

Accepted refereed manuscript of:

McDougall CW, Quilliam RS, Hanley N & Oliver DM (2020) Freshwater blue space and population health: An emerging research agenda. *Science of The Total Environment*, 737, Art. No.: 140196.

<https://doi.org/10.1016/j.scitotenv.2020.140196>

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1 Abstract

2 Growing evidence suggests that access and exposure to water bodies or blue spaces can provide a
3 variety of health and well-being benefits. Attempts to quantify these "blue-health" benefits have largely
4 focused on coastal environments, with freshwater blue spaces receiving far less attention despite over
5 50 % of the global population living within three km of a body of freshwater and populations living in
6 landlocked areas having limited coastal access. This critical review identifies opportunities to improve
7 our understanding of the relationship between freshwater blue space and health and well-being, and
8 outlines key recommendations to broaden the portfolio of emerging research needs associated with the
9 field of blue-health. Recognising fundamental distinctions in relationships between health outcomes
10 and access and exposure to freshwater versus coastal blue space is critical. Furthermore, research to
11 determine the mechanisms that link exposure to freshwater blue space with tangible health outcomes is
12 needed, and in particular an understanding of how such mechanisms vary across the wide spectrum of
13 freshwater environments present in landscapes. Current methods for quantifying access and exposure
14 to freshwater blue space often fail to account for the unique spatial properties of freshwater and come
15 with a variety of limitations. Based on the findings of this review, a suite of research needs are proposed,
16 which can be categorised into three broad themes: (i) establishing a freshwater blue-health
17 methodological framework; (ii) advancing the empirical freshwater blue-health evidence base; and (iii)
18 promoting freshwater blue-health opportunities. When taken together, these research themes offer
19 opportunities to advance current understanding and better integrate freshwater blue space into the wider
20 nature-health research agenda.

21 Key words: Blue-health; Green space; Public health; Nature exposure; Health-promotion

22 1.0 Introduction

23 Interest in the relationship between access and exposure to the natural environment and human health
24 is growing globally (Frumkin et al., 2017; Hartig et al., 2014). Nature-health research has mainly
25 focused on exposure to green space, which has been associated with a number of positive physical and
26 mental health outcomes (Twohig-Bennett and Jones, 2018). This growing evidence base has seen green
27 space provision become an established component of public health and landscape planning policies
28 across the globe (Rutt and Gulsrud, 2016; Wolch et al., 2014). The health-promoting potential of water
29 bodies or blue spaces has received less attention in comparison, despite a small but growing body of
30 evidence suggesting that access and exposure to blue space can provide a variety of health and well-
31 being benefits (Gascon et al., 2017; Völker and Kistemann et al., 2011).

32 Although the term ‘blue space’ has emerged fairly recently, the health and well-being benefits of
33 human-water interactions have been studied for decades across a number of disciplines including
34 environmental psychology (Herzog, 1985; Kaplan and Kaplan, 1989) and human geography (Gesler,
35 1992; Gesler, 1996). In research concerned with nature and population health, blue space is often
36 excluded (O’Callaghan-Gordo et al., 2020) or classified as green space (van den Berg et al., 2016).
37 However, the establishment of a number of large-scale research programmes (e.g. Depledge and Bird,
38 2009; Grellier et al., 2017) coupled with a renewed interest in water-health relations in human
39 geography (Foley and Kistemann, 2015) has seen the study of blue space and health shift from a by-
40 product of therapeutic landscape and environmental psychology research towards an established
41 academic field in its own right.

42 Blue space is generally understood to encompass both freshwater and marine settings (Grellier et al.,
43 2017; Foley and Kistemann, 2015). However, with the exception of large or saline lakes and estuaries
44 where freshwater and marine settings merge, these two environments substantially differ in their
45 physical and hydrological properties and the ecosystem services and amenity values they provide.
46 Furthermore, experiences at freshwater blue space are also likely to consist of different smells, sounds,
47 views and opportunities for recreation than experiences in coastal environments (Mavoa et al., 2019).
48 Current research attempting to quantify the health and well-being benefits of access and exposure to

49 blue space (henceforth blue-health benefits) has largely focused on coastal environments, with
50 freshwater blue spaces receiving far less attention (Gascon et al., 2017). Living in close proximity to
51 the coast has shown an association with greater physical and mental health (Hooyberg et al., 2020;
52 Pasanen et al., 2019; Wheeler et al., 2012) and being able to see the coast from one's home has also
53 been associated with positive effects on mental well-being (Dempsey et al., 2018).

54 A **review** of 36 research articles exploring human-freshwater interactions identified that freshwater has
55 a variety of salutogenic properties that can induce health and well-being benefits (Völker and Kistemann
56 et al., 2011), although the data used for this **review** were mainly comprised of experimental and
57 qualitative studies. This has exposed a significant gap in research that explores the benefits of access
58 and exposure to freshwater from a population health perspective. Although some studies have suggested
59 that access and exposure to freshwater blue space can provide benefits to population health (Pasanen et
60 al., 2019; Pearson et al., 2019; MacKerron and Mourato, 2013; Garrett et al., 2019a), this is not always
61 the case (White et al., 2013; Bezold et al., 2018; Mavoja et al., 2019). The volume and spatial coverage
62 of freshwater is substantially smaller than marine environments; however, investigating the health-
63 promoting potential of freshwater blue space is imperative as over 50 % of the global population live
64 within three km of a body of freshwater and populations living in landlocked areas have limited coastal
65 access (Kummu et al., 2011). Therefore, a better understanding of the relationship between access and
66 exposure to freshwater blue space and indicators of health, and the mechanisms underlying these
67 relationships, are fundamental to supporting a more holistic assessment of blue-health.

