

111   River watershed to define the trails. Stakeholder concerns include: water quality, historic

112   preservation, habitat conservation, working lands, navigation, commercial use, private property

113   rights, public recreation, safety, and stewardship (VA DCR 2011). Although recreation is the

114   primary goal of the JRHT network, once completed, the trails will act as managed corridors to

115   protect and enhance natural resources throughout this historic watershed (VA DCR 2011). The

116   creation of the trail network, therefore, provides an exceptional opportunity to align conservation

117   priorities with recreation planning.

118   ***Identification of Priority Landscape Components***

119   Two types of GI assessments, the state-produced Virginia Natural Landscape Assessment

120   and a morphological spatial pattern analysis, were used to identify priority green spaces in the

121   James River watershed. Information from these two assessments were combined with (1) data on

122   current protected lands from the United States Protected Areas Database and (2) an analysis of

123   river proximity to rank pixels on the landscape by their conservation value. All analyses were

124   done in ArcGIS 10.

125   *Virginia National Landscape Assessment*

126   The Virginia Natural Landscape Assessment (VaNLA) is Virginia's official statewide GI

127   plan. Residential and commercial development are the main causes of habitat loss and

128   fragmentation in the state. VaNLA uses geospatial analysis to identify, prioritize, and link

129   remaining natural lands in the state (VA DCR 2007).

130   Ecological cores were identified using satellite imagery and defined as areas of natural

131   land cover (e.g., forests, marshes, and dunes) of at least 40.5 hectares (100 acres) in size. Over 50

132   attributes were assigned to each ecological core based on rare species and habitats,

133   environmental diversity, species diversity, patch characteristics, patch context, and water quality

134   benefits (VA DCR 2007). The ecological attributes were then integrated into an ecological

135   integrity score, ranging from C1 (outstanding) to C5 (general), which represents a prioritization

136   ranking for conservation. For the purpose of this analysis, we focused only on C1 and C2 cores.

137   Landscape corridors that connect these cores were identified through least-cost path analysis

138 (Adriaensen et al. 2003; VA DCR 2007). The input data layers used in VaNLA, as well as the

139 final GI maps, are publically available and can be downloaded from the Virginia Department of

140 Conservation and Recreation website:

141 (http://www.dcr.virginia.gov/natural_heritage/vclnavnla.shtml).

142 *Morphological Spatial Pattern Analysis*

143 New, standardized methods have recently been proposed for prioritizing GI at regional

144 scales (Wickham et al. 2010). Morphological spatial pattern analysis (MSPA) uses structural

145 components of natural landcover to develop networks of core and corridor areas by categorizing

146 the landscape into discrete structural classes (e.g., Core, Islet, Perforation, Edge, Loop, Bridge,

147 and Branch) (Vogt et al. 2007). Focusing only on structural connectivity, where connections of

148 intact habitat physically exist, we produced a simplified MSPA layer using GUIDOS 1.3

149 (http://forest.jrc.ec.europa.eu/download/software/guidos).

150 Landcover data from the 2001 National Landcover Dataset (NLCD; Homer et al. 2007)

151 for the James River watershed were first reclassified into a binary map of 'Foreground' (forest

152 and wetland classifications) and 'Background' (all other landcover classifications). Next, an

153 MSPA was run to reclassify the 'Foreground' landcover class into the seven structural classes

154 identified above. For this analysis, Core patches greater than or equal to 101 hectares (250 acres)

155 were used as the ecological cores. Corridors were created from remaining Core areas combined

156 with the Edge and Bridge classes, two of the other MSPA classes that represent landscape

157 connections and lands immediately contiguous to Core patches, respectively. The more inclusive,

158 structurally defined MSPA rankings provided a complement to the more strictly defined,

159 functional priority areas derived from the VaNLA assessment.

160 *United States Protected Areas*

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161   United States Protected Areas (PAs) are lands designated and managed to preserve

162   biological diversity and to serve other natural, recreational, and cultural uses (PAD-US 2009).

