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1 A research agenda for the future of urban water 2 management: Exploring the potential of non-grid, 3 small-grid, and hybrid solutions

4 *Sabine Hoffmann*[†], *Ulrike Feldmann*[†], *Peter M. Bach*^{†,‡,§},
5 *Christian Binz*^{†,±}, *Megan Farrelly*[#], *Niki Frantzeskaki*^{¥,||},
6 *Harald Hiessl*[↑], *Jennifer Inauen*^{†,Ⓕ}, *Tove A. Larsen*[†], *Judit*
7 *Lienert*[†], *Jörg Londong*[‡], *Christoph Lüthi*[†], *Max Maurer*^{†,‡},
8 *Cynthia Mitchell*^{†,‡}, *Eberhard Morgenroth*^{†,‡}, *Kara L. Nelson*[‡],
9 *Lisa Scholten*[↑], *Bernhard Truffer*^{†,↑}, *Kai M. Udert*^{†,‡}

10 † Eawag, Swiss Federal Institute for Aquatic Science and
11 Technology, 8600 Dübendorf, Switzerland

12 ‡ ETH Zürich, Institute of Environmental Engineering, 8093
13 Zürich, Switzerland

14 § Monash Water for Liveability, Department of Civil
15 Engineering, Monash University, Clayton, 3800 VIC, Australia

16 ± Circle, Centre for Innovation, Research and Competence in
17 the Learning Economy, Lund University, 221 00 Lund, Sweden

18 # School of Social Sciences, Monash University, Clayton, 3800
19 VIC, Australia

20 ¥ Centre for Urban Transitions, Swinburne University of
21 Technology, Hawthorn, VIC 3122, Australia

22 || Drift, Dutch Research Institute For Transitions, Erasmus
23 University Rotterdam, 3062 PA Rotterdam The Netherlands
24 † Fraunhofer Institute for Systems and Innovation Research ISI,
25 76139 Karlsruhe, Germany
26 ‡ Institute for Psychology, University of Berne, 3012 Berne,
27 Switzerland
28 † Faculty of Civil Engineering, Bauhaus University, 99421
29 Weimar, Germany
30 § Institute for Sustainable Futures, University of Technology
31 Sydney, Ultimo NSW 2007, Australia
32 ¶ Department of Civil & Environmental Engineering, University
33 of California at Berkeley, Berkeley, California 94720, United
34 States
35 ¶ Delft University of Technology, 2628 CN Delft, The
36 Netherlands
37 ¶ Faculty of Geosciences, University of Utrecht, 3584 CS
38 Utrecht, The Netherlands
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40 **Abstract**

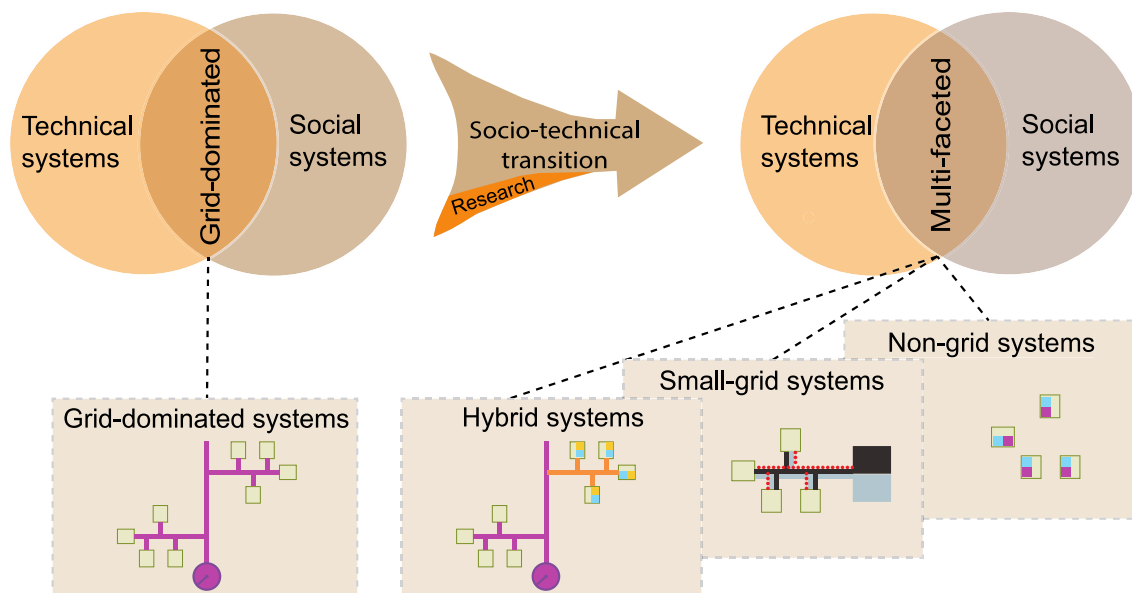
41 Recent developments in high- and middle-income countries have
42 exhibited a shift from conventional urban water systems to
43 alternative solutions that are more diverse in source
44 separation, decentralization, and modularization. These
45 solutions include non-grid, small-grid, and hybrid systems to

46 address such pressing global challenges as climate change,
47 eutrophication, and rapid urbanization. They close loops,
48 recover valuable resources, and adapt quickly to changing
49 boundary conditions such as population size. Moving to such
50 alternative solutions requires both technical and social
51 innovations to co-evolve over time into integrated socio-
52 technical urban water systems. Current implementations of
53 alternative systems in high- and middle-income countries are
54 promising, but they also underline the need for research
55 questions to be addressed from technical, social, and
56 transformative perspectives. Future research should apply a
57 transdisciplinary research approach through socio-technical
58 “lighthouse” projects that apply alternative urban water systems
59 at scale. Such research should leverage experience from
60 lighthouse projects in a range of socio-economic contexts,
61 identify their potentials and limitations from an integrated
62 perspective, and share their successes and failures across the
63 urban water sector.