68 This critical review aims to identify opportunities to improve understanding of the relationship between
69 freshwater blue space, health and well-being and thus broaden the portfolio of emerging research needs
70 associated with the field of blue-health. Specifically, the objectives of this review are to (i) evaluate
71 current issues in freshwater blue-health thinking; (ii) critically appraise the contrasting empirical
72 methods adopted to quantify access and exposure to freshwater blue space; and (iii) propose
73 recommendations for novel avenues of future research to advance our understanding of freshwater blue-
74 health.

75 2.0 Issues in current freshwater blue-health thinking

76 2.1 Understanding pathways to positive health outcomes

77 The underlying mechanisms or “pathways” that link access and exposure to natural environments and
78 tangible health outcomes have often been overlooked (Dzhambov et al., 2018). The most commonly
79 cited pathways to improved health via access and exposure to the natural environment are stress
80 reduction and restoration, social interaction, improved air quality and physical activity (Hartig et al.,
81 2014). Grellier et al. (2017) hypothesise that health and well-being benefits of blue space will follow
82 pathways similar to other natural environments; however, blue spaces have a number of distinctive
83 health-promoting and therapeutic properties, e.g. opportunities for physical immersion and water-based
84 activities (Foley, 2015).

85 There is a growing need to better understand the interaction between nature-health pathways and
86 freshwater blue space (Mavoa et al., 2019) (Table 1). Access and exposure to freshwater blue space
87 may reduce stress and provide cognitive restoration as aquatic environments are perceived to be highly
88 restorative (Maund et al., 2019; Wilkie and Stavridou, 2013; Wang et al., 2016; White et al., 2010) and
89 relaxing (Grassini et al., 2019). Furthermore, water is an important and highly valued aesthetic
90 component in terms of landscape preference (Velarde et al., 2007; Faggi et al., 2013; Kaltenborn and
91 Bjerke; 2002; Burmil et al., 1999). The presence of freshwater alone may induce health benefits by
92 improving a number of environmental attributes, e.g. improving soundscapes by buffering
93 anthropogenic noise (Jeon et al., 2012; Axelsson et al., 2014) and providing restorative or pleasant
94 sounds, such as flowing water or bird song (White et al., 2010; De Coensel et al., 2011). The presence
95 of freshwater can also enhance thermal comfort by reducing the urban heat island effect (Gunawardena
96 et al., 2017) and provide a variety of ecosystem services, including carbon absorption (Apostolaki et
97 al., 2019).

98 Social interaction (de Bell et al., 2017; Pitt, 2018; Völker and Kistestemann, 2015) and physical activity
99 (Vert et al., 2019; Jansen et al., 2017) are expected to increase with greater access, exposure and usage
100 of freshwater blue space; however, the importance of these pathways in facilitating tangible health

101 outcomes is still relatively unknown. For coastal blue space, physical activity has been shown to be a
102 key pathway in facilitating positive mental health outcomes, however, further research to understand
103 the different mechanisms that cause freshwater blue space to positively influence health is required
104 (Pasanen et al., 2019). Investigating the relationship between individual pathways and their contribution
105 to specific health outcomes can assist health officials, landscape planners and policymakers in designing
106 and managing blue space to optimise the provision of health and well-being benefits (Gascon et al.,
107 2018). Improved understanding of how different types of engagement with freshwater interact with
108 each health pathway, and the strength of these interactions relative to green space and coastal blue space
109 can underpin effective nature-based health interventions, advancing the wider nature-health research
110 agenda.

111

112 2.2 Classifying freshwater blue space

113 While the term ‘blue space’ is generally well understood in current nature-health literature, the treatment
114 of coastal and freshwater environments in studies concerned with access and exposure to blue space
115 and health varies widely. Access and exposure to freshwater and coastal blue space can be tested against
116 health outcomes and reported as individual categories (Choe et al., 2018; Wheeler et al., 2012; Pasanen
117 et al., 2019; Garret et al., 2019a) or as a combined “blue space” category (de Vries et al., 2016; Garret
118 et al., 2019b; Huynh et al., 2013). The study of blue space can relate specifically to freshwater if, for
119 example, the study location is landlocked (Dzhambov et al., 2018). Variations in blue space definitions
120 and how blue-health findings are reported make comparisons among studies challenging and limit
121 opportunities for evidence synthesis via meta-analyses and systematic review (Taylor and Hochuli.
122 2017). While combining freshwater and coastal blue space may be appropriate in order to address some
123 research questions, the approach can be problematic, particularly when attempting to draw conclusions
124 related to access and exposure to freshwater specifically. As exposure to coastal blue space may have a
125 stronger health and well-being effect than exposure to freshwater (Garrett et al., 2019a) and as the
126 physical properties of coastal waters can dominate the combined blue space category (Nutsford et al.,
127 2016), caution should be taken when assuming that combined blue space findings are transferable to

128 the freshwater evidence base. In order to better understand how access and exposure to freshwater blue
129 space impacts health and well-being, blue space categories need to be clearly defined, whilst the
130 relationships between health and access and exposure to freshwater and coastal blue spaces need to be
131 reported independently.