163   Over one million square kilometers of land are protected in the United States, which includes

164   national parks and forests, city parks, state beaches and parks, land trust preserves, county open

165   space reserves, and other types of land holdings owned or protected under conservation easement

166   by an agency or non-governmental organization (PAD-US 2009).

167   For this study, PA data were downloaded from the Protected Areas Database of the

168   United States (www.protectedlands.net). Only PAs with International Union for Conservation of

169   Nature (IUCN) classifications I and II were used in the analysis in order to focus on areas set

170   aside to protect large-scale ecological processes.

171   *Priority Surface*

172   We combined the VaNLA, MSPA, and PA data layers to generate a priority surface for

173   the study region that weighted lands based on perceived ecological value (Table 2). The surface

174   also took into account proximity to the river as a stated goal of the JRHT. Each 30-m pixel in the

175   watershed was classified in the following manner. PAs were assigned the highest weights (100)

176   because they are widely recognized as areas of significant ecological value and are generally

177   open to the public. By contrast, VaNLA and MSPA cores and corridors were delineated without

178   consideration of public access or stewardship. The functionally-defined VaNLA land

179   designations, which take into account characteristics such as species diversity and water quality

180   attributes, were assigned higher scores than their MSPA counterparts, which were based solely

181   on the spatial structure of forest and wetlands on the landscape. VaNLA Cores were assigned

182   weights of 50 and MSPA Cores were assigned weights of 25. Consistent with VaNLA

183   methodology, corridors were weighted lower than core areas (VA DCR 2007). VaNLA Corridors

184   were assigned weights of 10 and MSPA Corridors assigned weights of 5. All other land in the

185   watershed was assigned a value of 1.

186   To address JRHT goals for the trail network, greater importance was given to land

187   centered around the historic James River. A 100-meter buffer was created around the river. Like

188   the MSPA designations, this buffer region was not ground-truthed or accompanied by any

189   ancillary data, but the buffer width of 100 meters was chosen to be consistent with recommended

190   riparian corridor widths for conservation purposes (Bentrup 2008). The buffer also serves the

191   aesthetic goal of enhancing visual interest by increasing the value of land near the water. Pixels

192   within the buffer were multiplied by 100 (Table 2).

193   ***Connectivity Assessment***

194   We analyzed the connectivity of the priority surface using Circuitscape

195   (http://www.circuitscape.org). Circuitscape uses algorithms from electronic circuit theory to

196   predict patterns of movement across heterogeneous landscapes (McRae et al. 2008). The

197   approach builds upon other least-cost path approaches by simultaneously considering all possible

198   routes across the landscape and allowing movement to be dispersed among multiple potential

199   pathways. Conductance maps were interpreted as potential pathways for the JRHT that

200   efficiently flow through multiple locations of high natural resource value.

201   Each cell on the priority surface was treated as a node and potential conductance to

202   neighboring cells was based on first-order, four-neighbor rules (McRae & Shah 2011). High

203   value cells on the priority surface were considered high importance for the JRHT, therefore the

204   grid was coded in conductances to allow greater ease of current movement through higher

205   priority pixels (McRae & Shah 2011). Using the all-to-one mode, multiple iterations were run

206   and connectivity was calculated between pairs of focal nodes (McRae & Shah 2011): one pair

207   located at the mouth and headwaters on the north side of the James River, and a second pair

208   located on the south side of the river. The two Circuitscape output maps were then combined to

209   assess effective conductances for the entire watershed.

210   ***Evaluation of Ecological Conductance Network***

211   The evaluation of model outputs included analysis of areas of high conservation value on

212   the priority surface, areas of high conductance, zonal statistics of conductance for counties and

213   sub-watersheds, and conductance potential of existing trails. The James River watershed was

214   analyzed as a whole, at the level of counties and independent cities, and at the small watershed

215   level (5th and 6th order hydrologic units). Existing trails being considered for inclusion in the

216   JRHT conceptual plan were analyzed to determine their relative importance to the overall plan

217   based on ecological conductance.

