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1 **How to evaluate nature-based solutions performance for microclimate, water and soil**
2 **management issues – available tools and methods from Nature4Cities European project**
3 **results**

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18 **Keywords (max 6)**

19 Urbanization; evaluation tool; microclimate; water management; models ; water quality assessment ;
20 urban soils; Key Performance Indicators

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23 **Abstract**

24 In the context of climate change, Nature-Based Solutions (NBSs), a recently developed concept, are
25 increasingly considered as part of the adaptation strategies of the cities. Studies using expert models
26 and methods (EMM) receive a great deal of scientific attention. Considering EMM increasing use, this

27 study aims to perform an analysis of the reported evaluation results, reflecting the capability of the
28 EMM to accurately tackle urban challenges identified within the EU Nature4Cities project. Then, we
29 propose a set of indicators and recommendations about sixteen EMM to be used by funders,
30 researchers and practitioners when evaluating the performance of NBSs. The coupling of the different
31 components (climate, water and soil) is not a simple matter. The analysis relies on the definition of the
32 range of the reported metrics and on the investigation of the relationship between the various indices,
33 applied for the EMM evaluation. Secondly, the study assesses the existing EMM, indicating the
34 potential of NBSs: (i) to reduce urban heat island, (ii) to limit surface warming, (iii) to increase the
35 thermal comfort of people, (iv) to limit the overheating and runoff of surfaces due to impervious areas,
36 (v) to increase water retention during stormy episodes, (vi) to improve storm water quality at the outlet
37 of the sustainable urban drainage systems, (vii) to promote the filtration and epuration of storm water
38 runoff in soil and (viii) to be a support for vegetation. The analysis reveals that EMM can be
39 considered as helpful tools for urban microclimate, urban soil and water management analysis,
40 provided their limitations and characteristics are taken into account by the user when choosing tools
41 and interpreting results (e.g. application scale). With regard to the performance of NBSs, the most
42 commonly used indicators clearly depend on the scale of the project.

43 **1. Introduction**

44 Urban densification has resulted in an increase of impervious surfaces, leading to increased runoff
45 rates and volumes, losses of infiltration (Fletcher et al., 2013) and other environmental hazards (e.g.
46 heavy metals' pollution) (Chu et al., 2019). Studies have shown that urban soils have an unpredictable
47 and heterogeneous layer organisation, poor structure, poor vegetation development and sometimes
48 high concentrations of persistent contaminants such as trace elements (TE) (De Kimpe and Morel,
49 2000). Besides climate hazards, the urban population is exposed to toxic agents, as the result of
50 industrial activities and traffic (Khalifa et al., 2018).

51 Nature-Based Solutions (NBSs) are defined as the use of nature in tackling societal or urban
52 challenges (UCs) and maintaining biodiversity in a sustainable manner (Lafortezza and Sanesi, 2019).
53 For the scientific community, the concept is still very open and needs to be more clearly defined, also

54 to clarify its links with other nature related concepts (e.g. green infrastructure, ecosystem-based
55 approaches) (Nesshöver et al., 2017). Nevertheless, there is a growing consensus on the key aspects
56 that frame the concept. NBS can be developed in different environments, from natural and rural areas
57 to more anthropized areas and cities. Promoting the idea of getting more nature in cities, the EU is
58 currently especially pushing to develop NBS in urban context (Faivre et al., 2017). The presence of
59 NBSs in urban areas instead of surfaces with high thermal inertia that store heat limits the overheating
60 of the urban surface (Emmanuel and Loconsole, 2015) and thus improves the thermal comfort of
61 people (Depietri and McPhearson, 2017; Kabisch et al., 2017). Moreover, as cities have been blamed
62 for contributing disproportionately to global climate change (Dodman, 2009), NBSs associating
63 vegetation and soil can provide a mean to mitigate climate change by storing/sequestering carbon and
64 thus reduce the overall greenhouse gases emissions (GHG) of the urban areas (Velasco et al., 2016).

65 NBSs used in urban water management help get closer to a natural water cycle (Wild et al., 2017).
66 They are currently named under diverse terminologies, according to the country and/or the language
67 (sustainable urban drainage systems “SUDS”, low impact development “LID”, best management
68 practice “BMP”, see Fletcher et al., 2015). They are usually based on increasing storage, infiltration
69 and/or evapotranspiration processes. Indeed, NBSs have the ability to limit surface runoff, increase
70 water retention during stormy episodes and flood protection compared to impervious surfaces (Liquete
71 et al., 2016) and improve rainwater and runoff waters quality (Husseini et al., 2013). Thus they can
72 mitigate floods by source storm water storage, they lead to a more sustainable urban water
73 management by favouring groundwater recharge and decreasing impervious surfaces (Granados-
74 Olivas et al., 2016). However, due to possible contamination of water and urban soils by heavy metals
75 (Krishna and Govil, 2008; Szekeres et al., 2018), salts and hydrocarbon in particular, the potential
76 transfer of pollutants to the groundwater by recharge during water management should be considered
77 (Carlson et al., 2011; Ostendorf et al., 2009)(Ostendorf et al., 2009; Carlson et al., 2011). The
78 treatment performance will highly depend on the design of SUDS and both quality of runoff waters
79 and soils (Fardel et al., 2020). Urban water management and quality (UWMQ) challenges are usually
80 examined at the catchment scale (e.g. (Obropta and Kardos, 2007)) that can also be compared to the

81 neighbourhood scale (extended areas of a city that have relatively uniform land use with dimensions
82 ranging from 0.5 to 4.0 kilometers) for climate issues, for example (Stein, 2014). Indeed, the
83 neighbourhood scale is the smaller scale that integrates a certain complexity of urban pattern
84 (associating buildings, streets, green spaces, etc.) and enables the observation of the interactions
85 between the urban pattern's individual elements. However, the performance and the hydrological
86 behaviour of NBSs are more often studied at the local scale (Golden and Hoghooghi, 2018). As a
87 combination of different NBSs stands as the solution rather than only one type of NBSs, and as
88 sustainable water management is more a large spatial and time scales issue, the city scale has also to
89 be studied, municipal or metropolitan perimeters being especially relevant because they also coincide
90 with administrative boundaries within which the strategies of local authorities are developed. The
91 different scales are described in the supplementary material (Section A1). Evaluation of mixed
92 scenarios of NBSs at the city scale can also make it possible to avoid negative joint effects or to
93 promote positive ones (Gunawardena et al., 2017).

94 In urban areas, soils are often stripped, filled, mixed, compacted and supplemented with artificial
95 materials. The soil structure is modified, and built structures and drainage infrastructures are
96 introduced. NBSs can improve soil properties on two aspects. The first category consists of solutions
97 based on soil modifications, improvement of soil functions and, consequently, the resilience of the
98 built ecosystem to external factors. These solutions are based on the concept of soil health (Brady et
99 al., 2008). The second category includes solutions that are based on altering flows (water, sediment,
100 nutrients, pollutants) based on the concept of connectivity (Parsons et al., 2015). It include water
101 catchment, a range of aspects and topography, varied climatic conditions, sufficient species richness
102 and ecosystem function to allow for multi-functionality of interactions, a number of habitats and
103 sufficient area to permit the ingress of plant species and movement of vectors and animals (Turner,
104 2005) and understood in the landscape ecology meaning, that is to say an assemblage of
105 ecosystems interacting occurring in a geo-graphically defined region (Haber, 1990). The
106 inclusion of NBSs in the urban planning strategy would contribute to the mitigation of some major
107 environmental problems (e.g. loss of organic carbon) (Bouzouidja et al., 2019). Indeed, Foucault et al.

108 (2013) observed at a battery recycling site in Toulouse (France), that green manure increased soil
109 respiration rate by 25 to 50%, leading to a better organic matter humidification process and thus an
110 increase in organic carbon stock. The objective of adding NBSs related to soil quality and
111 management is to allow it to perform two essential functions, which are as follows: (i) to be a support
112 for vegetation. This function is possible if the urban soil has an appropriate agronomic quality (Morel
113 et al., 2015), (ii) to promote the filtration and epuration of urban water.

114 On the one hand, we have highlighted the complexity of the current challenges in urban areas. On the
115 other hand, it appears that nature-based solutions (NBSs) can efficiently address current environmental
116 issues (climate change adaptation, urban water and soil management) and adapt to each local context.

117 Implementing NBSs in urban projects would contribute to the mitigation of major environmental
118 issues and to the development of sustainable and resilient cities. This objective requires a
119 reconsideration of the management of urban areas and the development of adapted methodology,
120 methods and models. Currently, various studies and projects funded by the EU's Horizon 2020
121 (H2020) programme are working on a framework to recognize and assess the value of these NBS co-
122 benefits and to guide the design and implementation of urban development projects and cross-sectoral
123 policies. Cooperation between urban scientists (climate change, water and soil management) should
124 therefore be promoted. Consequently, to develop sustainable management of urban areas, it is of
125 utmost importance to use expert models and methods (EMMs) that take into account UCs and the
126 benefits of NBSs. These EMMs inform us about the performance of NBSs using various urban
127 performance indicators (UPIs) (e.g. Peak flow variation) (Montazeri et al., 2017).