132

133 2.3 Considering multiple freshwater blue space typologies

134 There is currently little understanding of how different typologies of freshwater blue space (e.g. lakes,
135 rivers, canals, wetlands, ponds, streams, waterfalls and even fountains) interact with health pathways
136 and consequently, how different typologies can impact health and well-being (Mavoa et al., 2019).
137 Previous research suggests different freshwater typologies may have varying potential for stress
138 reduction and restoration, for example, humans prefer views of rivers, lakes and ponds compared to
139 more swampy waterscapes, such as creeks or bogs (Herzog, 1985). To date, research directly
140 investigating interactions between different freshwater blue space typologies and the environmental
141 quality, social interaction and physical activity health pathways has been sparse. For the environmental
142 quality pathway, larger water bodies are expected to provide greater effects on surrounding
143 temperatures (Wu et al., 2018) and the cooling effect of lakes is often higher than that of rivers (Du et
144 al., 2016). Different freshwater typologies will likely vary in their ability to buffer noise and impact
145 soundscapes, as the sound of water is mainly driven by hydrology, i.e. the volume and speed of water
146 flow (Putland and Mesinger, 2020). Consequently, flowing rivers may have a more significant effect
147 on soundscapes than bodies of relatively still freshwater (Wysocki et al., 2007).

148 Types of freshwater also vary in their ability to facilitate certain opportunities for physical activity and
149 social interaction. Swimming and paddling are often associated with lakes (Angradi et al., 2018) and
150 outdoor swimming is more likely to occur in lakes than narrow waterways (Lankia et al., 2019). Indeed
151 swimming is often prohibited in urban waterways and canals due to health risks associated with
152 immersion in these bodies of water (Pitt, 2018). An improved understanding of how access and exposure
153 to different freshwater typologies impact health and well-being will likely assist in developing site-
154 specific health interventions and integrating a variety of freshwater blue space typologies into public

155 health strategies. Consequently, recognising the mechanisms that affect the health-promoting
156 capabilities of different freshwater blue space typologies and how these vary across different socio-
157 demographic groups is a key priority for future research.

158

159 2.4 Freshwater blue space quality

160 The perceived quality of the natural environment can impact how that environment is used (Giles-Corti,
161 2005; Akpinar, 2016) and poor environmental quality is a deterrent of use for both children (McCracken
162 et al., 2016) and adults (Wright Wendel et al., 2012). Research focussing on the role of access often
163 fails to consider the quality of freshwater blue space with little attention given to characteristics, such
164 as accessibility, parking facilities, chemical and bacteriological water quality, recreational
165 opportunities, or other salutogenic properties (Pitt, 2018). Water quality can influence the likelihood of
166 swimming (Lankia et al., 2019), boating (Curtis et al., 2017) and impact the experience of anglers
167 (Pulford et al., 2017). However, the majority of visitors to inland water bodies in England, do not make
168 direct contact with water (Elliot et al., 2018) and improved water quality does not necessarily enhance
169 the cultural ecosystem services offered by freshwater blue space (Ziv et al., 2016). Blue-health benefits
170 commonly occur in terrestrial locations, e.g. due to non-water based physical activity (Vert et al., 2019),
171 reduced psychological distress from viewing water (Nutsford et al., 2016) and social interaction in
172 waterside environments (de Bell et al., 2017). Furthermore, waterside features, such as high quality
173 paths (Verbič et al., 2016) and easily accessible waterside spaces (McDougall et al., 2020) can enhance
174 the overall experience at a range of different freshwater blue space typologies. Consequently, it is clear
175 that measures of freshwater blue space quality must account for both terrestrial attributes and traditional
176 indicators of water quality.

177 A number of dedicated systems (Ariza et al., 2010; Palazón et al., 2019) and a robust international
178 framework exists for assessing the quality of coastal environments and beaches, including beach
179 certification schemes such as the “Blue Flag” (Lucrezi et al., 2015). Whilst some indicators of coastal
180 and beach quality may be transferable to certain freshwater environments, such as large lakes with
181 beaches and shorelines, many are specific to marine settings and are, therefore, inadequate for assessing

182 freshwater blue space quality. Currently, the BlueHealth Environmental Assessment Tool (BEAT) is
183 the only dedicated tool for assessing the quality of coastal and freshwater blue space (Mishra et al.,
184 2020). BEAT uses a questionnaire-based approach to examine physical, social, aesthetic and
185 environmental aspects of blue space, which relate to opportunities for improved health and well-being.
186 While BEAT is highly suitable for assisting policymakers in designing and managing blue spaces to
187 facilitate public health benefits, the tool requires site visits and questionnaires, thus making it
188 challenging to implement at a population health scale. Moving forward, there is scope to establish ex-
189 situ indicators to quantify blue space quality that can be readily combined with geographic information
190 system (GIS) based approaches. Ex-situ indicators can be complemented by existing spatial data sources
191 such as area-level socio-economic data (Rigolon and Németh, 2018) or the presence of surrounding
192 services and green / open spaces, which are useful indicators of blue-health opportunities (Mishra et al.,
193 2020). Combining freshwater blue space quality data, alongside metrics of access and exposure and
194 health outcomes, would improve our understanding of which elements of freshwater blue space are
195 most important for the provision of blue-health benefits.

196

197 3.0 Quantifying access and exposure to freshwater blue space: A critical appraisal

198 Quantifying access and exposure to freshwater blue space is a crucial component of studies that attempt
199 to relate these variables to health outcomes. Commonly, access and exposure are measured using GIS
200 and combined with individual or area-level health data (e.g. Bezold et al., 2018; Pasanen et al., 2019;
201 Mavoia et al., 2019; Pearson et al., 2019; Wheeler et al., 2015; White et al., 2013). Assessing the
202 capability of these methods to account for the unique physical and spatial properties of freshwater blue
203 space would benefit future research.