218   *County-level Evaluation*

219   Zonal statistics (maximum, mean, and standard deviation) of potential conductance were

220   evaluated on the county and independent city level. Partitioning of resources and prioritization of

221   planning efforts at this scale will be critical to the successful implementation of any regional

222   plan, as there are 58 counties and independent cities located within the James River watershed.

223   *Watershed-level Evaluation*

224   Nongovernmental organizations, neighborhood associations, and other local-scale entities

225   are increasingly exerting their influence on natural resource management (Kaplowitz et al. 2012).

226   The scale of the overall analysis matches the focal extent of several large watershed

227   organizations (e.g., James River Association, Chesapeake Conservancy). The relative importance

228   to conductivity of all 5th and 6th order hydrologic units within the James River watershed were

229   also quantified and compared. The 67 5th order hydrologic units range in size from 16,000

230   hectares to 100,000 hectares, while the 298 smaller 6th order hydrologic units range from 4,000

231   hectares to 16,000 hectares (VA DCR 2012).

232   **Results**

233   ***Prioritization of Landscape Components***

234   Each 30-m grid cell was scored by combining existing protected areas (PAs) with the

235   proposed conservation areas from two green infrastructure networks (VaNLA and MSPA) and

236   information about proximity to the James River. Areas of *high priority* occurred where highly

237   ranked PAs, VaNLA components, and MSPA components overlapped, close to the river's banks.

238   The upper headwaters portion of the watershed, which includes parts of Shenandoah National

239   Park and George Washington National Forest, had the highest concentration of these high

240   priority areas (Figure 2). Areas of *low priority* included much of the middle-watershed Piedmont

241   section, which is dominated by agricultural and some urban land uses. The coastal section of the

242   watershed had several patches of high priority, such as the Great Dismal Swamp, Hog Island

243   State Waterfowl Refuge, and the Naval Weapons Station at Yorktown, but generally had lower

244   value than the upper portion of the watershed in the Appalachian Mountains.

245   ***Landscape Connectivity***

246   At the basin scale, the Circuitscape analysis highlighted the lack of connectivity between

247   relatively high value lands in the headwater region and high values lands in the coastal section of

248   the watershed (Figure 3). There were clear, preferred conductance pathways among the large,

249   high-value protected lands in the upper section of the James River watershed. In the middle

250   section of the watershed, however, the lack of green space created a series of bad routing

251   options, resulting in a braided network of moderately connected paths. The more clearly

252   delineated pathways in the lower section of the watershed resulted from the watershed's

253   narrowing boundary. There is only a small amount of land through which the paths could pass,

254   meaning the Circuitscape analysis forced flow through highly developed land in some cases.

255   Although these lands might have been assigned lower values in the priority surface mapping,

256   they were assigned high conductance in the analysis because they represented what were the best

257   routes through this narrow, highly populated section of the watershed.

258   ***County-level Prioritization***

259   Differences in conductivity among counties in the upper, middle, and lower sections of

260   the James River watershed reflect their varying physical geographies and land use (Figure 4**)**.

261   The location identified as having the highest conductance was in the headwater region, in

262   Botetourt County. This metric demonstrates the importance of Botetourt County to the overall

263   plan and reflects the spatial constraints created by the steep slopes and mixed land use in this

264   region of the basin. Counties and independent cities within the middle section of the James River

265   watershed generally had low mean conductances with correspondingly low variance, which

266   highlights the poor connectivity options through the central Piedmont region. In the Coastal

267   Plain, many cities and counties had high variance among pixels. The cities of Hampton,

268   Williamsburg, and Newport News had the highest mean values of all counties and cities

269   analyzed. However, they also had the highest internal variance; therefore, careful planning would

270   be required within these cities to locate new trails that could also serve as potential wildlife

271   corridors.