64 **Keywords**

65 Urban water management, non-grid systems, small-grid systems,
66 hybrid systems, research agenda, transdisciplinary integration

67 **Graphical Abstract**



68

69

70 1. Introduction

71 Cities in high- and middle-income countries generally rely on
72 centralized systems to provide vital water services,¹ including
73 water supply, urban hygiene, urban drainage, and water pollution
74 control.² These services are usually provided through networks
75 of buried pipes, termed grids, which connect users to sources of
76 water and sinks for wastewater.³ Such conventional systems are
77 characterized by strong path dependencies and technological and
78 institutional lock-in effects,⁴ which usually undergo
79 incremental changes rather than radical transformations.⁵
80 However, incremental changes are not sufficient to meet such
81 current and future challenges in the urban water sector as rapid
82 urbanization, urban sprawl, eutrophication, climate change,
83 resource scarcity, and aging infrastructure.⁶

84 Alternative urban water systems have been studied in research,⁷⁻⁹
85 discussed in policy,¹⁰⁻¹² and implemented in practice.¹³⁻¹⁵
86 Alternative solutions include potable and non-potable water
87 reuse,¹⁶ source separation, decentralization,¹⁷ and the
88 modularization of treatment systems comprising small-scale,
89 mass-produced, standardized, and automated technology
90 components.^{18, 19} These alternatives address pressing urban water
91 challenges by closing loops, recovering valuable resources, and
92 involving infrastructures that can easily adapt to changes in
93 boundary conditions such as population size.

94 Although promising alternative urban water systems have been
95 developed in recent decades, their market applications remain
96 limited to a few places worldwide.²⁰ Pilot applications have been
97 implemented in major cities such as San Francisco,²¹ Melbourne,
98 Sydney,²² Hamburg,²³ Beijing,^{24, 25} Bangalore,²⁶ and Zurich.²⁷ Recent
99 developments in high- and middle-income countries have thus
100 shown an emergent shift from conventional urban water systems to
101 alternative solutions that are more diverse in source
102 separation, decentralization, and modularization.

103 This shift towards alternative solutions implies far-reaching
104 changes to the urban water sector. Technologies are highly
105 intertwined with institutions²⁸ and involve mutual
106 interdependence between technical and social structures. Both
107 need to transform and co-evolve over time into new and stable
108 "configurations that work"²⁹ to continue safe and reliable
109 service provision while tackling emerging challenges.³⁰ The

110 complexity, ambiguity and uncertainty of such socio-technical
111 transition calls for the “constructive combination or
112 integration”³¹ of a wide range of perspectives from research,
113 policy, and practice in ways that are best addressed by
114 transdisciplinary approaches.³² Such approaches transcend
115 disciplinary boundaries (interdisciplinarity) while spanning
116 research, policy, and practice (transdisciplinarity). They are
117 intended to advance fundamental understanding of current and
118 future challenges to urban water management, to generate
119 promising solutions,³³ and to enable mutual learning between
120 research, policy, and practice.³⁴

121 In this paper, we explore the challenges to and opportunities
122 for a transition to alternative urban water systems in high- and
123 middle-income countries. Recent studies have (i) discussed the
124 need to design, operate, and manage urban water systems in
125 fundamentally different ways,^{8, 35} (ii) scrutinized promising
126 alternative solutions,^{7, 36} and (iii) analyzed barriers to change
127 in the urban water sector.^{28, 37} However, few studies have outlined
128 a transdisciplinary research agenda that discusses key research
129 questions from technical, social, and transformative
130 perspectives, and across interrelated macro, meso, and micro
131 levels. Integrating these perspectives and levels advances our
132 understanding of the complexity of both alternative socio-
133 technical systems and socio-technical transitions in the urban
134 water sector.

135 We therefore synthesize the discussion from a high-level expert
136 workshopⁱ attended by experts from process engineering,
137 environmental engineering, transitions studies, innovation
138 studies, decision analysis, governance studies, environmental
139 studies, social psychology, and transdisciplinary research. The
140 discussion identified key research questions from technical,
141 social and transformative perspectives at three levels: (i)
142 macro, relating to formal and informal rules and regulations and
143 long-term transformations of technological paradigms and
144 societal beliefs; (ii) meso, relating to the spatial
145 organization of technical systems and their governance
146 structures; and (iii) micro, relating to technological
147 components, individual actors, and short-term transformations.
148 We conclude by reflecting critically on the challenges we faced
149 while integrating diverse disciplines and fields in a single
150 research agenda.

151

152 **2. Recognizing the diversity of technical systems**

153 To discuss technical alternatives to today's conventional
154 systems, we define both the extreme solutions, grid-dominated
155 and non-grid, and the intermediate solutions, small-grid and
156 hybrid. Grids are constituent elements of today's centralized
157 systems, whose capital expenditure on pipes and sewers typically
158 amounts to 70-80%, leading to technological lock-in effects.³⁸
159 We define non-grid systems as systems without pipes or sewers
160 between individual buildings, but with piping within buildings

161 and on premises, and small grids as systems with sewers and pipes
162 between a smallⁱⁱ number of individual buildings. Both non-grid
163 and small-grid systems are modular structures that can be
164 upscaled and downscaled to meet changing boundary conditions,
165 thus reducing the lock-in effects observed in grid-dominated
166 systems. Hybrid systems integrate non-grid and small-grid
167 solutions into grid-dominated systems, such as non-grid or
168 small-grid treatment of urine within conventional systems (see
169 Figure 1).^{2,39}