128 One of the challenges of NBS assessment is the multiplicity of parameters to follow derived from the
129 multiple challenges. Our issue is that the NBS assessment framework cannot be the sum of indicators
130 and EMMs of each challenge addressed. The main aim of this study is to analyse a set of current
131 simulations of EMMs dedicated to urban microclimate, water and soil management, in order to answer
132 the following questions: What are the main variables or list of indicators computed in these EMMs?
133 What cases are implemented? Is the feedback from the climate, water and soil aspects included? The

134 final aim is to propose an evaluation framework adapted to the capture of multipurpose functionality
135 of NBSs, including the simultaneous achievement of environmental benefits (climate, water and urban
136 soil management).

137 The structure of this study is the following. First, section 2 provides an overview of the various urban
138 challenges (UCs). Second, taking these challenges into account, an analysis of the performance of
139 NBSs using UPIs in response to the UCs is conducted. We then show in section 3, on the one hand,
140 which expert models and methods (EMMs) are dedicated to urban microclimate, water and soil.
141 Which indicators are able to determine and which are the main variables calculated by these tools.
142 Which data are implemented and whether there is feedback in relation to the selected challenges
143 (climate, water and soil). On the other hand, we analyse the issues that need to be addressed especially
144 in terms of the capacity of EMMs to tackle UCs and their objectives in relation with the performance
145 of NBSs, but also the spatial scale of EMMs applications based on the assumptions made in the
146 characterization of NBSs. In section 4, we propose an evaluation framework adapted to the capture of
147 the multipurpose functionality of NBSs, including the simultaneous achievement of environmental
148 benefits (climate, water and urban soil management).

149 **2. Material and methods**

150 **2.1. Available urban NBS performance indicators**

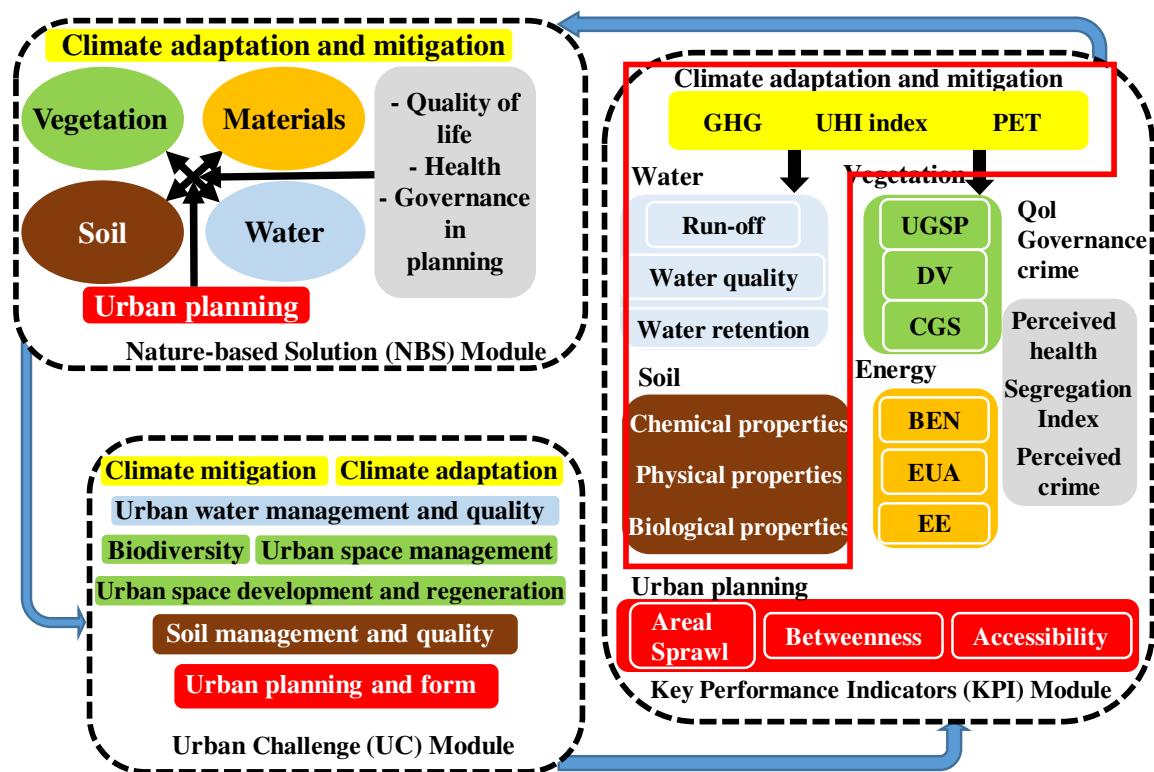
151 The N4C project (Nature4Cities, H2020, 2016-2020) aims to identify indicators that can assess the
152 performance of NBSs in relation to UCs. Among the eleven UCs, defined in the N4C project (Figure
153 1), stand the three we are interested in: (i) climate change adaptation, (ii) water management and (iii)
154 soil management because of their importance in the urban context. To assess the way NBSs perform to
155 address these challenges, the experts of the project have identified a set of UPIs. A total of 110 UPIs
156 has been collected (Green4cities et al., 2018) and evaluated using the RACER (Relevant, Accepted,
157 Credible, Easy and Robust) framework (Lutter and Giljum, 2008) to assess the value of scientific tools
158 for use in policy making. As we focus on the performance assessment of NBSs supporting function for
159 vegetation, with regards to water quality and quantity, soil quality, and urban microclimate regulation,

160 19 indicators over the initial 110 were retained here (Table 1). These indicators are described in the
161 supplementary material (Section A2).

162 The subject area of Urban-Scale Modelling (USM) encompasses numerous techniques and application
163 domains. We have therefore selected models, tools or methods widely used by the expert partners of
164 the N4C project for the simulation of urban-scale climate, water and soil systems. The EMMs
165 presented in this article are a selection of the EMMs studied in the N4C project (Bouzouidja et al.,
166 2018a). At the end, for the targeted challenges, 18 EMMs were documented (7 for climate, 3 for water
167 and 6 for soil). The list of tools presented in this section is not exhaustive. In the following, we will try
168 to investigate deterministic models and laboratory analysis methods available for assessing NBSs
169 performance at the urban level without taking the evolution and dynamics of this performance into
170 account. It should be kept in mind however that in some cases, the assessment of NBSs capacity to
171 address urban issues remains limited.

172 **2.2. NBS environmental performance analysis tools**

173 The subject area of Urban-Scale Modelling (USM) encompasses numerous techniques and
174 application domains. We have therefore selected models, tools or methods widely used by the
175 expert partners of the N4C project for the simulation of urban-scale climate, water and soil
176 systems. The EMMs presented in this article are a selection of the EMMs studied in the N4C
177 project (Bouzouidja et al., 2018a). At the end, for the targeted challenges, 16 EMMs were
178 documented (7 for climate, 3 for water and 6 for soil). The list of tools presented in this
179 section is not exhaustive. In the following, we will try to investigate deterministic models and
180 laboratory analysis methods available for assessing NBSs performance at the urban level
181 without taking the evolution and dynamics of this performance into account. It should be kept
182 in mind however that in some cases, the assessment of NBSs capacity to address urban issues
183 remains limited.



184

185 **Figure 1.** Schematic diagram adapted from Bouzouidja et al., (2020) of the methodology for
 186 analysing the impact of NBS at the urban scale - how to consider the impact of nature on soil
 187 management challenge in relation to others challenges. GHG means greenhouse gas
 188 emissions. UHI means urban heat island. PET means physiological equivalent temperature.
 189 UGSP means urban green space proportion. DV means diversity of vegetation. CGS means
 190 continuity of green space. BEN means building energy needs. EUA means energy use in
 191 agriculture. EE means energy efficiency. Qol means quality of life.

192 **2.3. Framework of modelling/method choice**

193 After the EMMs inventory, a matching table was established that identifies which EMM can simulate
 194 and determine which UPI for each UC and at which scale (e.g. building or parcel, neighbourhood, and
 195 city).

196 We suggest evaluating the selected EMMs using structural and technical comparisons, based on six
 197 main evaluation criteria, some of which were divided into subcriteria (forming nine subcriteria in

198 total). A score between 1 and 5 was attributed for each subcriteria (1: strongly disagree, 5: strongly
199 agree) (Table 2): The criteria and sub criteria above are not equally important in a model/method
200 selection process, therefore a weighting score was added, based on expert opinions of the project
201 experts (between 1-3, where 3 indicated that the criteria/sub criteria is very important, while 1 is the
202 least relevant). The integrated evaluation was completed with calculating aggregated scores (Y_{aggr}) for
203 every EMM from the evaluation (x_i) and weighting scores (w_i) as a weighted sum expressed in % (Eq.
204 1) (Madansky and Alexander, 2015). Where x_{max} is the maximum evaluation score (5 points).

205 **Table 1.** Selected UPIs related to the three urban challenges (UCs) (climate, water
 206 management and soil management) based on Green4cities et al., (2018).