204

205 3.1 Proximity-based approaches

206 Proximity-based approaches (e.g. Pearson et al., 2019; Hooyberg et al., 2020; Pasanen et al., 2019;
207 White et al., 2013) are concerned with the distance relative to the blue space and can be divided into

208 two key approaches: (i) determining the distance to the nearest blue space from a particular point
209 (commonly the residence); and (ii) identifying the presence of a blue space within a defined distance or
210 “buffer”. Proximity buffers are commonly applied around the residence, although, there may be some
211 merit in considering proximity to blue space in other locations such as schools, hospitals or workplaces,
212 in order to capture the health effects of access and exposure to blue space in non-residential contexts
213 (Koohsari et al., 2015). Proximity can be calculated as a linear distance or as a network distance. Linear
214 distance approaches calculate the shortest distance from a selected location to the edge of the nearest
215 blue space or buffer boundary, whereas network distance calculates the shortest distance from a selected
216 location to the edge of the nearest blue space or buffer boundary along a street network, simulating
217 walkability (Fig.1). Network distance may be more appropriate for research focused on health outcomes
218 that require access and visitation such as physical activity (Labib et al., 2020) or when investigating
219 distance to freshwater blue space in urbanised areas with complex street networks. Network distance
220 approaches may be particularly useful when considering freshwater blue space with inaccessible
221 sections, as linear methods cannot consider this issue (Fig. 1). Linear distance methods may be more
222 appropriate when considering health benefits that can occur irrespective of access, i.e. viewing blue
223 space from a distance or environmental improvements such as noise reduction and temperature
224 mitigation.

225 A variety of different buffer sizes have been adopted in order to quantify differences in access and
226 exposure to freshwater blue space among populations (Bezold et al. 2018; Dzhambov et al. 2018).
227 Heterogeneity among buffer sizes makes comparing the results of studies and evidence synthesis
228 challenging: the adoption of standardised distance buffers would benefit future freshwater blue space
229 research (Gascon et al., 2017). Standardised buffer distances should be underpinned by empirical
230 evidence and will likely differ from those adopted for coastal blue space, as much smaller distances
231 influence the usage and visitation of freshwater blue space (Völker et al., 2018) and as these distances
232 may vary across different freshwater typologies (Elliot et al., 2020). The adoption of differing buffer
233 distances in coastal and freshwater blue space research reinforces the variance in scale of both resources

234 and further highlights the risks of combining the findings of studies that examine the health effect of
235 access and exposure to coastal and freshwater collectively.

236

237 3.2 Area-based approaches

238 Area-based methods use land cover data to determine the percentage of surface water within a
239 predefined area or administrative boundary, such as a zip code area or census tract (Pearson et al., 2019;
240 Alcock et al., 2015; de Vries et al., 2003; Garrett et al., 2019a). Such methods indicate both the presence
241 and quantity of blue space within an area, which can assist in answering research questions concerning
242 the effect of varying levels of blue space exposure on health. However, the use of area-based methods
243 to quantify exposure and access to freshwater blue space comes with a number of limitations. Area-
244 based methods are better suited to larger bodies of freshwater and certain freshwater typologies such as
245 lakes, which are likely to have greater surface areas (Fig. 2). Such methods may, therefore,
246 underestimate the salutogenic effects of typologies with lower surfaces areas such as rivers and canals,
247 which also offer valuable opportunities for health and well-being (Vert et al., 2019; Pitt, 2018). There
248 is an absence of empirical evidence to justify the notion that access and exposure to certain freshwater
249 typologies are likely to result in greater positive health outcomes than others. Moreover, land cover data
250 is commonly used to identify the presence of freshwater (de Vries et al., 2016) and narrow water bodies
251 (e.g. river corridors and canals) are more likely to be misclassified than larger and more spatially explicit
252 bodies of freshwater, highlighting a further bias. If sufficient data are available, future research may
253 benefit from considering the percentage of surface area covered by freshwater relative to the number of
254 freshwater blue spaces or the perimeter of freshwater, which can account for the presence of different
255 freshwater typologies and begin to address issues related to their misrepresentation.

256 The adoption of administrative zones when quantifying exposure to freshwater blue space can also be
257 problematic as administrative zones vary in size (Wheeler et al., 2015). Area-based methods represent
258 blue space as a percentage, therefore, freshwater blue spaces of equal size may be deemed to have
259 different health-promoting capabilities depending on the size of the administrative zone it is located

260 within (Fig. 3). As administrative zones are often based on population density, the physical properties
261 of certain blue spaces are likely to be favoured over others. Freshwater blue spaces in densely populated
262 urban areas, such as rivers and canals, are likely to be in smaller administrative zones, whilst lakes and
263 wetlands are less likely to be present in densely populated areas due to their physical properties and are
264 more likely to be located on the urban fringe (Liu et al., 2007). Consequently, the use of administrative
265 zones may underrepresent exposure and access to large lakes, which are important for providing benefits
266 to mental health (Pearson et al., 2019). Administrative zones also notably differ in size across countries
267 (Labib et al., 2020) making international transferability of area-based research and comparison among
268 studies challenging.