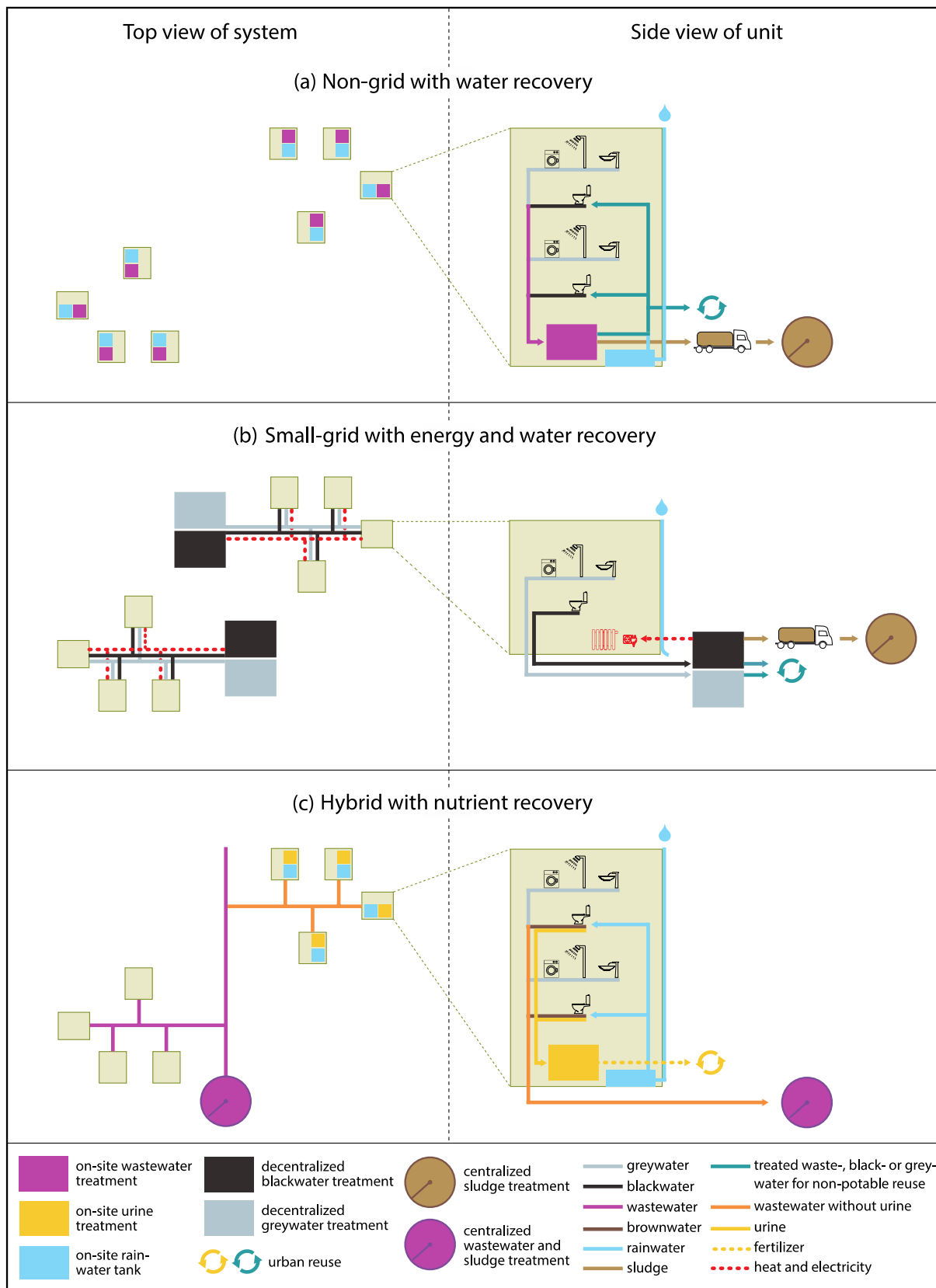
170 We discuss the technical systems at the macro, meso, and micro
171 levels. The macro level defines the services that urban water
172 systems are expected to provide, the meso level the spatial
173 organization of alternative systems, and the micro level the
174 individual technologies. All three levels are interrelated. Our
175 discussion excludes the variety of well-established alternative
176 stormwater systems that are flexibly adapted to non-grid, small-
177 grid, and hybrid systems (collectively known as Water Sensitive
178 Urban Design, Low Impact Development, and other terms⁴⁰), as that
179 field has progressed significantly in recent decades.^{41, 42} This
180 progress has enabled research on stormwater management to shift
181 its focus to maximizing the multiple benefits of stormwater
182 systems with best planning practices⁴² and ensuring their
183 compatibility with alternative water and wastewater systems.⁴³

184

185

- Figure 1 -

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190 **Figure 1.** Schematic visualization of (a) non-grid, (b) small-
191 grid, and (c) hybrid urban wastewater systems (left column: top
192 view) and units (right column: side view) based on empirical
193 examples: (a) Beijing, China:^{24,25} non-grid systems without sewers
194 between individual buildings but with pipes inside buildings.
195 Blackwater (e.g. from toilet) and greywater (e.g. from sinks,
196 showers, washing machines or dishwashers) is collected in a
197 single wastewater stream and treated on-site for non-potable
198 reuse inside and outside individual buildings (e.g. toilet
199 flushing, irrigation, and/or infiltration for aquifer recharge).
200 Sludge is collected by trucks and treated in centralized sludge
201 treatment plants. Rainwater is harvested and used for toilet
202 flushing. (b) Hamburg, Jenfelder Au, Germany:²³ small-grid
203 systems for groups of individual buildings with different pipes
204 for source-separated wastewater streams. Blackwater and
205 greywater are collected and treated separately in decentralized
206 treatment plants. Treated greywater is reused outside buildings.
207 Energy is recovered from blackwater as heat and electricity and
208 used in buildings. Sludge is collected by trucks and treated in
209 centralized sludge treatment plants. (c) Eawag, Zurich,
210 Switzerland:²⁷ hybrid systems integrate non-grid and small-grid
211 solutions into a grid-dominated system. Brownwater (e.g. from
212 toilets, but without urine) and greywater is collected in a
213 single wastewater stream and treated in a centralized wastewater
214 treatment plant. Urine is collected through urine-diverting
215 toilets and treated on-site. Urine is transformed into

216 fertilizer for reuse in urban agriculture⁴⁴. Rainwater is
217 harvested and used for toilet flushing.

218

219 **Services of urban water management (macro level)**. The services
220 that urban water systems are expected to provide are generally
221 defined at the macro level.² Formal rules of service provision
222 are commonly set by states and nations and are typically informed
223 by international trends. Although in theory no technical
224 decisions are taken at the macro level, it provides the
225 boundaries for the technology choices at the meso and micro
226 levels. In practice, technical decisions are sometimes
227 effectively taken at the macro level due to, for instance,
228 requirements for secondary treatment (e.g., the provisions of
229 the US Clean Water Act).