UCs	Urban Performance Indicators
Climate adaptation	AT - Air temperature PET - Physiologically equivalent temperature
	TLS - Thermal load score MRT - Mean radiant temperature
	TCS - Thermal comfort (outdoor) PMV - Predicted mean vote score
	UTCI - Universal thermal climate index
Water management and quality	FPR - Flood peak reduction WQ - Water quality
	SBA - Soil biological activity SAW - Soil available water for plants
Soil management	SWI - Soil water infiltration SCF - Soil classification Factor
	SMP - Soil macro porosity SCR - Soil Crusting
	SCT - Soil contamination SOM - Soil Organic Matter
	CFS - Chemical fertility of soil ECF - Ecotoxicology factor

$$Y_{aggr} = \left(\frac{\sum_{i=1}^9 w_i \times x_i}{\sum_{i=1}^9 w_i \times x_{max}} \right) \times 100 \quad (\text{Eq. 1})$$

208 For a group of given EMMs, while considering the same spatial scale, the EMM with the highest score
 209 is proposed to be used in the modelling/methodology procedure.

210 Reciprocally, these criteria will inform on the operational availability of indicators (an indicator, even
 211 very interesting from a theoretical point of view, will be of limited interest if we could not find any
 212 tool to calculate it).

213 **Table 2.** *Criteria for selecting appropriate expert model and method (EMM).*

Criteria	Sub-criteria	Weighting factors
Parametrization	The parameterization of the model enables the exact representation of different NBS groups and spatial scenarios	3
	The required input data are suitable (obtainable, not too complex) for parameterizing the expert model	2
Background documentation	The structure (architecture) of the model or the method and the workflow of the calculations are well-documented and available	3
Reliability of the model/method	Validation studies (that is, comparison with accurate field measurements) exist and the model have got positive feedback from users	3
Modelling (preparations and model running)	time The model or method build up requires short time which enables the usage of the model in expert modelling	2
	The running time is not too long which enables the usage of the model in expert modelling	1
User friendliness	The model or method can be used easily and correctly by experts (outside of the N4C expert team as well)	1

	The model is freely available	2
Application	The model or the method is frequently used for scientific purposes (by international users)	3

214 **3. Results and discussion**

215 **3.1. Climate change adaptation challenge**

216 The performance analysis from the point of view of climate adaptation is a challenging task, as the
 217 positive effects of NBSs are connected to different sub-processes: different NBSs perform shading and
 218 evapotranspiration quite differently, which is not easy to handle in one modelling framework. The
 219 other aspect of complexity is the fact that human thermal comfort depends on many climatic
 220 parameters (air temperature and velocity, humidity, radiation circumstances, etc.), which can be
 221 evaluated with different indicators (which is of course the case for our UPIs as well). Moreover, NBSs
 222 efficiency is strongly linked to local urban form. Table 1 summarizes the selected UPI attached to the
 223 EMMs related to the climate change adaptation challenge.

224 *Table 3. Main climatic expert models and methods (EMMs) developed in Nature4Cities (N4C) project.*

Objective	related UPI	Expert models and References	
to urban challenge		methods	
Reduce urban heat island	AT - Temperature	Air FLUENT-ANSYS	(Chatzidimitriou and Yannas, 2016; Gromke et al., 2015; Tominaga et al., 2015; Yang et al., 2017)
		ENVI-met	(Wu et al., 2019)
		TEB model	(Lemonsu et al., 2012; Masson et al., 2002)
	TLS - Thermal Load Score	ENVI-met	(Bruse, 1999; Huttner and Bruse, 2009)

Increase	the UTCI	- Universal ENVI-met	(Goldberg et al., 2013; Minella et al., 2014; Park et al., 2014)
thermal comfort of people	Thermal Index	Climate	
		TEB model	(De Munck et al., 2018; Lemonsu et al., 2012; Masson et al., 2002)
		RayMan model	(Goldberg et al., 2013; Matzarakis et al., 2010; Thom et al., 2016)
		SOLENE-Microclimat	(Malys et al., 2015)
		FLUENT-ANSYS	(Montazeri et al., 2017; Saneinejad et al., 2014a, 2014b)
	PMV - Mean Vote	Predicted ENVI-met	(Hedquist and Brazel, 2014; Maras et al., 2013; Wang et al., 2015)
		FLUENT-ANSYS	(Robitu et al., 2006; Zhang et al., 2012)
		RayMan model	(Abdel-Ghany et al., 2013; Matzarakis et al., 2010; Oertel et al., 2015)
	PET Equivalent Temperature	Physiologically RayMan model	(Charalampopoulos et al., 2013; Gulyás et al., 2006; Hwang et al., 2011; Kántor et al., 2016; Kovács et al., 2016; Matzarakis et al., 2010)
		ENVI-met	(Acero and Herranz-Pascual, 2015; Chen and Ng, 2013; Duarte et al., 2015)
		FLUENT-ANSYS	(Yang et al., 2017; Zheng et al., 2016)
		SOLENE-Microclimat	(Malys et al., 2015)
	TCS - Comfort (outdoor)	Thermal Score	(Bruse, 1999; Hutter et al., 2009)

ENVI-met	
Limit overheating surfaces	the MRT - Mean RayMan model (Krüger et al., 2014; Lee and Mayer, 2016; Matallah et al., 2020)
	of Radiant Temperature
	SOLWEIG-model (Gál and Kántor, 2020; Lindberg et al., 2018)
	ENVI-met (Chow and Brazel, 2012; Emmanuel and Fernando, 2007; Krüger et al., 2011; Tan et al., 2016)
	FLUENT-ANSYS (Yamaoka et al., 2008)
SOLENE- (Malys et al., 2015)	
Microclimat	

225 Given the importance of the subject, a large number of existing scientific studies have applied EMMs
226 to assess the impact of different mitigation strategies for the improvement of the urban thermal
227 environment and its implicit effects. To date, the objectives that have been mainly studied with the
228 different models include the following groups: (i) the reduction of UHI by using NBSs, (ii) increase
229 the thermal comfort of people (iii) limit the overheating of surfaces by using bio-based solutions
230 (Table 3).

231 Several studies have focused on the reduction of UHI (among others, Bozonnet et al., 2013; Chow and
232 Brazel, 2012; Duarte et al., 2015; Emmanuel and Fernando, 2007; Feyisa et al., 2014; Gromke et al.,
233 2015; Masson et al., 2002; Musy et al., 2015). These studies have used different indicators: AT and
234 TLS. In this context, microclimate models such as ENVI-met, FLUENT-ANSYS and TEB model have
235 been widely applied to examine the positive impact of various urban green infrastructures on the
236 outdoor thermal environment (Lauzet et al., 2019).

237 **3.2. Water management and quality challenge**

238 The performance assessment of water management and quality for NBS is conducted in N4C project
239 at “parcel”, neighbourhood and city (a set of catchments and sub catchments) scales for swales, green
240 roof and vegetated areas (SUDS) by using different methods. The EMM was parameterised with
241 respect to cover rate and vegetation height (low vegetation and high vegetation mixed). For urban
242 stormwater quantity purposes, the method consists of using urban hydrological modelling. For urban
243 stormwater quality purposes, the method uses the adapted comparison between physico-chemical
244 properties, nutrients concentrations and “micro-pollutants concentrations of water” and European
245 standards for surface waters. Concerning storm water quality, the “good status” of surface waters
246 defined in the EU Water Framework Directive (WFD) relies both on the ecological and the chemical
247 status. The former includes biological indicators, physicochemical parameters controlling biological
248 status, specific pollutants of ecological status and hydro-morphological parameters. The latter is based
249 on the compliance with environmental quality standards (EQSs). The EQSs in Directive 2008/105/EC
250 are concentration limits of the priority substances (45) and 8 other pollutants in water (or biota), i.e.
251 concentration limits. In the case of water quality evaluation for SUDS, the WFD scheme is simplified
252 as biological indicators and hydro-morphological parameters are not relevant. Table 4 summarizes the
253 selected UPI attached to the EMMs related to the water management challenge. Additionally, the
254 groundwater quality, potentially impacted by NBS stormwater infiltration, should be taken in
255 consideration with the same significance as the surface water quality, given the value of groundwater
256 for drinking water supply (Standen et al., 2020). In terms of storm water runoff, NBSs can positively
257 influence the regulation of surface runoff due to their retention potential. Zölch et al., (2017) used a
258 PFV indicator and found that the vegetation together with the substrate store rainwater and make it
259 available for evapotranspiration (1.4% and 14%). In addition, NBSs could increase water retention
260 during rain events. For example, 20% to 100% (10 mm h^{-1} to 3 mm h^{-1} respectively) of rainfall were
261 stored (e.g. (Carter and Rasmussen, 2006). Trees planted on prairie slopes increased water storage
262 under their canopy, again reducing erosion and surface water runoff (Joffre and Rambal, 1993). For
263 example, Ellis et al., (2006) found that treed roads could reduce runoff from a grassy slope by 32 to
264 68% in a 10-year storm (24.5 mm in 30 min) and by 100% in a two-year storm (48 mm h^{-1} for
265 13 min). Finally, by intercepting rainfall in their crowns, trees could reduce storm water runoff and

266 thus protect water quality (McPherson et al., 2011). NBSs can contribute to the improvement of water
 267 quality through various physical and chemical processes, resulting from the interaction between
 268 pollutants (either dissolved or particulate), soil surface, vegetation, and porous media reactive
 269 surfaces, after water infiltration (Fardel et al., 2020).