269

270 3.3 Visibility-based approaches

271 Visibility-based methods consider topographic and built landscape features in order to determine what
272 areas are likely to be visible to humans from a certain point in the landscape, commonly a household
273 (Qiang et al., 2019). Visible exposure to blue space aligns closely with the stress reduction and
274 restoration health pathway and relates to improved health without actual visitation, as positive health
275 outcomes can be obtained from viewing water from a distance (Nutsford et al., 2016). Incorporating
276 visibility-based methods into freshwater blue-health research may be challenging as freshwater and
277 vegetation (or green space) are often intertwined in landscapes. Indeed, when a blue space becomes a
278 green space and vice versa is often unclear, with no criteria yet defined to aid our understanding of this
279 transition. This issue may be further complicated as definitions of blue space tend to include waterside
280 space and vegetation (Grellier et al., 2017). Why the relationship between blue and green space has
281 been somewhat overlooked in research is unclear but may relate to: (i) methodological issues of
282 unpacking complex interactions between these spatial zones; or (ii) that most blue space research has
283 focused on the coast, thus providing a relatively more defined blue-green split. Generally, the distinct
284 physical properties of coastal landscapes make defining coastal blue space interaction simpler than for
285 freshwater blue space typologies where interactions between water and vegetation are more common.

286 Acquiring sufficient and appropriate quality vegetation data and accounting for the seasonal, semi-
287 transparent and non-uniform characteristics of vegetation is a key challenge of visibility-based
288 approaches (Murgoitio et al., 2014). Previous studies of blue space visibility have excluded the effect
289 of vegetation in their analysis (Dempsey et al., 2018; Qiang et al., 2019). It may be the case that
290 vegetation has negligible effects on coastal visibility, however, given that vegetation can substantially
291 reduce human views of freshwater (McDougall et al., 2020) it is imperative that future studies
292 attempting to quantify freshwater visibility account for vegetation. Quantifying freshwater visibility in
293 non-residential settings such places of work or education is needed in order to provide a more realistic
294 representation of total freshwater exposure. Determining freshwater visibility throughout one's daily
295 activities could be assisted by innovative approaches such as analysing street view imagery (Helbich et
296 al., 2019) or utilising camera-based methods (Pearson et al., 2017).

297

298 3.4 Self-reported access and exposure

299 Self-reported methods provide insight into actual blue space usage and engagement, which cannot be
300 achieved using objective measures of access and exposure alone, such as understanding the importance
301 of certain freshwater blue space features in facilitating health outcomes (de Bell et al., 2017). Such
302 methods can be useful for understanding relationships between different types of freshwater blue space
303 and health, which are often difficult to consider due to a lack of available data (Mavoa et al., 2019).
304 Self-reported methods also provide an understanding of blue space exposure in non-residential contexts
305 and allow for multiple types of exposure to be considered. The latter can include: (i) indirect exposure,
306 e.g. views of blue space from the residence; (ii) incidental exposure, e.g. contact with a blue space
307 during daily life activities such as commuting; and (iii) intentional exposure, e.g. deliberately visiting a
308 blue space (Garrett et al., 2019b). While self-reported methods offer a number of interesting research
309 opportunities, these methods have some limitations. Attaining a representative sample of a study area
310 or study population can be challenging (Völker et al., 2018; Garrett et al., 2019b). To date, studies using
311 self-reported methods have been relatively limited in their sample size in comparison to studies that use
312 objective quantifications of access and exposure (i.e. Alcock et al., 2015; Pasanen et al., 2019). As self-

313 reported methods often rely on respondents to identify the presence of blue space and quantify exposure
314 to these spaces, there is some scope for human error and subjectivity, which may introduce bias and
315 limit comparability among studies.

316

317 4.0 Recommendations for future research

318 Research concerned with blue space and health has largely focused on coastal environments. Freshwater
319 blue space has received substantially less research attention and consequently, there are significant gaps
320 in our understanding of the health-promoting capabilities of these spaces. In order to fully understand
321 the role of blue space as a public health resource a concerted effort is required for greater and more
322 nuanced consideration of freshwater blue space in future research. Thus, a suite of research
323 recommendations have been identified that, when taken together, offer opportunities to advance current
324 understanding and better integrate freshwater blue space into the wider blue-health research agenda
325 (Table 2). Primarily, there is a need to: (i) establish a methodological framework for freshwater blue-
326 health research; (ii) broaden and advance the current freshwater blue-health empirical evidence base;
327 and (iii) promote and sustain opportunities for freshwater blue-health.

328

329 4.1 Developing methodological framework for freshwater blue-health research

330 Establishing a methodological framework to underpin future research that accounts for the unique
331 characteristics of human-freshwater interactions is a precursor to a better understanding of the
332 relationship between freshwater blue space access and exposure and population health. Such a
333 framework, promoting scale-appropriate and empirically tested methods, can complement conceptual
334 research on the salutogenic benefits of freshwater conducted by Völker and Kistemann (2011) and begin
335 to integrate freshwater blue-health evidence into the public health and landscape planning discourse.

336 Opportunities for evidence synthesis and meta-analyses can be increased by clearly defining the spatial
337 dimensions of freshwater blue space and the freshwater typologies considered within each study. By
338 testing and reporting exposure to freshwater and coastal blue space, there is an opportunity not only to

339 better understand the relationship between exposure and access to freshwater blue space and health, but
340 to also understand the strength of this relationship relative to coastal blue space, which is a crucial
341 research need (Pasanen et al., 2019). This is currently hindered by a lack of consensus on the most
342 suitable approach to quantify access and exposure in the freshwater blue-health literature. Establishing
343 multiple standardised metrics for quantifying access and exposure is recommended; however, these
344 should be grounded in empirical evidence and allow for a variety of research questions to be tested.
345 Such methods should not only account for the quantity of freshwater, but also consider varying qualities
346 of waterside space, which is essential for understanding many freshwater blue space interactions (Elliot
347 et al., 2018; Vert et al., 2019).