272   ***Watershed-level Prioritization***

273   To address potential issues associated with using politically-derived county and city

274   boundaries as the basis for regional prioritization and planning, we compared the 5th and 6th order

275   hydrologic units within the James River watershed in terms of their Circuitscape conductance

276 (Figure 5). This assessment also allowed us to directly contrast prioritization schemes based on

277 two hierarchically nested scales of analysis. The differences in conductance values between 5th

278 and 6th order hydrologic units can be seen near Richmond, Virginia. Sites of high conductance at

279 the larger scale did not consistently have high conductance at the finer scale (map insets in

280 Figure 5). In other words, just because a 5th order hydrologic unit was deemed to be of high

281 conductance, did not mean that all constituent 6th order watersheds were also of high

282 conductance value. Instead, some of these smaller watersheds were of much higher value than

283 others. In contrast, areas of low conductance at coarse scale generally also had low conductance

284 at finer scale. From a trail placement perspective, this implies that large regions of low

285 conductance can be excluded from the trail planning process. However, areas of high

286 conductance require further study to assess the best positioning of trails given the fine-scale

287 environmental variability and additional recreational and logistical concerns that must be

288 considered in the final implementation.

289 ***Evaluation of Existing Trails***

290 Existing trails are an important part of the JRHT conceptual plan and show how existing

291 recreational infrastructure can be an important resource in facilitating connectivity between

292 ecological core habitats. Trail type varies from hiking trails to on-road bike paths and paved

293 pedestrian walkways. The conductance values were also highly variable among trails (Table 3).

294 Those trails that were most important to the conductance network can be classified into two

295 broad categories: long trails that pass through large regions and intersect prime lands for

296 conservation, and shorter trails that cross through "choke points" in highly urbanized areas.

297 The Appalachian Trail was one of the higher ranked trails in the watershed. However,

298 most of the trail is not located immediately adjacent to the James River. Instead, the high value

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299 of this trail was derived from the fact that along its great length it runs through several high

300 priority conservation lands. The state's on-road bike route was also ranked relatively high. The

301 bike route is one of the most extensive existing recreational assets in the James River watershed,

302 often following the James River closely, and therefore was ranked high despite not consistently

303 passing through ecologically important areas. The variance in values along this trail was also

304 very high. The highest ranked trail, the City Point Beach Trail, is located in the urban, lower

305 section of the James River watershed where other potential pathways are limited. Small trails

306 such as this one in the narrow coastal zone, along with the existing large regional hiking and

307 biking trails, form a solid foundation for the future JRHT network.

308 **Discussion**

309   This study demonstrates how concepts of green infrastructure and ecological connectivity

310 modeling can be used as a basis to target and connect ecologically important areas for multi-use

311 trail development, in order to promote both ecological conservation and recreational use. At the

312 basin level, the results identify specific regions to focus trail development. The trails would meet

313 the broad requirements of the recreational trail system, by providing an extensive, interconnected

314 pathway within the vicinity of the historic James River. By removing these lands from the threat

315 of potential development, the trails would also provide a valuable function as potential wildlife

316 corridors and riparian buffer areas.

317   The detailed location of trails would ultimately need to incorporate many additional

318 considerations related to other recreational goals, priorities, and logistical constraint. As part of

319 a more intensive *boots-on-the-ground* planning with local stakeholders, areas of high

320 conductance could be reanalyzed at much finer scale with the Circuitscape priority-surface

321 calibrated to consider factors such as trail intent, user perceptions, land ownership, and physical

322   characteristics not evident at the basin level (Figure 6). The method is highly scalable and can be

323   tailored to varying situations and goals by selecting from numerous potential recreation and

324   ecological spatial variables. It is entirely reasonable to expect that in refining our model

325   outcomes for actual trail implementation, some areas of low ecological value would be added

326   into the network and some locations of high ecological value would be excluded. For example,

327   trails could be designed to skirt sites with known occurrences of disturbance sensitive species.

328   The James River watershed provides a useful case study for the application of these tools

329   because the James River Heritage Trail has stated goals of aligning recreation and conservation

330   values. The geography of the watershed also reflects a common pattern in the southeastern

331   United States of protected montane headwaters feeding substantial agricultural areas and

332   terminating in highly urbanized coastal zones. The diverse geography and patterns of

333   development found in the James River watershed illustrate some of the challenges that come

334   with multi-use trail creation.