270 **Table 4.** Main urban water management expert models and/or experimental methods (EMMs)
 271 developed in N4C. UC means urban challenge.

Objective related to UC	UPI	Expert models and References methods	
Limit surface runoff due to the presence of impermeable areas	- Flood Peak Reduction	URBS-MO	(Rodriguez et al., 2008)
		TEB-Hydro	(Stavropulos-Laffaille et al., 2018)
Increase water retention during rain events	- Soil Water Storage	URBS-MO	(Rodriguez et al., 2008)
		TEB-Hydro	(Stavropulos-Laffaille et al., 2018)
Improve water quality at the outlet of the NBS	- Water Quality	Simplified method based on European WFD	(National Research Council et al., 2008)

272 3.3. Soil management challenge

273 Urban soils are characterised by strong heterogeneity in terms of physico-chemical properties mainly
 274 due to various and contrasted material supplies (Greinert, 2015; Hulisz et al., 2018; Huot et al., 2015),
 275 sometimes including the presence of contaminants (De Kimpe and Morel, 2000; Gestel et al., 2001).
 276 Moreover, these soils differ from natural or cropped soils: they display a lower nutrient content
 277 (except the urban allotment gardens often super fertilised (Laaouidi et al., 2020)) and a higher pH
 278 (Roberts et al., 2006; Zainudin et al., 2003), high physical compaction as a result of mechanical stress
 279 (road traffic) potentially impacting plant root and aerial growth (Grabosky and Gilman, 2004).
 280 Organic matter content is also more contrasted depending on the soil use, but generally low, especially

281 due to the lack of organic matter return as litter fall, particularly in isolated street tree pits (Roberts et
 282 al., 2006).

283 Thus, soil management requires knowledge of various processes: physical, chemical and biological. It
 284 is not possible to dissociate them. Table 5 summarizes the different EMMs taken into account in urban
 285 soil management. According to FAO, (2009), soils are the foundation for vegetation and they have a
 286 reciprocal relationship. In addition, a proper soil management can promote filtration (e.g. Tedoldi et
 287 al., 2017) and pollutant mass load reduction of urban water (e.g. Shirazi et al., 2012).

288 **Table 5. Summarizing urban soil management expert models and/or experimental methods (EMMs)**
 289 *that are developed in N4C.*

Objective related to urban UPI challenge	Expert models and methods	References
Be a support for vegetation	SCR - Soil Crusting Fertility Evaluation method	(Šimanský et al., 2014)
	SMP - Soil macro porosity Fertility Evaluation method	(Yilmaz et al., 2018)
	SAW - Soil available water for plants Fertility Evaluation method	(Vidal-Beaudet et al., 2017)
	SCF - Soil Textural classification Factor method	(Morel et al., 2017)
	SBA - Soil Soil biological activity Biological Evaluation (SBA EM) Activity Method	(Keuskamp et al., 2013)
	SOM - Soil organic Matter Fertility Evaluation method	(Cambou et al., 2018)
	CFS - Chemical fertility of Fertility Evaluation method	(Bouzouidja et al., 2020)

	soil		
Promote the filtration and	SWI - Soil water Fertility Evaluation method		(Zhang, 1997)
pollutant load	infiltration		
reduction of urban			
water			
	SCT - Soil Fertility Evaluation method		(Jean-Soro et al., 2015)
	contamination		
	ECF - Ecotoxicology Ecotox evaluation method		(Gestel et al., 2001)
	factor	(Ecotox EM)	

290 **3.4. Selected Expert Models and Methods based on the evaluation criteria**

291 The comparison between the selected EMMs according to the scoring system and their spatial scale is
292 presented in Table 6 (details of the scoring system are presented in the supplementary material Table
293 S1). In the context of climate change adaptation challenge, SOLWEIG-model has obtained the highest
294 score (84.0%) in terms of the criteria selected and the neighbourhood scale (Table 2). This model
295 works at the object and neighbourhood scales. One important advantage of SOLWEIG-model among
296 microclimate simulation models is that it is usable at the neighbourhood scale through the GIS
297 representation of buildings and other important elements of modelling. Between 1989 and 2020,
298 almost 219 papers have been identified based on Scopus database; 81.7% of them concern articles
299 published in scientific journals, while the rest 16.0% and 2.3% correspond to conference papers and
300 book chapters respectively (data not shown). As SOLWEIG works now as a part of a plugin (UMEP),
301 it is ready to be integrated directly in QGIS, which makes it very practical for usage in integrated
302 urban assessments. Meanwhile, the core indicator calculated by SOLWEIG is the mean radiant
303 temperature; the model focuses on radiation scenarios, instead of complex indicators (e.g. PET). The
304 one that scored almost the same is RayMan model with 83%. RayMan model is a good alternative to
305 tackle climate adaptation USC instead SOLWEIG-model at object and neighbourhood scales.
306 Although, RayMan model is not GIS-based, it can import building geometry data from QGIS when
307 working on a large domain. By default, it only calculates point results but no continuous surface data,

308 but continuous surface data can be obtained by running the model on a grid (of any size) and then
309 interpolating the point data. On the contrary, ENVI-met simulates an area by default. RayMan
310 simulates the complex radiation environment, while ENVI-met can predict all the meteorological
311 parameters (including air temperature, relative humidity, wind speed and solar radiation). RayMan
312 uses real meteorological data, while ENVI-met builds the most probable weather conditions (using an
313 urban weather generator) to provide the input data to the model (Bande et al., 2019). RayMan
314 considers the thermal effects of vegetation and buildings only, while ENVI-met considers the land
315 cover by defining the percentage of vegetation over a given surface. RayMan can create several year-
316 long output data, while due to the complexity of the model (e.g. spatial representation of wind
317 velocity), ENVI-met requires greater computational capacity and runtime (e.g., for 2 weeks of
318 neighbourhood data, the computational time is 1week) (e.g., Fachinello Krebs et al., 2017) than
319 RayMan (about 3 days on average, depending on resolution). Finally, ENVI-met is a widely used
320 EMM. Tsoka et al. (2018) reported in a review on ENVI-met use in 2018 that almost 280 respective
321 papers have been identified in the Scopus database; 68% of them concern articles published in
322 scientific journals, while the rest 31% and 1% correspond to conference papers and book chapters
323 respectively.

324 At the neighbourhood scale, ENVI-met got 80%. This model is a three-dimensional, grid-based
325 microclimate model designed to simulate and predict complex surface-vegetation-air interactions in
326 the urban environment. Also, ENVI-met model can simulate the diurnal cycle of major climate
327 variables involving meteorological data (air and soil temperature and humidity, wind speed and
328 direction, radiative fluxes, etc.) with a typical horizontal resolution of 0.5 to 5 m and a time step of 1
329 to 5 sec (Huttner, 2012). At the city scale, only TEB-model has a relevance, getting a score of 75%
330 (Table 6). TEB is based on a canyon street model (Masson, 2000), which can be used for street-level
331 calculation as well as to calculate UHI and impact of mitigation solutions at the city scale using
332 MESO-NH model (De Munck et al., 2013). The city is then discretised into homogenous cells whose
333 geometrical and material characteristics are calculated by averaging real values. The behaviour of the

334 resulting representative canyon-street is then calculated. TEB performs water and heat balance under
335 climatic forcing (Lemonsu et al., 2004).

336 Concerning urban water management and quality challenge, it can be noticed that the different EMMs
337 are dedicated to only one scale. It is therefore useful to compare these EMMs with each other with
338 respect to the scale of application. Moreover, they all have almost the same score (between 71 and
339 74%). For example, URBS-MO and TEB-Hydro are both able to represent all hydrological processes
340 involved in the urban storm water budget, such as evapotranspiration, infiltration in roads, or direct
341 infiltration of soil water in sewers. They differ in the spatial segmentation: TEB-Hydro is based on a
342 regular mesh grid with a sewer network adapted to its grid resolution whereas URBS-MO includes an
343 irregular morphological segmentation of the urban environment based on cadastral parcels and urban
344 databanks analysis. The models are able to predict both the spatial and temporal variability of
345 hydrological processes on urban catchments, at the hydrological unit scale (Rodriguez et al., 2007;
346 Stavropoulos-Laffaille et al., 2018). URBS-MO is able to simulate the storage capacity and saturation
347 level of each unit. EMMs are distinguished by their field of application: URBS-MO and TEB-Hydro
348 are able to determine the quantity indicators, i.e. FPR (Flood Peak Reduction), whereas the water
349 quality is determined along with the European Water Framework method (Seelen et al., 2019).