348 Developing exposure and accessibility metrics that are able to account for freshwater blue spaces of
349 varying scale, quality and perceived importance within the same study area is a significant challenge.
350 One option is to identify freshwater blue spaces that may have substantial importance and ensure these
351 spaces are analysed independently, as demonstrated by Pearson et al., (2017) for the “Great Lakes”.
352 Multiscale approaches that use multiple methods to quantify accessibility and exposure have been
353 proposed for green and blue space (Labib et al., 2020) and such approaches are likely to help to account
354 for the varying scale and unique spatial characteristics of freshwater.

355

356 4.2 Broadening and advancing the freshwater blue-health evidence base

357 The ecosystem services offered by freshwater blue spaces vary substantially based on climatic and
358 social contexts (Sterner et al., 2020). However, freshwater and coastal blue space research is
359 predominantly carried out in developed industrialised countries (Gascon et al., 2017). Despite recent
360 studies in developed areas of Asia (Garret et al., 2019b; Helbich et al., 2019), further work is required
361 to examine the effects of access and exposure to freshwater blue space in more diverse geographies in
362 order to globalise the evidence base. Underrepresented human geographies that merit further study
363 include areas where freshwater has deep cultural and religious significance e.g. the Ganges River
364 catchment (Sharma et al., 2019), and low-income countries, where research has been sparse. An
365 improved knowledge of freshwater blue-health in diverse physical geographies such as areas where

366 freshwaters regularly freeze, are visibly contaminated with, for example, plastics or where water quality
367 is generally unsafe for recreation will further advance the evidence base. Furthermore, research focusing
368 specifically on access and exposure to estuaries, where freshwater and marine environments merge, and
369 unique lakes that share oceanic characteristics, such as size, expansive views (e.g. Lake Malawi, Malawi
370 and Lake Michigan, USA) and salinity (e.g. Great Salt Lake, USA and Lake Urmia, Iran) offers
371 potential to expand current understanding of both freshwater and coastal blue-health and explicate the
372 blurred lines that arise from classifying blue space as two distinct categories.

373 With few studies having investigated the relationship between access and exposure to freshwater blue
374 space and health, there is clearly a need for more empirical research. Randomised control trial
375 experiments, such as clinical trials of blue space exposure can support larger GIS-based research and
376 advance current understanding of freshwater blue-health, but are costly to implement (Frumkin et al.,
377 2017). Natural experiments (also known as quasi-experimental approaches), in which circumstances
378 suitable for experimentation occur without researcher influence, such as observing physical activity
379 levels prior to and after the regeneration of an urban riverside setting (Vert et al., 2019), offer a cost-
380 effective alternative to randomised control trial experiments. If well-designed, natural experiments can
381 be highly effective for eliminating self-selection bias and understanding causation (Greenstone and
382 Gayer, 2009), although such research is often subject to significant logistical challenges (Frumkin et
383 al., 2017). Population health studies focusing on general health outcomes are particularly sparse relative
384 to mental health research and merit greater consideration in future research. Longitudinal study design
385 should be prioritised (Gascon et al., 2017) as longitudinal research can allow causation to be established
386 and negates issues of self-selection, which is often present with cross sectional study designs (de Keijzer
387 et al., 2016). Cross sectional studies would be improved by operating within an established framework
388 of methods as outlined above, negating issues of self-selection by adopting residential sorting
389 approaches to model neighbourhood demand for blue space (Klaiber and Phaneuf, 2010) and integrating
390 data on blue space quality.

391 By establishing an understanding of how frequency and duration of freshwater blue space exposure and
392 the type of activity carried out in or around blue space relate to health outcomes, there are opportunities

393 to quantitatively understand dose-response relationships (Shannahan et al., 2015; White et al., 2019).
394 Understanding the so called, “dosage” of nature that is required in order to return tangible health benefits
395 is a key objective of the wider nature-health research agenda (Frumkin et al., 2017); however, very little
396 is known about dosage in a freshwater blue space context. Furthermore, an improved understanding of
397 the relationship between specific health pathways and different physical and mental health outcomes
398 and the strength of these relationships relative to green space and coastal blue space is required. Such
399 research can be supported, for example, by structural equation modelling, which has proved to be a
400 particularly effective methodology for quantifying the role of different pathways in supporting positive
401 health outcomes as a result of exposure to natural environments (Dzhambov et al., 2018; Yang et al.,
402 2020).

403 A number of novel research opportunities have become available through emerging technology. The
404 use of virtual reality technology can advance experimental research by simulating a variety of senses at
405 freshwater blue spaces, which may be particularly useful for comparing blue-health opportunities of
406 different freshwater typologies and builds upon environmental psychology research that utilised static
407 images of water (Herzog, 1985; White et al., 2010). Furthermore, the exploitation of Big Data may
408 provide useful avenues for research. The use of global positioning system (GPS) data that can be
409 acquired from fitness wearables and activity tracking applications may also provide new insight for
410 understanding physical activity levels surrounding freshwater blue space. Such methods can deliver
411 accurate high resolution data on actual exposure to complement high resolution spatial data which is
412 used to infer exposure, but falls short of understanding how people engage with nearby blue space.
413 Furthermore, natural language processing of text from social media posts, e.g. Flickr, represents a novel
414 approach for understanding how freshwater blue spaces are used and valued among populations
415 (Figueroa-Alfaro and Tang, 2017; Gosal et al., 2019).