230 In the 19th century, decision-makers identified urban hygiene
231 as the main service to be delivered, leading to the installation
232 of sewers, with unintended detrimental effects on water quality.
233 In the 20th century, water pollution control was added, resulting
234 in the construction of wastewater treatment plants.⁴⁵ Towards the
235 end of the 20th century, authors started to discuss the
236 sustainability of urban water management.^{2,46} In the 21st century,
237 the focus on sustainability appears to be contributing to a shift
238 towards incorporating urban water management into the evolving
239 circular economy.⁴⁷⁻⁵⁰ The circular economy involves resource
240 recovery from wastewater, primarily water, energy, and
241 nutrients, as an additional service while balancing service

242 goals and overall resource efficiency, such as energy demand for
243 alternative technologies.² Water reuse opportunities are usually
244 found at household and industry level as substitution of other
245 water sources,⁵¹ at city level for recreational and ecological
246 purposes and cooling,⁵² and at landscape level for streamflow
247 augmentation⁵³ and agricultural irrigation.⁵¹ Energy reuse is
248 typically relevant in households in the recovery of heat and
249 treatment facilities in the recovery of chemical energy from
250 sludge as heat or electricity.⁵⁴ Nutrient reuse can be found at
251 all levels from gardens to large-scale agriculture. The wider
252 the variety of services that urban water systems are expected to
253 provide, the more challenging service provision becomes. The
254 complexity of ensuring hygiene in on-site water provision from
255 greywater exemplifies this challenge well.⁵⁵

256 **Spatial organization of urban water management (meso level).**

257 The spatial organization of urban water services, including
258 system type, system size, and mixing of water flows are all
259 defined at the meso level. The integration of such services with
260 other sectors and their services, such as energy supply and food
261 supply, is also determined at this level. The meso level provides
262 some of the most obvious arguments for alternative urban water
263 systems: conventional grid-dominated systems require sufficient
264 financial capital, long planning horizons, stable institutions,
265 and sufficient water resources.⁷ In many low- and middle-income
266 countries, few or none of these conditions prevail, and even in

267 high income countries, sufficient financial capital and water
268 resources are not always available.⁵⁶

269 However, even where such conditions are met, new demands for
270 resource recovery services increase the demand for alternative
271 solutions. It is often advantageous to recover resources from
272 less diluted sources (e.g. nutrients from urine) or less
273 contaminated ones (e.g. water from greywater). This may result
274 in greater demand for source separation (see Figure 1),^{7,57} which
275 can best be realized by means of non-grid or small-grid systems.
276 Similarly, streamflow augmentation of small water courses with
277 treated wastewater may lead to more widely distributed treatment
278 systems.⁵³ Progress in such digital technologies as wireless
279 communication, automation, and remote sensing, monitoring, and
280 controlling support radically different approaches to urban
281 water management⁵⁸ and allow distributed non-grid or small-grid
282 systems to be operated remotely and semi-automatically.⁵⁹

283 However, the technological lock-in effects of legacy
284 infrastructure, make it likely that, in the short term, non-grid
285 and small-grid solutions will be implemented in new development
286 areas or integrated into existing grid-dominated systems,
287 resulting in increasing system hybridization.³ In the long term,
288 alternative systems have the potential to disrupt the urban water
289 sector, resulting in deeper sectoral transformation, discussed
290 further below.

291 **Single technologies (micro level).** Most research on and
292 development of alternative urban water systems take place at the

293 micro level, mainly as on-site or small-scale technologies for
294 treating combined or source-separated domestic wastewater.
295 Source separation requires different treatment technologies for
296 greywater, blackwater, urine, and feces¹⁷. Such technologies face
297 specific challenges, such as robustness and ease of maintenance,
298 and may rely on new types of interfaces, such as urine-separating
299 toilets.

300 Hybridizing existing technologies for multiple purposes both
301 creates economic incentives and furthers system flexibility.
302 Much can be learnt from research on alternative stormwater
303 systems,^{41,43} including the adaptability of existing nature-based
304 systems for wastewater and greywater treatment (e.g. subsurface
305 constructed wetlands⁶⁰ and dual-mode biofilters⁶¹) to provide
306 additional local amenity benefits. The integration of treatment
307 or resource recovery in single household devices, such as
308 recycling showers⁶² offer an alternative to intra-household
309 grids. However, they require close collaboration between
310 research and industry to meet the increasing complexity of
311 designing, installing, and operating these systems.

312

313 **3. Acknowledging the key role of social contexts**

314 Strong lock-in effects occur also at the social level.²⁸ Moving
315 from grid-dominated systems to non-grid, small-grid, and hybrid
316 solutions implies far-reaching changes in social contexts. These
317 contexts involve two distinct elements: actors and institutions.
318 Actors comprise the firms, utilities, universities, policy

319 makers, users, and non-government organizations involved in
320 designing, operating, managing, regulating, and using urban
321 water systems. Institutions set the "rules of the game" that
322 shape actors' behaviors and thus condition the opportunities for
323 and barriers to innovation.⁶³ Institutions come in numerous
324 forms, ranging from formal regulations, such as laws and water
325 quality standards, to more intangible rules, such as cultural
326 norms on how to properly use a toilet, and cognitive frames,
327 such as "ways of doing things" in a wastewater utility.⁶³ These
328 institutional characteristics interact and reinforce each other
329 and thus maintain overall stability. Consequently, alternative
330 urban water management approaches challenge widely held and
331 deeply embedded societal norms, regulations, and beliefs.

332 Developing, diffusing, and adopting alternative urban water
333 systems requires a series of institutional changes at various
334 levels. These include adapting existing laws, regulations, and
335 health standards at national and international levels, urban
336 planners and architects rethinking urban design, utility staff
337 and treatment equipment suppliers embracing new business models,
338 and users adjusting their behavior to new technologies and
339 interfaces. The scale and diversity of these reconfigurations
340 highlight the multi-dimensional, interconnected, and context-
341 specific character of the transitions required. This implies
342 that even if public and private stakeholders agree to transform
343 urban water management, they will be confronted with
344 considerable path dependencies and unintended consequences at

345 all levels, similar to those of the technical systems discussed
346 above.