350 Eventually, in the context of urban soil management, textural function method with a score of 90% is
351 able to access the physical process of soil management. In addition, SBA EMM with a score of 79%
352 may also determine the biological activity of soil. Ecotox EM has obtained a score of 61%. However,
353 basic soil properties (e.g. organic matter) can explain the level of contamination in the soil (Bouzouidja
354 et al., 2020). Indeed, in some NBS such as green roofs or urban allotment gardens, substrates/soils are
355 derived from already contaminated materials, but also from practices such as the use of pesticides
356 (Gasperi et al., 2014; Nunes et al., 2016).

357 **Table 6.** Expert models and methods (EMMs) selected according to the scoring system and spatial
358 scales. *coupling with MESO-NH model (Lac et al., 2018). UCs means urban challenges.

UCs	EMMs	Score	Scale
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				Parcel	Neighbourhood	City
Climate change adaptation challenge	FLUENT-ANSYS	67.0	X	X		
	ENVI-met	80.0		X		
	TEB-model	75.0		X	X*	
	RayMan model	83.0	X	X		
	SOLENE-Microclimat	65.0		X		
	SOLWEIG-model	84.0	X	X		
Urban water management and quality challenge	URBS-MO	74.0		X		
	TEB-Hydro	71.0			X	
	Simplified method based on European WFD	72.0	X			
Soil management challenge	Fertility Evaluation method	72.0	X			
	Textural function method	90.0	X	X	X	
	Soil Biological Activity Evaluation Method	79.0	X			
	Ecotox evaluation method	61.0	X	X	X	

359 **3.5. Consistency between models/methods with parametrization**

360 Both RayMan and SOLWEIG models require quite important spatial datasets, as both models need a
361 description of the investigated area, including the geometry of the buildings and vegetation, along with
362 their radiative properties. These data are frequently available in municipalities (e.g. building databases,
363 simple digital elevation models, etc.), but some of them are not easy to obtain (e.g. tree canopy
364 dimensions and trunk heights) and their integration can be difficult. RayMan model provides good

365 simulation results for radiation flux densities and thermo-physiologically significant assessment
366 indices (Matzarakis et al., 2010). The model, which takes complex structures into account, is suitable
367 for utilization and planning purposes on local and regional level (Matzarakis and Rutz, 2010). It is
368 well-suited to calculate radiation fluxes (Charalampopoulos et al., 2013; Gulyás et al., 2006). The
369 main advantage of the RayMan model is that it facilitates the reliable determination of the
370 microclimatological modifications of different urban environments, since the model considers the
371 radiation modification effects of the complex surface structure (buildings, trees) very precisely(Gulyás
372 et al., 2006). The results obtained using RayMan model can be a valuable source of information for
373 planners, decision-makers and practitioners when planning and constructing new urban areas (Gulyás
374 et al., 2006). The parametrization of SOLWEIG is based on the same principle as RayMan, but it
375 allows an easier representation of different NBSs. The vegetation scheme of the model handles
376 vegetation with digital surface models; it does not need any information on species or specific size
377 parameters. Thus, it theoretically enables the representation of every type of urban vegetation and
378 NBSs.

379 SOLENE-Microclimat, ENVI-met and FLUENT-ANSYS give access to more detailed information,
380 particularly air-flows and their impact on local microclimate. Therefore, their parameterization is more
381 complex, and two categories of parameterizations are required to operate them: (i) parameters for
382 building layout, vegetation, soil type and (ii) simulation parameters for location, meteorological
383 condition initialization values, and schedules (Tsoka et al., 2018). Those data are not readily available
384 and measurement is time consuming. SOLENE-Microclimat allows the parameterization and
385 representation of natural soil, green walls, green roofs, lawns, street humidification, trees and shrubs -
386 no rivers and large water bodies (Bouyer et al., 2011; Malys et al., 2016, 2014; Morille et al., 2016;
387 Musy et al., 2015; Robitu et al., 2006). However, it is difficult to have a good parameterization, as for
388 example SOLENE-Microclimat requires leaf area index (LAI) and water availability, as well as
389 soil/buildings characteristics. A major limitation of ENVI-met is that inter-reflections are not
390 accounted for in the calculated shortwave radiation and longwave radiation takes into account
391 averaged temperatures so rendering difficult to assess the local impact of surface temperature change

392 (Lauzet et al., 2019). The main disadvantage is stability issues when simulating winding urban
393 canyons or abutting neighbourhoods (Elwy et al., 2018). Furthermore, relative humidity is not a
394 prognostic factor, as the simulation of cities in humid regions (RH above 50%) leads to erroneous
395 results of RH above 100%. Recently, the forcing function has made a big improvement to the model,
396 but it still has its own instabilities. FLUENT-ANSYS is basically adapted to fluid mechanics problems
397 coupled with thermal and radiative transfers. Recent adaptations include the interaction of the local
398 environment with plants (e.g. Bouhoun Ali et al., 2018). High level of realism was obtained in a
399 constrained environment with relatively small dimensions (tens of meters). FLUENT-ANSYS requires
400 a large set of data, particularly in case of 3D simulations (meteorological data, thermal and radiative
401 properties of walls; some of them being more difficult to assess, e.g. LAI and water availability of the
402 soil) (Boulard et al., 2017).

403 Unlike the previous EMM, TEB was conceived for a use at a larger scale using a 1D meteorological
404 forcing (De Munck et al., 2018). The model is run in order to compute water, energy and momentum
405 surface exchanges over the impervious covers (roofs, roads, walls) at a neighbourhood or city scale,
406 using mean value for the entire area. This approach is less computationally intensive for large scale
407 studies, but the aggregation of parameters datasets must be performed for the results to be relevant.
408 The contributions of gardens take place through the long-wave emission that is received by roads and
409 walls (Lemonsu et al., 2012). Vegetation is directly included inside the canyon, allowing shadowing of
410 grass or trees by buildings, better representation of urban canopy form and, a priori, a more accurate
411 simulation of canyon air microclimate (Lemonsu et al., 2012; Redon et al., 2017). The radiation and
412 energy budgets and the turbulent exchanges within the canyon of the model are represented in detail in
413 Lemonsu et al., (2012) and Masson, (2000).

414 The water and energy urban scheme TEB with HYDRO module allows the evaluation of the greening
415 strategies in regards to urban hydrology and climate (Chancibault et al., 2014; Stavropoulos-Laffaille et
416 al., 2018). At the scale of a large urban area (in the city of Nantes, France), some greening strategies
417 have been simulated: green roofs, trees /grassed areas and different fractions of natural surfaces
418 (Chancibault et al., 2014). This model can be run either coupled with other meteorological models or

419 forced by observed atmospheric data. It combines two surface schemes, TEB (Masson, 2000) and
420 ISBA-DF (Boone et al., 2000), that are based on a regular mesh grid. URBS-MO inputs at the scale of
421 an urban hydrological element consist of the meteorological “forcing”, which includes precipitation
422 and potential evapotranspiration; and the initial saturation depth (Rodriguez et al., 2008). URBS-MO
423 is based on urban databanks to print the morphology of the urban surface: the parcels and the street
424 network (Rodriguez et al., 2007). Thus, urban catchments are represented as a set of elementary
425 surfaces connected to a hydrographic network, based on the city’s main structural components. URBS-
426 MO requires both morphological features and physical parameters (Rodriguez et al., 2007). This
427 detailed representation is well adapted for the introduction of plot-scale greening strategies (Rodriguez
428 et al., 2007). Most entries should have been deduced from physical considerations, either literature
429 reviews, field measurements or parameters adjustment (Rodriguez et al., 2008). The method for water
430 quality evaluation is divided into two steps: 1) evaluation of ecological status (physicochemical); 2)
431 evaluation of chemical status. In the first step, basic physicochemical data are required to obtain a
432 global evaluation of the quality. If relevant, some complementary chemical analysis on metallic and
433 organic contaminants may be performed, after characterization of pollutant sources in the vicinity of
434 the NBS or due to maintenance.

435 To parameterize the Ecotox EM, doses of chemical stressors that affect soil organisms (regarding
436 EC50, LD50, etc.) can be acquired from freely available databases (see below). The question arises
437 about the bio-indicators to be included in the method. So far, there is no consensus. In France, 18 bio-
438 indicators were approved by ADEME and some combinations were suggested for different purposes
439 (Pérès et al., 2011). EC50, LD50 and TD50 and several other parameters regarding physico-chemical
440 characteristics of soils to be taken into account (texture, Henry constant, solubility, etc.) are quite
441 easily available in database, e.g. EPA¹ (USA); INERIS² and INRS³ (France). Concerning Fertility EM,
442 soil moisture status is largely determined by porosity, which is a key attribute of soil structure. The
443 size or diameter of pores regulates the energy state at which moisture is held in soil and its availability

¹www.epa.gov (accessed September, 15 2020)

²www.ineris.fr (accessed September, 15 2020)

³www.inrs.fr (accessed September, 15 2020)

444 to plants (Jim and Peng, 2012). Fertility EM requires input data obtained from direct measurement
445 (e.g. SWI, SCF), derived from models or equations (e.g. SMP, SAW, SOM) (Cambou et al., 2018;
446 Yilmaz et al., 2018). Concerning Textural function method, statistical correlations between soil
447 texture, soil water potential, and hydraulic conductivity can provide estimates sufficiently accurate for
448 many analyses and decisions (Saxton and Rawls, 2006). The texture function-based method reported
449 by Saxton et al., (2006) has been successfully applied to a wide variety of analyses, particularly those
450 of agricultural hydrology and water management. The required input data for SBA EM is acquired
451 with laboratory experiments and in-situ tests are necessary. However, SBA EM is a unique,
452 multifunctional method requiring few resources and minimal prior knowledge. The standardisation
453 and simplicity of the method make it possible to collect comparable, globally distributed data through
454 crowdsourcing (Ogden, 2017).