335   Large parks and mountainous geography characterize the headwater region of the James

336   River watershed. As a result, the region has remained relatively undeveloped with large tracts of

337   forest of high conservation value. While riparian pathways are prioritized within our analysis, the

338   Circuitscape tool allows planners the flexibility to take advantage of already-developed trails,

339   logistical opportunities, and exceptional ecological habitats, even when these options are not

340   immediately adjacent to the river, by providing information on multiple potential routings.

341   The highly modified agricultural and urban landcover characteristic of the middle section

342   of the James River watershed led to the identification of a series of poor trail options for

343   traversing the Piedmont region. From a planning perspective, this region provides the greatest

344   challenge to creating a connected, multi-purpose trail network that incorporates existing core and

345   corridor habitats. The trail network in this region of the watershed may be better envisioned as

346   restoration rather than conservation. Instead of protecting sites of currently high ecological value,

347   new trails could be designed to reclaim neglected riparian corridors, reestablish needed nutrient

348   retention functions, and mitigate non-point source pollution from entering the river.

349   Several of the cities located in the region have already begun linking the recreational,

350   health, and traffic benefits of trails with efforts to restore ecologically sensitive floodplains.

351   Richmond, for example, has its own GI plan, the Richmond Region Green Infrastructure

352   Assessment Project (RRGIAP) (Green Infrastructure Center and E^2 Inc. 2010) that includes

353   numerous parks and trails within the James River corridor. The scale of our analysis was focused

354   on larger tracts of land consistent with the statewide GI approach, and did not take into account

355   these smaller green spaces. This disconnect between city and state GI planning is unfortunately

356   too common, and our analysis highlights the essential role that city planning can play in bridging

357   regional gaps, especially in highly modified landscapes.

358   The narrower watershed boundary and constraints imposed by development in the coastal

359   region allowed for fewer trail options. In these cases, leveraging existing trails will often be

360   required due to high competition for land. Spatial pattern and connectivity analysis can help

361   determine the potential contribution of current trails to the overall trail network conductance

362   (Table 3). Particularly in urban areas, riparian trails offer unique opportunities for integrating

363   stormwater control and habitat restoration. Instead of investing substantial funds in new trail

364   development, resources may be better allocated towards simple modifications of existing trails

365   and adjacent areas to treat urban runoff and restore ecological functions. In future studies of the

366   unrealized opportunities for existing trails to provide a broader array of services, attributes such

367   as trail type should also be taken into consideration. Paved bike trails, for example, could be

368   converted to pervious surfaces to provide additional water quality benefits.

369   In summary, unique trail planning recommendations emerged from the analysis for each

370   of the three physiographic provinces within the James River watershed. Planning in the relatively

371   undeveloped Appalachian Mountains can take advantage of the large areas of high conservation

372   value in the region. In the agriculturally intensive Piedmont region, which also contains the

373   urban and suburban sprawl of the state's capital city, new riparian trails can be thought of as

374   restoration opportunities rather than conservation strategies. In the highly developed Coastal

375   Plain, funding may be better utilized by improving existing trails of high conductance rather than

376   investing in new ones.

377   **Conclusion**

378   Applications of efficient, cost-effective methods in spatial analysis offer innovative ways

379   to leverage new trail projects to contribute to conservation needs. The James River Heritage Trail

380   (JRHT) is envisioned as an interconnected network of trails that would benefit both the

381   recreational and environmental resources of the largest watershed in the Commonwealth of

382   Virginia. At a coarse level, the goals of the JRHT trail network are simply to create a coherent

383   system of trails between the Allegheny Mountains and Chesapeake Bay that, when possible, are

384   located in close proximity to the river. These goals leave considerable flexibility to incorporate

385   additional objectives, including the protection of habitat of high ecological value.