416

417 4.3 Promoting freshwater blue-health opportunities

418 In addition to growing the freshwater blue-health evidence base, there is a parallel need to communicate
419 these findings to policymakers and the general public effectively. Establishing communication

420 pathways between research and public health professionals is useful for exploring opportunities to
421 integrate freshwater blue-health into ongoing public health strategies. A clear priority for research is to
422 provide guidance on managing, conserving and in some cases developing freshwater blue spaces in
423 order to fully exploit their health-promoting capacity. However, this cannot be achieved without a
424 detailed understanding of how different characteristics and types of freshwater blue space interact with
425 health and well-being. Policymakers may benefit from the use of in-situ assessment tools such as BEAT,
426 which provides a highly practical resource for evidence-based planning and management to maximise
427 the health-promoting potential of freshwater blue spaces. Furthermore, a wealth of interdisciplinary
428 research opportunities exist in order to complement the provision of freshwater blue-health benefits
429 with synergistic outcomes. This would necessitate the consideration of economic, social and
430 environmental issues to enable a more holistic approach to future decision-making that accounts for the
431 diverse needs of freshwater ecosystems. In particular, the integration of environmental economics
432 methods, such as stated and revealed preference approaches, can assist in understanding preferences
433 among the general public (Hanley et al., 2019) and different water users on how best to manage these
434 spaces. Crucially, these approaches allow monetary values to be attached to policy decisions meaning
435 the highest value investments in terms of positive health outcomes and cost-effectiveness can be
436 assessed. However, economic valuation approaches may be unable to capture many qualitative elements
437 of human-blue space interactions (Foley et al., 2019).

438 Longer-term research priorities should be framed around ensuring freshwater blue-health opportunities
439 are available to all. Research to understand barriers of access to blue space and consequently, the
440 provision of blue-health benefits is limited and may require a variety of qualitative approaches. Barriers
441 to access may occur due to socio-economic factors such as housing status, which may lead to
442 unfamiliarity with the amenities in an area (Haeffner et al., 2017) or more nuanced issues like fear of
443 accessing waterside spaces due to an inability to swim (Pitt, 2019). The impact of swimming ability on
444 perceived access to freshwater blue space may be a particularly useful area of study as socio-economic
445 status could be a significant driver of swimming ability (Irwin et al., 2009; Pharr et al., 2018). Finally,
446 exploring the wider socio-economic, and sometimes unintended, consequences of improving and

447 managing freshwater blue spaces is of high importance. For example, access to water tends to increase
448 house prices (Dahal et al., 2019) and consequently, increasing access to freshwater blue space may
449 induce gentrification and the displacement of residents (Vert et al., 2019). The use of public
450 participation geographic information systems (PPGIS) may be particularly useful in remediating these
451 unintended consequences and developing inclusive freshwater blue-health strategies that can cater to
452 the needs of a number of different water-users (Raymond et al., 2016).

453

454 5.0 Conclusion

455 There is emerging evidence that access and exposure to freshwater blue space can provide health and
456 well-being benefits. However, despite growing evidence, freshwater remains under represented in blue-
457 health research. More in-depth understanding of the relationships between population health and
458 freshwater blue space requires moving beyond traditional disciplinary collaborations and approaches.
459 While environmental science and health research agendas have aligned in the past, our understanding
460 of freshwater blue spaces and health and well-being interactions is often partial, or conflicting. This
461 stems from the frequent failure of research to span traditional disciplinary boundaries in order to fully
462 integrate disciplinary paradigms, e.g. due to philosophical, methodological and communication barriers.
463 Moving forward, researchers across multiple and diverse fields face the challenge of refining the
464 empirical methods used to quantify access and exposure to freshwater blue space and addressing a
465 number of conceptual issues in current freshwater blue-health thinking. The evidence base supporting
466 the health and well-being benefits of exposure to freshwater requires further empirical testing and future
467 interdisciplinary research should seek to investigate the role of freshwater blue space within the wider
468 nature and human health research agenda, while continuing to advance the emerging blue-health
469 research field.

470

471 Acknowledgements

472 The Scottish Government Hydro Nation Scholars Programme provided funding to support this work.

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- 771

772 Table 1: Summary of freshwater blue-health pathways

Pathway	Explanation	Exemplar reference
Stress reduction / restoration	Perceived to have high restorative potential Opportunities for immersion within water Often perceived as relaxing, attractive and calming	Ulrich, 1991; White et al., 2010; Grassini et al., 2019;
Environmental improvement	Enhance thermal comfort and reduce urban heat island Improve soundscapes and buffer anthropogenic noise Provide ecosystem services, e.g. carbon absorption	Gunawardena et al., 2017; Jeon et al., 2012; Apostolaki et al., 2019
Physical activity (PA)	Unique opportunities for PA e.g. swimming and fishing Water-based PA preferred outdoors than indoors Encourage non-water based physical activity	Foley, 2015; Perchoux et al., 2015; Vert et al., 2019
Social interaction	Opportunities for planned and unplanned social contact More relaxed ambience than urban areas Opportunities for group exercise and leisure	Pitt, 2018; Völker and Kistestemann, 2015; Thomas, 2015;