455 **3.6. Status of documentation on models/methods**

456 Sufficient amount of information about RayMan has been available since its creation in 2007
457 (Matzarakis et al., 2010, 2007; Matzarakis and Rutz, 2017, 2010). Concerning SOLWEIG, an online
458 manual is available (Lindberg and Grimmond, 2011). There is a wiki and a forum group to help, but
459 SOLENE-Microclimat is dedicated to research so that it is needed to use Python and to be able to
460 change parameters in scripts. ENVI-Met is well documented (Bruse, 2004) concerning its use, but not
461 with regards to the physical modelling. FLUENT-ANSYS is a commercially available software that is
462 largely used in the industry. Publications using the software are numerous (e.g. Chatzidimitriou and
463 Yannas, 2016; Hanna et al., 2006). Nevertheless, applications of this EMM including vegetation are
464 not so common and require specific developments through user defined function (implemented in
465 routines) (Ansys, 2017). It should be noted that both ENVI-met and FLUENT-ANSYS benefit from
466 the support provided by the commercial entities responsible for their developments, for a cost.

467 TEB-Hydro is a part of SURFEX. The structure and the workflow of the calculations of the modelling
468 platform SURFEX, in which the model TEB-Hydro is available, are well documented. The equations
469 and the structure of the TEB-Hydro module are well explained in Chancibault et al., (2014) and
470 Stavropoulos-Laffaille et al., (2018). It will be soon available, in the version 8 of SURFEX. The

471 structure of the URBS-MO and the workflow of calculations is well developed in (Rodriguez et al.,
472 2008). The basic documentation for the water quality evaluation is those of the European WFD, which
473 was transcribed in each European country. The documentation of the national institutions in charge of
474 water management will be the basic sources of information. The specific urban pollutants were
475 selected from French review studies.

476 The structure of Ecotox EM is documented in Huber and Koella, (1993). This method is based on an
477 interpolation log method using the following formula to calculate EC50 value. Direct Interpolation
478 method is similar to interpolation log method but without logarithmic transformation of
479 concentrations. The formula for EC50 calculation is set according to Alexander et al., (1999). Fertility
480 EM is well documented in Vidal-Beaudet et al., (2017). Furthermore, some studies described certain
481 UPIs: SMP (e.g. Bouzouidja et al., 2018b; Jim and Peng, 2012), SCR (e.g. Szymański et al., 2015). A
482 total of 20 institutions from 12 European countries collaborated in establishing the database of
483 HYdraulic PRoperties of European Soils (HYPRES) using textural function method. The structure of
484 textural function method is well documented (e.g. Minasny and McBratney, 2001; Shirazi and
485 Boersma, 1984). SBA EM is very well documented in Keuskamp et al., (2013). At the same time, a
486 site is dedicated to this method⁴.

487 **3.7. Reliability of the Expert Models and Methods**

488 RayMan is well validated by several former studies (among others, (Lin et al., 2010; Matzarakis and
489 Rutz, 2010; Thorsson et al., 2004) that attest RayMan's very good accuracy (Fröhlich and Matzarakis,
490 2013). For example, Thorsson et al., (2004) found that RayMan worked very well during the middle of
491 the day in July, i.e. at high sun elevations. However, the model considerably underestimates MRT in
492 the morning and evening in July and during the whole day in October, i.e. at low sun elevations. In
493 addition, RayMan underestimates MRT during much of the year (autumn, winter and spring) as well
494 as in the mornings and evenings in the summer. In most publications, where SOLWEIG-model was
495 used, field validation exists and is presented (e.g. Chen et al., 2014; Lindberg and Grimmond, 2011).
496 This can be explained by the fact that the main calculated parameter (mean radiant temperature) can be

⁴<http://www.teatime4science.org/method/stepwise-protocol/> (Accessed September, 15 2020).

497 measured with different methods. Concerning SOLENE-Microclimat, different modules have been
498 validated. In particular, attention has been paid to validate the radiative part with comparison with
499 measurements (e.g. Hénon et al., 2012a, 2012b; Idczak et al., 2010). Some modules have also been
500 validated as soil, green wall, building (e.g. Azam et al., 2018; Musy et al., 2015). However, the overall
501 model has not been validated considering the difficulties to measure a wide range of parameters
502 covering different physical problems, on a large number of locations. Several articles were published
503 on the validation of ENVI-met during the last two decades. They also focus on the study of current
504 microclimatic conditions and on the comparative evaluation of the performance of various mitigation
505 strategies for the effect of UHI (among others, (Chatzidimitriou and Yannas, 2016; Chen and Ng,
506 2013; Tsoka et al., 2018; Yang et al., 2011). FLUENT-ANSYS is a standard for CFD studies and has
507 been validated in numerous studies (e.g. Bouhoun Ali et al., 2018; Bournet and Boulard, 2010).
508 Concerning the coupling with vegetation, several validations were performed for cases inside
509 greenhouses (Bouhoun Ali et al., 2019, 2018) and an ongoing study is running to adapt the crop sub-
510 model to urban environments. The validation of TEB model with urban measurements has been
511 carried out since 2000 (Masson, 2000). Different modules have been added (e.g. presence of
512 vegetation) (Lemonsu et al., 2004). Addition of the vegetated roof module (C. De Munck et al., 2013)
513 and the street tree module (Redon et al., 2017) are more recent.

514 TEB-Hydro is evaluated by comparing simulated and observed discharges of three catchments (5 ha,
515 31 ha and 513 ha) included in a French long-term urban observatory (Chancibault et al., 2014;
516 Stavropoulos-Laffaille et al., 2018). The comparison of simulated discharges with observed ones shows
517 an overestimation from the model but a realistic dynamic at a daily scale (Chancibault et al., 2014).
518 URBS-MO has been the subject of some validation studies (Al Ali et al., 2018; Li et al., 2014;
519 Rodriguez et al., 2007, 2008). This work is in progress (data not shown). In order to evaluate this
520 model, it has been applied at two different scales, on two urban catchments of various land use, where
521 hydrological data were available. This evaluation is based on the comparison of observed and
522 simulated flow rates and saturation levels, and details the various compartments (soil, impervious or
523 natural areas) to the outflow (Rodriguez et al., 2007). The adapted method for water quality evaluation

524 is based on the literature on pollutants in storm water (Gasperi et al., 2014) and the European
525 authority regulation implemented in each European country (ex. (French legal decree, 2008)), since
526 the beginning of the 2000s.

527 Several studies have focused on ecotoxicology and used Ecotox EM, particularly in urban areas. This
528 in order to prevent risks to soil organisms (e.g. impact of pesticides) (among others, Ahmed and
529 Häder, 2010; Azizullah et al., 2013), suitability for use groundwater (e.g. Afonso et al., 2010) or an
530 important habitat for rare and unprotected specialized animals (e.g. stygofauna) (Reboleira et al.,
531 2013). In most publications, where Fertility EM was used, field validation exists and is presented
532 (among others, Damas and Rossignol, 2009; Gosling et al., 2013; Vidal-Beaudet et al., 2017). Due to
533 the heterogeneity of texture classification systems around the world, textural classes should be
534 harmonized to the international system. For instance, Minasny and McBratney (2001) observed that
535 the silt texture was not included in the Australian texture classification. They found that the
536 USDA/FAO occupied 60% of the Australian soil texture triangle. The soil texture representation with
537 the standard textural fraction triplet “sand–silt–clay” is commonly used to estimate soil properties. The
538 differences between the texture triangles, in terms of textural classes, come mainly from the soil
539 databases used to build them. The objective of this work was to test the hypothesis that other fraction
540 sizes in the triplets may provide a better representation of soil texture for estimating some soil
541 parameters (Fini et al., 2017). To date, the SBA EM has been used in upwards of 2000 locations across
542 the globe. Studies have validated this method throughout the world (e.g. Marley et al., 2019; Seelen et
543 al., 2019).