386   This case study used an integrated workflow of spatial analysis tools to identify potential

387   locations for the trail system based on existing protected areas (PAs), Virginia's proposed GI

388   network (VaNLA), and a GI network developed using morphological spatial pattern analysis

389   (MSPA). A conductance map of high ecological value sites was developed using methods from

390   circuit theory. The results identified three distinct regional challenges to trail planning using GI

391   as a guide that correspond to the three unique physiographic regions within the watershed. The

392   basin-scale model also provided a baseline map of potential priority pathways and identified

393   specific counties and sub-watersheds for finer-scale assessment of potential placement of trails

394   based on local stakeholder input, recreational priorities, and logistical constraints. Combining

395   conservation and recreational goals is a way to stretch limited funding and engage communities

396   directly in the protection of their natural resources.

397   **Acknowledgements**

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Tables

Table 1. Example trail networks in the vicinity of the study area. The number of regional, multi-use trail networks has been growing worldwide as localities recognize their overlapping recreational, transportation, education, and environmental benefits.

Name	Location	Length	Uses
Washington and Old Dominion Trail (W&OD Trail) (http://www.wodfriends.org/trail.html)	Purcellville to Falls Church, Virginia, USA	72 km	Biking and walking path, bridle trail, active transportation
Greater Philadelphia Regional Trail Network (http://www.pecpa.org/southeast-pa-regional-trail-network)	Southeastern Pennsylvania, USA, New Jersey, USA, and Delaware, USA	644 km	Multi-use paths, on-street bikeways, recreation, active transportation
Chesapeake & Ohio Canal National Historical Park (C&O Canal) (http://www.nps.gov/choh/index.htm)	Cumberland, West Virginia, USA to Georgetown, Washington DC, USA	297 km	Footpath, camping, ranger-guided programs

Table 2. Priority weighting scheme. An inverse cost-surface was created by assigning values based on priority to different landscape designations, then multiplying those values by a scale based on the pixel's distance from the James River's edge. PAs and VaNLA components were considered to be higher importance, as they are already recognized as conservation planning tools by the Commonwealth of Virginia.

Land Designation	Value
Protected Areas (PAs)	100
VaNLA Cores	50
MSPA Cores	25
VaNLA Corridors	10
MSPA Corridors	5
Other	1

X

Distance from River	Value
< 100 meters	100
>100 meters	1

Table 3. The mean and standard deviation trail conductance values (unitless) for a sampling of trails in the James River watershed based on the Circuitscape analysis. Trails are sorted based on the mean conductance value of trail pixels.

Trail Name	Trail Value	
	Mean	St. Dev.
City Point Beach Trail	163.4	46.3
On-Road Bike Route	10.9	58.0
Appalachian Trail	5.3	7.9
Proposed Cumberland-Appomattox Route	2.6	0.6
Proposed Seaboard Coastline Trail	1.7	19.6
Proposed Blue Ridge Railway Trail	1.5	2.7
Chessie Trail	1.0	0.6

Figures

Figure 1. The James River watershed, located within the Commonwealth of Virginia, encompasses 26,511 square kilometers. The watershed is comprised of a mountainous headwater region, an agriculturally intensive piedmont region, and a highly developed coastal area.