347 **Changing widely-held societal norms, regulations and beliefs**
348 **(macro level)**. Widely-held cultural norms, regulations and
349 beliefs need to be identified that influence the success or
350 failure of alternative systems. The urban water sector depends
351 on a particularly strong set of 'taken-for-granted'
352 technological paradigms and societal beliefs that stabilize the
353 currently prevalent system.⁴⁵ Scholars have long called for
354 unpacking macro-level institutional black boxes, such as global
355 industry structures dominated by large firms and donors, the
356 "yuck factor" most cultures associate with water reuse, and the
357 globally standardized curricula for civil engineers, which
358 strongly prioritize conventional grid-dominated systems. To
359 date, few studies have examined whether, where, and how such
360 macro structures exert their influence and how innovative actors
361 may circumvent institutional barriers when pursuing alternative
362 solutions. A key challenge in this respect is the socio-technical
363 complexity and spatial diversity of alternative systems, which
364 blur traditional operational scales, boundaries, and actors'
365 roles and responsibilities.⁶⁴

366 To date, research in this field has focused on defining
367 institutional design principles,⁶⁵ ⁶⁶ benchmarking change
368 processes,¹ mapping legitimation processes,²¹ and assessing
369 institutional capacity for change.⁶⁷ Overall, this body of work
370 is scattered and has overlooked some core research areas,

371 particularly in global water governance structures, interactions
372 between actors, institutions, and technologies,⁶⁸ and policy
373 mixes that may support the diffusion of alternative solutions in
374 various socio-economic settings. For instance, case studies
375 examining the success or failure of the systems in Beijing,
376 Hamburg, and Zurich emphasize context-specific institutional
377 barriers while downplaying path dependencies that looked similar
378 across all cases.⁴⁵ Future research should generate deeper
379 understandings of the macro-level dynamics that shape and
380 enforce the formal rules governing who, how, and how well urban
381 water systems are managed.

382 **Reforming organizations, industry, and governance structures**
383 **(meso level)**. Moving to alternative systems also implies changes
384 within and across organizations, industry, and economic
385 incentive structures. Firms providing conventional systems
386 reportedly struggle with radically novel business models and
387 service structures for alternative systems.⁶⁹ As these systems
388 mature, start-ups and spin-offs may increasingly disrupt the
389 incumbents' income streams while maintaining or even improving
390 the overall service level for end users.^{70, 71} While considerable
391 spatial variety exists, adapting the internal organization,
392 innovation structures, and income streams of traditional firms
393 and utilities to alternative solutions is far from
394 straightforward.³⁷

395 Consequently, the economic feasibility and social impacts of
396 alternative solutions need to be better understood. Their multi-

397 dimensional costs and benefits have strong implications for
398 finding the optimal degree of decentralization in diverse
399 spatial and socio-economic contexts.⁷² Likewise, policy makers
400 will have to rebalance the allocation of public and private costs
401 and benefits in the urban water sector.²² Important policy
402 questions about the environmental impact and social equity of
403 different socio-technical system designs arise here,⁷³ in
404 particular whether and how alternative solutions can contribute
405 to guaranteeing equitable access to urban water services.

406 Another open question concerns how to effectively organize the
407 operation and maintenance of alternative solutions. Several
408 promising niche experiments have implemented alternative systems
409 at scale in San Francisco,²¹ Beijing,^{24,25} Bangalore,²⁶ and various
410 European^{23,27,} and Australian cities.^{9, 69} The results of these
411 early initiatives are mixed, but they highlight the lack of any
412 systematic evaluation and categorization of the organizational
413 challenges that they face or of governance structures and
414 regulative frameworks that are conducive to innovation while
415 protecting public health and vulnerable societal groups.

416 **Changing behaviors and routines (micro level)**. Moving away from
417 conventional grid-dominated systems requires that a broader
418 range of stakeholders engage in ensuring that alternative
419 solutions are accepted, adopted, and safely managed. While some
420 alternative systems may operate in a fully automated way, in
421 most cases individuals, households, utility practitioners,
422 private businesses, and regulators will have to become more

423 involved in using and managing such systems. Part of the
424 challenge thus involves encouraging and empowering a shift in
425 key stakeholders' daily routines and practices. For instance,
426 how can users be motivated to become more involved in investing,
427 installing, adopting, operating, and managing the systems and
428 changing their behaviors and routines? To answer this question,
429 a nuanced understanding of (i) contextual expectations about the
430 role of government, (ii) contemporary societal norms and values
431 related to conventional urban water management, and (iii) users'
432 perceptions and understandings of alternative systems is
433 required. Such insights provide detailed insights into the
434 variety of psychological drivers, objectives, and motives for
435 adopting and maintaining new technologies. Such understanding
436 assists in designing suitable, context-specific interventions
437 that encourage the acceptance and safe management of alternative
438 solutions.⁷⁴ For instance, public commitment may enhance people's
439 use of alternative solutions.⁷⁵

440 A key challenge for research in this area is that relatively
441 few non-grid, small-grid, and hybrid systems have been
442 implemented to date. Therefore, previous research has mostly
443 focused on community acceptance and emotional responses,^{76,77} but
444 studies associated with (i) defining and allocating rights and
445 responsibilities related to alternative systems and (ii) using
446 and maintaining such systems in the long term are scarce from
447 either user or utility perspectives. Future research will
448 benefit from experimental studies on implemented pilot systems

449 by acquiring knowledge of the long-term use and maintenance⁷⁸ and
450 the rights and responsibilities associated with them. For
451 example, a psychological analysis of why urine-separating
452 toilets were accepted at the Eawag headquarters in Switzerland
453 but were not in similar buildings in Germany would be a highly
454 interesting research endeavor.

455

456 **4. Managing socio-technical transitions: An integrative and** 457 **dynamic perspective**

458 As argued in the preceding sections, the future pervasiveness
459 of alternative solutions will depend not only on the availability
460 of new technical configurations and suitable institutional
461 arrangements but also on their alignment. Thus, the timing and
462 co-management of innovation processes becomes crucial. The
463 challenge is to inquire into conditions for transitioning the
464 entire socio-technical system towards a more multi-faceted urban
465 water sector.²⁹ Maintaining existing services while enabling
466 radical shifts in the way urban water services are provided
467 requires the formulation of long-term visions^{2, 79} and context-
468 sensitive implementation of alternative systems.