544 **3.8. Expert Models and Methods time (preparation and running)**

545 ENVI-met model scenarios may take some time to build. This depends on the size of the cells. A small
546 model with a 65*65*30 grid cells can be prepared and simulated quickly. However, a 24-hour
547 simulation of 250*250*30 grids can take more than a week (Elwy et al., 2018). RayMan is developed
548 for case studies and for operational use for different planning levels (Matzarakis et al., 2007). The
549 advantages of RayMan are the ease of input and the combination of different options in buildings and
550 vegetation properties, fish-eye photographs. RayMan requires a relatively short preparation time and

551 run, however this depends on the data quantum (simulation objective). In general, the users have to
552 perform a complex (time-consuming) preparation of input data. A time-increasing process compared
553 to some other models: the wind speed must be reduced manually before the simulation (Égerházi et al.,
554 2014). Because RayMan can model only the surrounding radiation (e.g. MRT) and bioclimatic indices
555 (e.g. PET), the simulation CPU time is less compared to ENVI-Met. Depending on the amount of data
556 the running time at a given grid point ranges from several seconds to 5-10 minutes (even in case of
557 several-year long databases). The time for SOLWEIG build up can be higher if the input data needs
558 much preparation time by the user (e.g. tree cadastre data for vegetation DSM). In addition, at the
559 micro scale, the running time does not limit the use of it in expert modelling. In terms of build-up,
560 preparation and running time compared to ENVI-met, SOLENE-Microclimat was about 10 times
561 quicker. We can run 2 or 3 weeks simulations in 2 days on a typical workstation. It is important to be
562 able to have different days (different wind directions, radiative conditions, etc.) and to take into
563 account buildings and soil inertia, which requires simulating several days before the period of interest.
564 Users have to attend a specific training to get accustomed to FLUENT-ANSYS EMM. This EMM also
565 requires high knowledge of numerical methods and fluid mechanics. Defining the geometry and
566 building, the grid used for calculation also requires a specific “skill” and some time. Finally, large 2D
567 cases as well as 3D cases may require a high CPU time and computer resources to run. The time is a
568 direct function of the spatial dimensions of the problem as well as the expected level of precision.
569 Concerning TEB, the model build up time depends on the available data quality and the area of the
570 study site. More than two days are useful to build up the model. The running time depends on the
571 resolution, the configuration, and the area of the domain and the length of the simulated period. For
572 example, the simulation of a domain with an area of 75 m² with TEB, at a 1 h resolution forcing time
573 step and a 30 sec numerical time step during 365 days takes 6 minutes.

574 URBS-MO and TEB-Hydro build up time depends on whether the data is available or not and the area
575 of the study site. For both, the running time depends on the resolution, the configuration, the size of
576 the catchment and the simulation period length. For example the simulation with URBS-MO of the
577 Pinsec catchment, in Nantes, France (0.31 km²), 335 parcels, during a simulation period of one year

578 takes three minutes, using a 5 min time step. For the simulation with TEB-Hydro, of a domain with an
579 area of 46 km², at a 200 m × 200 m spatial resolution, a 1h resolution forcing time step and a 5 min
580 numerical time step during 884 days takes a few hours. The water quality evaluation requires water
581 samplings or on-site measurements. Before this step, the study of the urban context is mandatory to
582 determine the target pollutants. Moreover, the hydraulic functioning should be taken into account to
583 optimize the water sampling. This preparation of the sampling/measurement campaigns may be then
584 more time-consuming than the data collection itself.

585 To build up and run Ecotox EM, data has to be acquired first (some of them from databases and others
586 from experiments that may sometimes take time (a few days to a month). The Fertility EM build up
587 and run require relatively little time. However, this time may increase if the preparation of input data
588 takes extra time. Due to its simplicity, the construction time of the Textural function method is less
589 than one minute. In addition, there is no running time if the input data are available. Finally
590 concerning SBA EM, the time required to prepare and analyse the results is 3 days. While the
591 execution time is 90 days (Keuskamp et al., 2013).

592 **3.9. User friendliness**

593 Due to its clear structure, RayMan model can be applied not only by experts in human-
594 biometeorology, but also by people with less experience in this field of science (Matzarakis and Rutz,
595 2010). The presented model provides: (i) diverse opportunities in applied climatology for research and
596 education (Matzarakis and Rutz, 2010), (ii) user friendly windows-based interface (Charalampopoulos
597 et al., 2013) and (iii) the estimation is very flexible and practical (Mahmoud, 2011). RayMan model is
598 a free software and available for general use (Zaki et al., 2020). SOLWEIG-model is now integrated in
599 QGIS (as a part of the UMEP module), which is one of the leading GIS software, used by urban
600 micro-climatologists or green infrastructure experts as well. This makes the usage easy for these
601 experts. The model is freely available (assistance can also be acquired from the developers by
602 University of Gothenburg). SOLENE-Microclimat is free, however difficult to obtain. Training is
603 required to be able to use the model. ENVI-met is not freely available. Different prices exist

604 depending on the use (e.g. educational, research or industrial)⁵. FLUENT-ANSYS is too complex and
605 cannot be used easily without substantial training. In addition, the model is under academic and
606 industrial licences (several thousands of Euros). Academic licence is far cheaper than an industrial
607 licence. Finally, TEB model is a part of the surface modelling platform SURFEX, which is accessible
608 on open source, where the codes of the surface schemes TEB and ISBA can be downloaded from the
609 National Center for Meteorological Research (CNRM) website⁶.

610 For both TEB-Hydro and URBS-MO models, once the EMM built up is realized on a specific site or
611 catchment, their use is rather easy thanks to relevant publications or user's guide. TEB-Hydro is
612 accessible on open source: the codes of the surface schemes TEB and ISBA can be downloaded⁷. The
613 hydrological module TEB-Hydro will be soon available at the same address. URBS-MO is also
614 accessible as an open source. The adapted method for water quality evaluation requires some statistical
615 analysis in optimal conditions of monitoring and a flowchart. It is under development but the code for
616 the WFD calculations is freely available in France.

617 Ecotox EM cannot be used easily because data has to be acquired first (most of them from databases
618 and the others from experiments) that may sometimes take time. Fertility EM is freely available.
619 However, this method needs analysis required to gain data, i.e. physical and chemical properties of
620 soil (e.g. bulk density, soil texture, soil organic matter, total Nitrogen, total carbonates, pH of soil).
621 Textural function method is free, available and open source⁸. Because of the biological aspect, the use
622 of the SBA EM requires knowledge of agronomy and a mathematical basis for solving the equations.

623 **3.10. Scope of application of the models/methods**

624 RayMan Model has been widely used since the two last decades (among others, Charalampopoulos et
625 al., 2013; Égerházi et al., 2014; Fröhlich and Matzarakis, 2013; Gulyás et al., 2006; Hwang et al.,
626 2011; Lindner-Cendrowska and Błażejczyk, 2018; Matzarakis and Rutz, 2010). Concerning
627 SOLWEIG-model, it has been increasingly used in recent years (e.g. Lau et al., 2016; Lindberg et al.,

⁵<https://www.envi-met.com/buy-now/> (accessed September 15, 2020)

⁶<http://www.Cnrm-game-meteo.fr/surfex/> (accessed September 15, 2020)

⁷<http://www.Cnrm-game-meteo.fr/surfex/> (accessed September 15, 2020)

⁸https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167 (accessed September 15, 2020)

628 2018). SOLENE-Microclimat has been mainly used by French research groups since 2006 (e.g. Malys
629 et al., 2015; Morille et al., 2016; Musy et al., 2015; Robitu et al., 2006). FLUENT-ANSYS is largely
630 used from car, plane, chemical processes, greenhouse, livestock building to urban applications, both in
631 industrial and research sectors (Gromke et al., 2015). TEB-model has been used since 2000 but
632 essentially by urban microclimate researchers (De Munck et al., 2013; Hamdi and Masson, 2008;
633 Lemonsu et al., 2004; Redon et al., 2017).

634 TEB-Hydro is derived from two widely used models namely TEB and the soil-vegetation-atmosphere
635 transfer (SVAT) ISBA (Interactions between the Soil Biosphere and Atmosphere) ((Boone et al.,
636 2000; Mahfouf et al., 1995; Masson et al., 2013; Noilhan and Planton, 1989). This EMM is under
637 development (Stavropoulos-Laffaille et al., 2021, 2018). TEB and ISBA tools have been used
638 extensively in recent years ((C. De Munck et al., 2013; Lemonsu et al., 2012; Masson et al., 2013).
639 Concerning URBS-MO model, this EMM is still under development (Li et al., 2014; Rodriguez et al.,
640 2008). Water quality evaluation is extensively done in European countries. The adapted method is a
641 simplified method and should be easily appropriate.