Figure 2. Map of priority ranks. Importance was calculated by combining the different landscape designations and weighting by proximity to the James River.
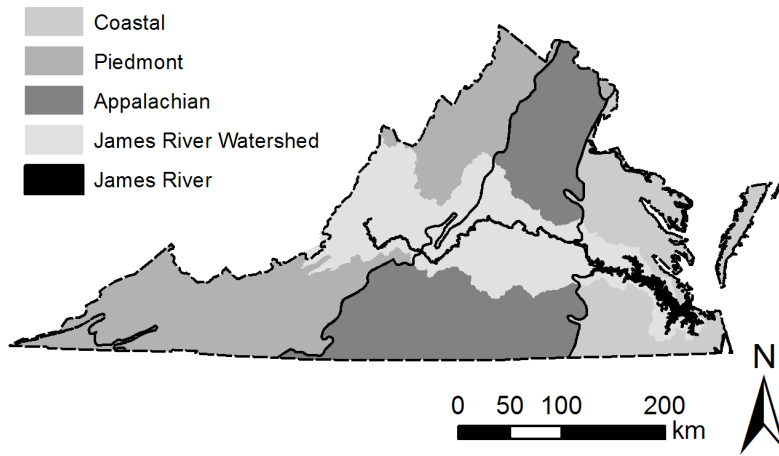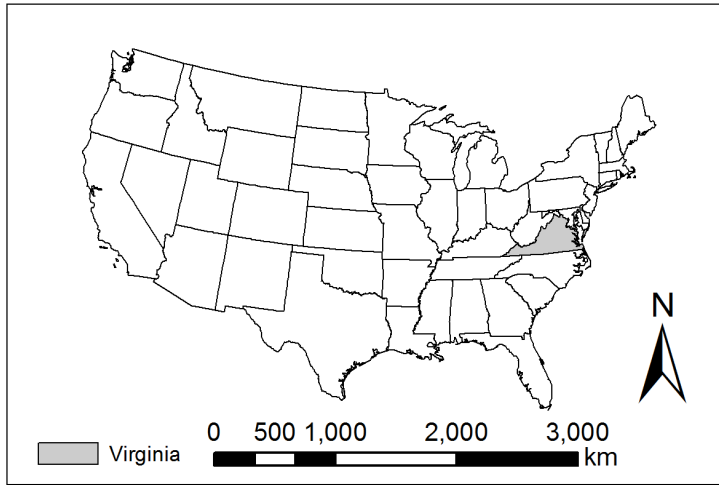
Figure 3. Conductance map created through Circuitscape. The connectivity analysis was based on the landscape priority surface (**Figure 2**).
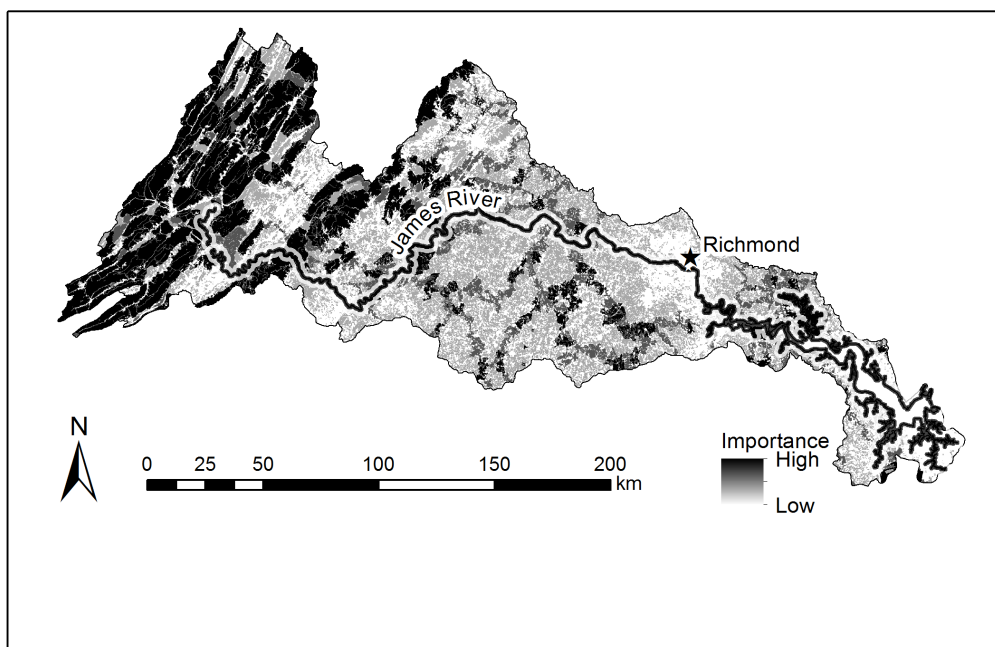
Figure 4. County-level assessment of conductance. White parts of counties are outside the watershed boundary and not included in the analysis. **A)** Mean conductance; **B)** Standard deviation of conductance; and **C)** Maximum conductance values of counties and independent cities are provided for the James River watershed based on the Circuitscape analysis.
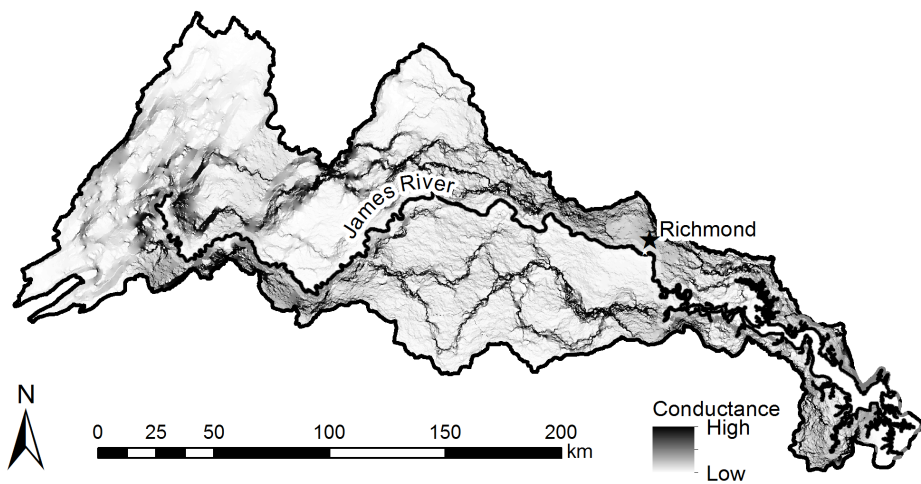