469 These kinds of transitions have to be analyzed at two levels:
470 (i) In the short term, new solutions have to be implemented in
471 protected niches⁸⁰ that enable testing of and learning from
472 alternative systems under current technical and institutional
473 conditions; (ii) in the longer run, lessons learned from such
474 experience need to be mainstreamed. During this transition,

475 different types of learning by utilities, technology providers,
476 governments and users will be essential. First-order learning
477 about facts ("Are we doing things right?") is required for
478 improving the efficiency of the new systems under otherwise
479 unchanged technical and institutional conditions. Second-order
480 learning about "taken-for-granted" beliefs ("Are we doing the
481 right things?") is necessary for expanding the field of
482 alternatives. Third-order learning about underlying assumptions,
483 theories, paradigms, and principles ("How do we decide what is
484 right?") is essential for enabling deep shifts in policy
485 priorities and institutional frames,⁸¹ as is underway in the
486 renewable electricity sector. First-order and second-order
487 learning will be more prominent in short-term transformation,
488 while in the longer term, third order learning will become
489 increasingly prevalent.⁸²

490 **Implementing multi-faceted urban water systems under current**
491 **sectoral conditions.** In the short term, research has to focus on
492 whether and how current utilities, regulators, consultancies,
493 and users are able to implement alternative solutions. New ways
494 of participatory planning and experimental implementation of
495 alternative solutions have to be developed alongside the
496 prevailing grid-dominated systems. Often, the implementation of
497 alternative solutions will depend on protected spaces that
498 shield actors from the path dependencies of the centralized
499 system. In Beijing^{24, 25} and Bangalore,²⁶ such protection stemmed
500 from city and state regulations, in San Francisco²¹ and Hamburg²³

501 from utilities that pro-actively promoted experimental
502 approaches. The alternatives developing in such protected niche
503 contexts directly challenge the competencies, routines, and
504 organizational structures of existing water utilities,
505 regulators, and users.⁶⁹ Widespread implementation will require
506 first-order and second-order learning for many actors across
507 different organizations and decision levels. Research should
508 deal with how innovation management can be improved within the
509 water sector, such as by creating protected spaces. It should
510 also focus on how the water sector can tap into synergies with
511 other sectors, such as energy and waste, to overcome the silo
512 effect.⁸³

513 Insights from the energy and waste sectors' past experiences
514 and responses to similar challenges could be highly instructive
515 for urban water management.²⁰ In particular, contextual studies
516 are required to characterize change processes that have enabled
517 or hindered innovations alongside prescriptive methods that
518 induce or facilitate these change processes. Approaches already
519 exist in various areas of political and organization science⁸⁴⁻⁸⁶
520 and in decision and management science⁸⁷⁻⁹¹ to describe, analyze,
521 plan, and evaluate various transition pathways from the existing
522 centralized systems to more multi-faceted urban water systems.
523 These approaches include models for assessing spatial
524 infrastructure systems, for instance by integrating geographical
525 data, methods for reliably eliciting decision-makers'
526 priorities,⁹² and tools for analyzing and comparing system

527 alternatives.⁹³ Moreover, research accompanying niche experiments
528 is critical to tracking learning processes and identifying key
529 conditions for upscaling and mainstreaming alternative
530 solutions. The research should focus on how different aspects of
531 socio-technical systems, including innovation management,
532 business models, regulation, pricing models, and user behaviors,
533 can be developed in a balanced way.

534 **Supporting the mainstreaming of multi-faceted urban water**
535 **systems.** The co-evolution of technical and social systems into
536 socio-technical “configurations that work”²⁹ is complex. This
537 complexity requires the capacity to revisit and revise
538 fundamental assumptions: third-order learning.⁸² Here, the role
539 of researchers is to anticipate and evaluate emergent trends
540 among diverse sectoral stakeholders.⁹⁴ We can expect that as
541 alternative systems mature, prices for modular technologies will
542 drop as a result of mass manufacturing (“economies of numbers”),¹⁸
543 utilities and firms will establish robust business models and
544 operational procedures, technical standards will be codified,
545 and regulators will learn how to deal with more widely
546 distributed systems. Based on insights from the transition
547 literature⁶ and recent experiences with the energy transition,
548 we can expect that these transformations will occur very rapidly
549 once sufficient momentum has accumulated.

550 A key research challenge in this area is to specify longer-run
551 needs and opportunities. This relates mostly to leveraging
552 current and assessing longer-term transformation pressures that

553 will act on the sector, including climate change, shifts in
554 demand patterns and societal values, and rapid urbanization and
555 socio-economic change. Futures methods, such as scenario
556 analysis, are useful in addressing uncertainties related to such
557 pressures.^{90, 91, 95} Several key research questions emerge from this
558 challenge: How can visions and long-term transition strategies
559 for municipalities, regions, and entire countries be identified
560 and formulated? What kind of political power struggles will
561 emerge once the sector's income and actor structures are deeply
562 transformed? How can funding priorities of urban, national, and
563 international governments and donors be adapted in favor of
564 alternative solutions? How can incremental change induce the
565 transition from one system state to another, and how can this
566 transition be steered? And, finally, what can be learned from
567 experience around the globe in transforming urban water systems?

568

569 **5. Towards an integrative research agenda**

570 Considering the technical, institutional, and transition
571 challenges and opportunities outlined above, we summarize the
572 path forward for future research on urban water management as
573 key research questions (see Table 1).

574 A key insight from our discussion is that experimentation in
575 isolated pilot projects is not enough to mainstream alternative
576 urban water systems. Future research should use a
577 transdisciplinary approach to generating evidence through socio-
578 technical "lighthouse" projects that apply alternative urban

579 water systems at scale, such as across a whole city district,
580 and thus engage research, policy, and practice in joint learning
581 processes. Such research should highlight drivers of and
582 barriers to innovation and demonstrate the potentials and
583 limitations of alternative systems from an integrated socio-
584 technical system perspective. It should also leverage experience
585 from lighthouse projects in diverse socio-economic contexts,
586 document this experience, and share successes and failures in
587 research, policy, and practice across the urban water sector.