642 Concerning Ecotox EM, this EMM is quite widespread for the ecological risk assessment of polluted
643 soils (Azizullah et al., 2013). Also, in recent years, the Ecotox EM has been successfully applied to
644 assess the toxicity of various common ecosystem pollutants such as pesticides, heavy metals,
645 fertilizers, herbicides, etc. in both short-term and long-term exposure (Ahmed and Häder, 2010;
646 Azizullah et al., 2012). Concerning Fertility EM, this EMM is more and more frequently used in
647 scientific publications in particular in the evaluation of the performance of green roofs and
648 brownfields (e.g. Bouzouidja et al., 2018b; Yilmaz et al., 2018); as well as the analysis of NBSs in
649 urban (Gosling et al., 2013; Lorenz and Lal, 2009). As mentioned above, Textural function method is
650 essential for identifying the physical properties of soils. This EMM has been used for several decades
651 in the study of soils, whether urban, rural or even other types of soils (Minasny and McBratney, 2001;
652 Phinn et al., 2002; Saxton and Rawls, 2006). Finally, SBA EM started to be developed in 2013 and is
653 currently being disseminated throughout the scientific community. In addition, at the time of writing,

654 there have been 99 publications citing Keuskamp et al., (2013), according to Scopus (e.g. Becker and
655 Kuzyakov, 2018; Duddigan et al., 2020; Marley et al., 2019; Ogden, 2017; Seelen et al., 2019).

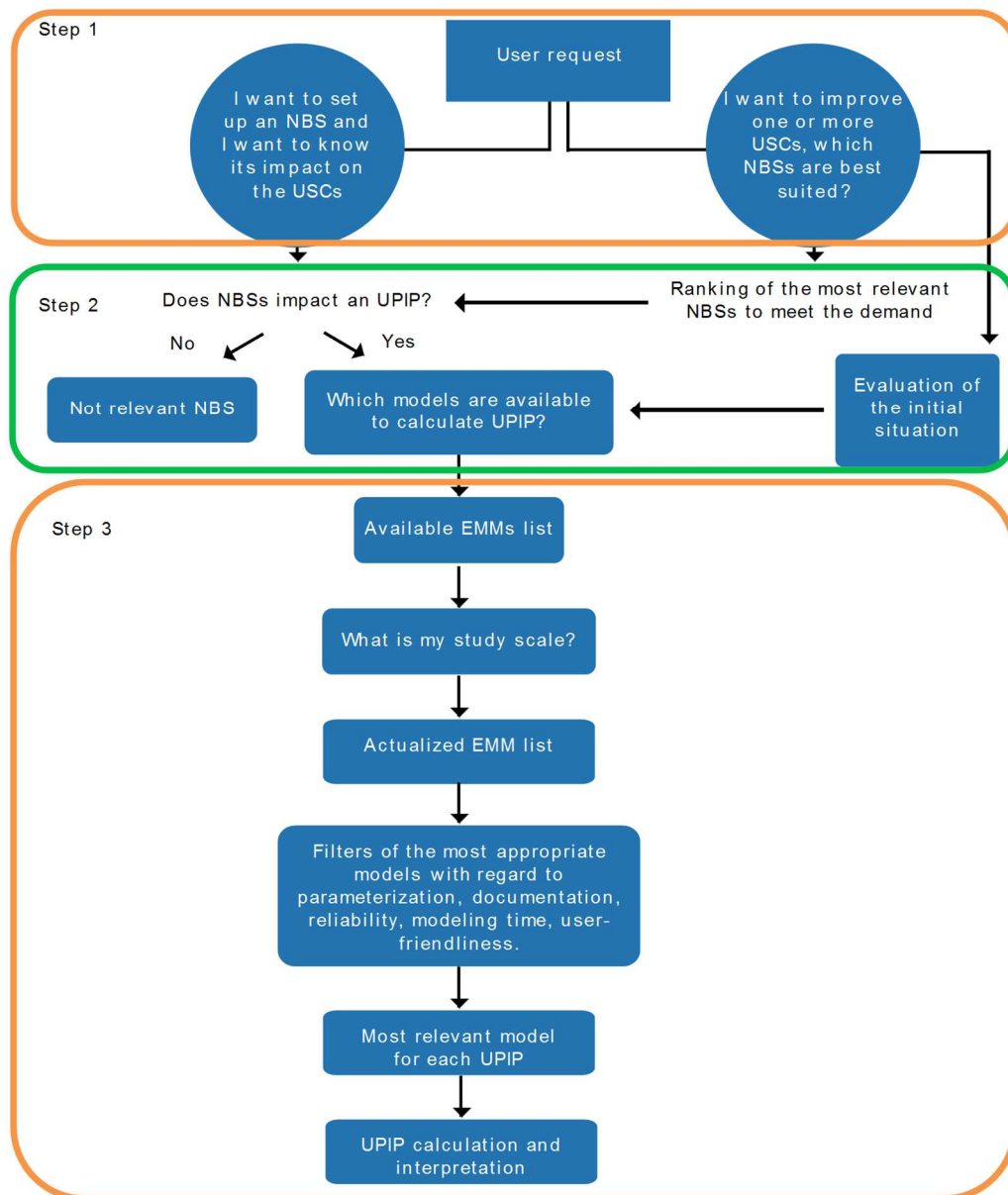
656 **4. Towards the Expert models based decision support systems**

657 The role of Expert model based decision support systems EMB DSS is to underline the enhancement
658 of strategies with scientific evidence and quantitative illustrations to help stakeholders for the
659 sustainable implementation of NBSs in cities. In the wider sense, this work leads to the development
660 of an integrated European reference framework on robust cost-benefit assessment of nature-based
661 solutions. In this way, a flowchart is presented in Figure 2.

662 The first stage of the EMB DSS aims to acquire data on the type of NBS to be characterised and the
663 UCs to be improved. It requires the definition and selection of UCs. Such an approach is carried out
664 through a combination of data collection.

665 The second step is the integration of the data into the first module of the EMB DSS, which aims at
666 identifying the interactions between NBSs and UPIs, as well as the classification of suitable NBSs.
667 This allows to assess the initial status of NBSs with respect to UCSs. This step also allows a first
668 selection of EMMs.

669 Then, the third and last step aims to give a semi-quantitative evaluation, depending on the scale
670 requirement and on the scores of the EMMs in relation to the targeted challenge. This evaluation is
671 determined from a selection of criteria (parameterization, documentation, reliability, modelling time,
672 user-friendliness) relevant for each EMM. These criteria are weighted according to their relevance to
673 the requirements of the EMMs. Finally, this flowchart makes it possible to generate scores (1) to
674 evaluate the relevance of an NBS in a given context, and (2) to propose a selection of NBSs adapted or
675 capable of improving UCs.



676

677 **Figure 2.** The steps for the evaluation of Nature-based solutions (NBSs) capabilities to tackle
 678 urban challenges (UCs) – the Expert model based decision support system (EMB DSS). UPIP
 679 means urban performance indicators pools.

680 **5. Conclusion and outlooks**

681 This study has investigated the main features expected by Expert Models and methods (EMMs) to
 682 improve and therefore optimize the services provided by nature-based solutions (NBSs) in an urban
 683 microclimate, water and soil context. After a categorization of EMMs tools that may be applied to

684 NBSs evaluation in cities, the various tools developed in Nature4Cities (N4C) project have been
685 labelled along with the various spatial cases and their ability to evaluate NBSs performance.

686 Key findings are:

687 - for each urban scale (object, neighbourhood/district, and city), specific EMMs have been proposed,
688 in relation with several relevant Urban Performance Indicators (UPIs). Although the studied EMMs
689 are not exhaustive, and could be replaced by specific tools proposed by other research teams, the tools
690 proposed here are totally relevant and advanced in the field of the main urban challenges treated
691 here, *i.e.* climate, water and soil management.

692 - A specific toolbox has been developed, regrouping the different EMMs. This decision support
693 system called EMB DSS, as “Expert Model based decision support system”, is innovative through its
694 multi-disciplinary co-construction between urban micro climatologists, urban hydrologists and soils
695 scientists. Thanks to a smart description and linkage of UPIs, urban challenges and NBSs features, this
696 DSS makes it possible to assess the *ecosystem services* provided by NBSs, including (i) reduction of
697 urban heat island; (ii) limitation of surface warming; (iii) increase of the thermal comfort of people;
698 (iv) limitation of the overheating and runoff of surfaces due to their imperviousness and the use of
699 materials that favour energy storage; (v) increase of the water retention during stormy episodes, (vi)
700 improvement of surface storm water quality at the outlet of the NBS; (vii) promotion of the filtration
701 and epuration of urban water and (viii) support in order to guide managers in the decision-making
702 processes required for the sustainable construction of urban areas

703 There are, however, a number of key issues deserving more attention in the forthcoming N4C project
704 and opening specific perspectives and future developments:

705 ● The spatial scale definition is hard to explain and to delineate as a result of the consideration
706 of various themes (climate, water and soil). In addition, all European town and even more
707 international ones (administration aspects) and cities were not designed in the same way and
708 do not have the same history. For example, the planning practices of European countries also
709 differ in this aspect. This point may be an issue for the NBSs assessment.

710 ● When soil methods are studied, data should be representative over the soil profile (or at least
711 over a depth of several decimeters), rather than just over a thin layer at the soil surface.

712 Future developments should be tested in situ on contrasted situations before being used by managers,
713 planners and operators. A further step would be to launch, in addition to this mutual work between
714 experts in climate, water and urban soil, a collaboration with economists and ecologists to improve the
715 evaluation of NBS performance in urban areas.

716 **Credit author statement**

717 All co-authors contributed equally to conceptualize and write the paper.

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