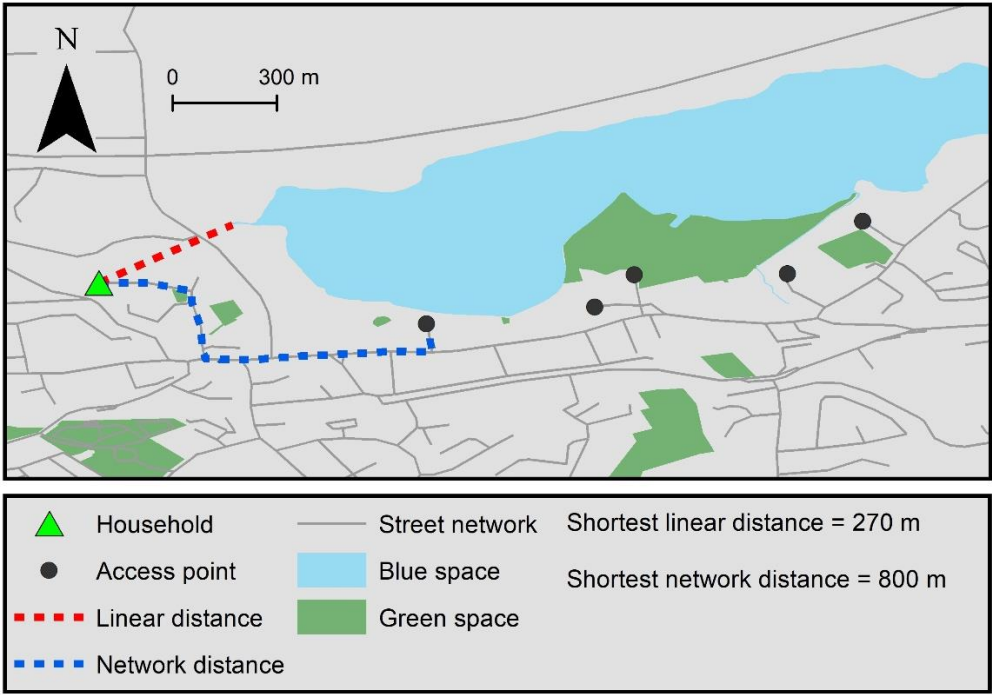
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774 Table 2: Overview of key research recommendations

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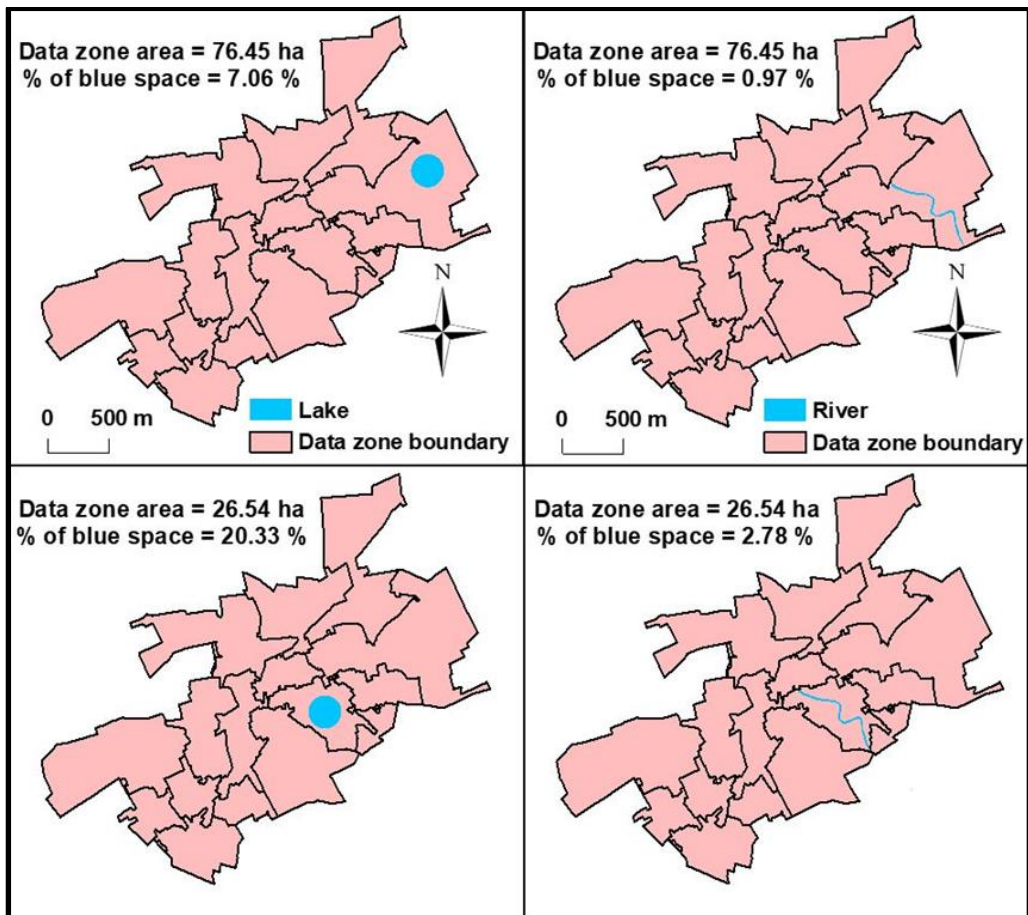
Establishing a methodological framework	Advancing the blue-health evidence base	Promoting freshwater blue-health opportunities
Define the spatial dimensions of freshwater blue space considered in research	Broaden research landscape to consider diverse climatic and human geographies	Develop communication pathways between research and public health professionals
Establish standardised metrics for quantifying access and exposure	Further empirical research with focus on general health	Provide blue-health focused guidance for managing freshwater sites
Report results for freshwater and coastal blue space exposure independently	Prioritise longitudinal research to establish causation	Understand barriers of accessing freshwater blue space
Adopt multiscale approaches to quantify access and exposure	Utilise big data from social media or activity tracking applications	Explore wider socio-economic consequences of blue-health strategies

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778 Fig.1: Summary of linear and network distance approaches for quantifying access to blue space



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780 Fig. 2: Area-based representations of freshwater blue space are dependent on blue space typology
 781 (e.g. river or lake) and the size of the administrative (data zone) boundary