Figure 5. Mean values of conductance of **A)** 5th order hydrologic units and **B)** 6th order hydrologic units based on the Circuitscape analysis. Insets highlight area of contrast between the two scales.
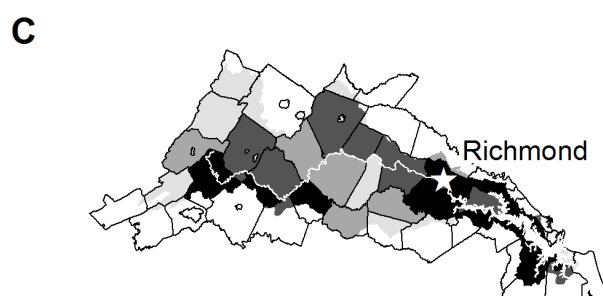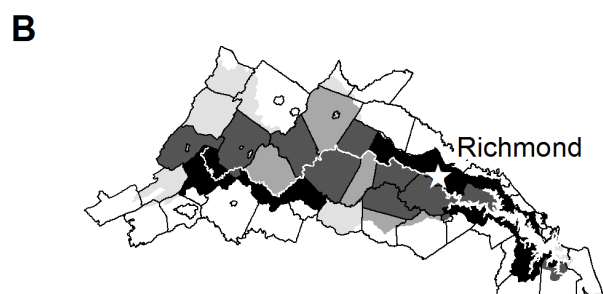
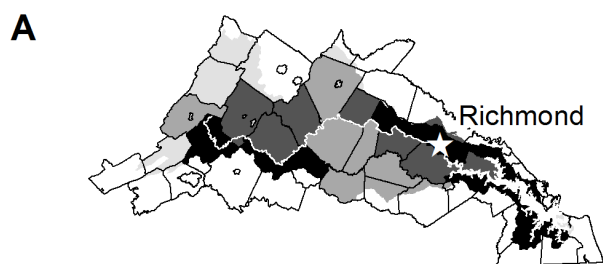**Figure 6.** Example fine-scale map illustrating potential pathways between protected areas identified as priorities by the Circuitscape analysis.

Coastal
Piedmont
Appalachian
James River Watershed
James River

Virginia

N

0 500 1,000 2,000 3,000 km

0 50 100 200 km

James River

Richmond

N

0   25   50   100   150   200
km

Conductance
High

Low

A

Richmond

B

Richmond

C

Richmond

N

0 25 50   100   150   200
km

Conductance
High

Low

A

Richmond

Richmond

B

Richmond

Richmond

Conductance

High

Low

N

0 25 50   100   150   200
km

Richmond

N

0   50 100   200
km

James River

Conductance
High

Low

Protected Areas

N

0   3.5   7   14
km