588 To our knowledge, many potential "lighthouse" projects are
589 emerging in cities as diverse as San Francisco, Bangalore, and
590 Hamburg with highly context-sensitive drivers and niche actors.
591 However, system knowledge remains scattered and tacit and is not
592 systematically compared. Yet, such cross-contextual knowledge
593 exchange and mutual learning is of crucial importance to spurring
594 global innovations within the water sector and to accelerating
595 the evolution, diffusion, and general validation²¹ of alternative
596 urban water systems. We thus encourage international non-
597 government organizations, city networks, and donors to engage in
598 increased strategic networking and in facilitating cross-
599 contextual knowledge exchange and mutual learning about the most
600 relevant successes and failures, for instance through IWA
601 Specialist Groups, C40 Cities Networks, and capacity building
602 programs from such development partners as the World Bank.

Table 1. Summary of open research questions to be addressed in future research on alternative urban water systems

	Macro level	Meso level	Micro level
Technical perspective	<p>How can urban water services be defined to reflect the specific challenges of the 21st century?</p> <p>How can these new defined services be translated into ideal combinations of non-grid, small-grid, hybrid, and grid-dominated systems at the meso level and new technical developments at the micro level?</p>	<p>How can ideal combinations of non-grid, small-grid, hybrid, and grid-dominated systems be determined for given contexts? Which degree of source separation, decentralization and modularization is optimal? How can different systems be integrated into a coherent system of systems?</p> <p>How can digital technologies support remote and semi-automatic operation of a large number of distributed treatment systems?</p>	<p>How can on-site and small-scale technologies fulfill the goals set at the macro level? How can these technologies be integrated into households without creating new lock-in effects, for instance, in the form of intra-household grids?</p> <p>How can small-grid systems be designed without creating new lock-in effects?</p>
Social perspective	<p>How do existing laws, norms, and beliefs influence the adoption of alternative urban water systems?</p> <p>What institutional arrangements are optimal for the safe operation and maintenance of non-grid,</p>	<p>What new business models, market structures and firm strategies can potentially transform the conventional urban water system?</p> <p>What economic and financial incentives can support non-grid, small-grid, and hybrid</p>	<p>How do users understand and perceive non-grid, small-grid, and hybrid systems?</p> <p>Which motives and drivers predict stakeholders' acceptance, adoption, and maintenance of alternative systems?</p>

	<p>small-grid, and hybrid systems in various contexts?</p> <p>What context-sensitive legitimation strategies can support the diffusion of non-grid, small-grid, and hybrid systems?</p>	<p>systems in a fair and inclusive way?</p> <p>How can a large number of distributed systems be effectively operated, maintained, regulated, and controlled?</p>	<p>Which interventions can promote the adoption, use, and maintenance of alternative systems?</p> <p>How can different stakeholders shape institutions in favor of alternative urban water systems?</p>
	<p>Short term</p>	<p>Long term</p>	
<p>Transformative perspective</p>	<p>How can experimental implementation of alternative systems be established and developed at scale?</p> <p>How can consideration of and learning about alternative systems be achieved and sustained as standard processes?</p>	<p>How can visions and transition strategies for municipalities, regions, and entire countries be formulated, integrated, and supported within the water sector and across interdependent sectors?</p> <p>How can social and technical innovation processes be coordinated over the course of several decades without disrupting services along the way or creating stranded investments and still break with established path dependencies?</p>	

603

604 **6. Epilogue - Reflections on integrating multiple perspectives**

605 In this paper, we integrate a range of disciplinary
606 perspectives and fields to outline an integrative research
607 agenda for the future of urban water management. Although we
608 propose a transdisciplinary approach for future research, we are
609 fully aware of the difficulties posed by such an approach.⁹⁶ Our
610 challenge in integrating these different perspectives and fields
611 within this paper provides insights into the issues that
612 transdisciplinary teams will have to address. We found it crucial
613 to establish the intrinsic purpose of our integration effort,
614 weigh the contributions of the various perspectives and fields,
615 combine these contributions, and remain critical of the emerging
616 conclusions. As in any team effort, we faced the challenge of
617 balancing the various and sometimes competing expectations,
618 interests, and needs of all co-authors and the often
619 underestimated challenge of appreciating and honoring the
620 specific contributions of each co-author.⁹⁷ Writing this paper
621 was a highly iterative and dynamic two-year process. The result
622 can be regarded both as a "system of thought in reflective
623 equilibrium" and as a work in progress that is subject to
624 continuous revision.⁹⁸

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627 **Corresponding Author**628 *Phone: +41 41 58 765 6818; email: sabine.hoffmann@eawag.ch

629

630 **ORCID**

631 Hoffmann, Sabine: [0000-0001-6750-8069](https://orcid.org/0000-0001-6750-8069)

632 Feldmann, Ulrike: [0000-0001-6564-768X](https://orcid.org/0000-0001-6564-768X)

633 Bach, Peter: [0000-0001-5799-6185](https://orcid.org/0000-0001-5799-6185)

634 Christian, Binz: [0000-0002-6878-2606](https://orcid.org/0000-0002-6878-2606)

635 Farrelly, Megan: [0000-0002-0453-059X](https://orcid.org/0000-0002-0453-059X)

636 Frantzeskaki, Niki: [0000-0002-6983-448X](https://orcid.org/0000-0002-6983-448X)

637 Hiessl, Harald: [0000-0002-3410-6407](https://orcid.org/0000-0002-3410-6407)

638 Inauen, Jennifer: [0000-0002-7884-3222](https://orcid.org/0000-0002-7884-3222)

639 Larsen, Tove: [0000-0002-9978-6191](https://orcid.org/0000-0002-9978-6191)

640 Lienert, Judit: [0000-0003-1925-3895](https://orcid.org/0000-0003-1925-3895)

641 Londong, Jörg: [0000-0002-2861-056X](https://orcid.org/0000-0002-2861-056X)

642 Lüthi, Christoph: [0000-0003-2495-5541](https://orcid.org/0000-0003-2495-5541)

643 Maurer, Max: [0000-0002-5326-6035](https://orcid.org/0000-0002-5326-6035)

644 Mitchell, Cynthia: [0000-0001-9842-540X](https://orcid.org/0000-0001-9842-540X)

645 Morgenroth, Eberhard: [0000-0002-1217-269X](https://orcid.org/0000-0002-1217-269X)

646 Nelson, Kara: [0000-0001-8899-2662](https://orcid.org/0000-0001-8899-2662)

647 Scholten Lisa: [0000-0002-4487-758X](https://orcid.org/0000-0002-4487-758X)

648 Truffer, Bernhard: [0000-0002-8635-0911](https://orcid.org/0000-0002-8635-0911)

649 Kai Udert: [0000-0002-8051-7362](https://orcid.org/0000-0002-8051-7362)

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652 **Author Contributions**

653 The manuscript was written with contributions from all authors.
654 All authors have given approval to the final version of the
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656

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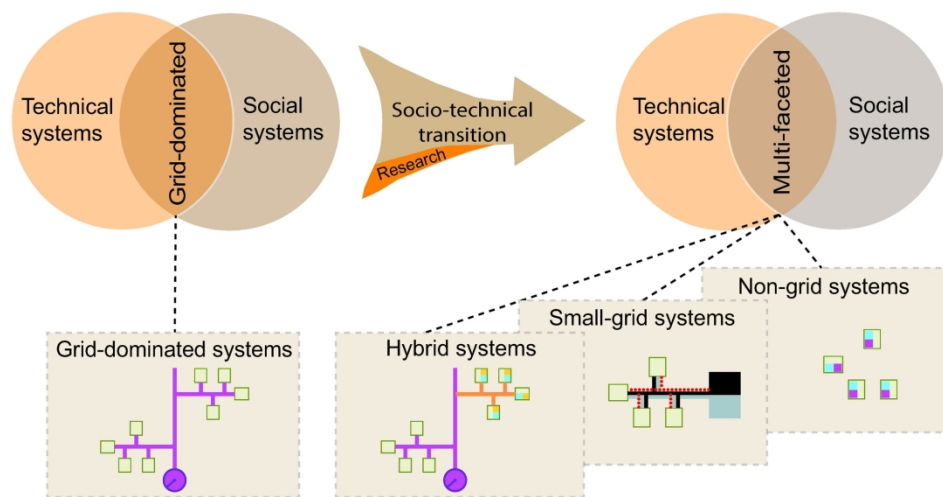
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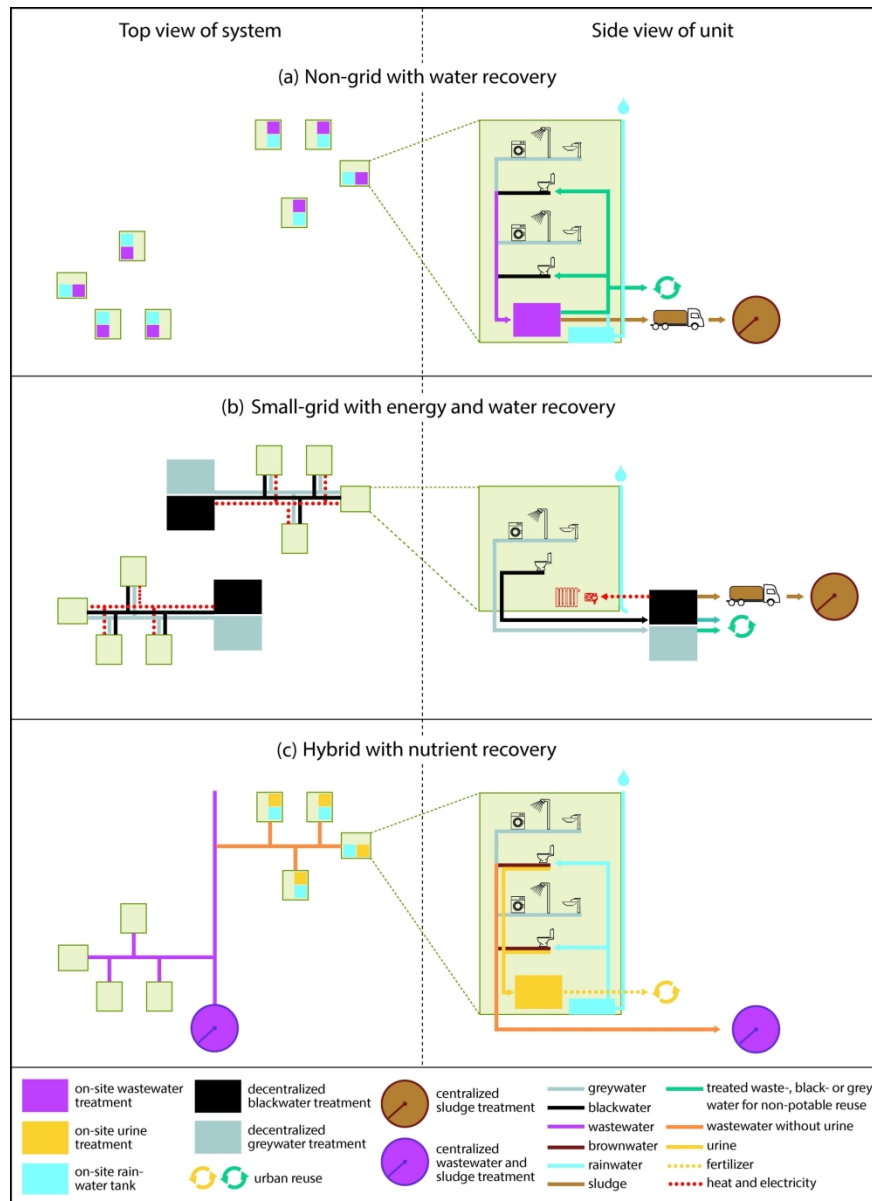
ⁱ An international group of 35 researchers and practitioners from 21 organisations, including the co-authors of this article, gathered in March 2018 at Monte Verità (Switzerland) to discuss the outlooks for a socio-technical transition in the urban water sector.

" The definition of "small" is relative to context and varies from, for example, tens of houses in a rural or peri-urban setting to several thousand residential and commercial units in a highly urbanized setting.



Graphical Abstract

190x98mm (300 x 300 DPI)



Schematic visualization of (a) non-grid, (b) small-grid, and (c) hybrid urban wastewater systems (left column: top view) and units (right column: side view) based on empirical examples: (a) Beijing, China: 24, 25 non-grid systems without sewers between individual buildings but with pipes inside buildings. Blackwater (e.g. from toilet) and greywater (e.g. from sinks, showers, washing machines or dishwashers) is collected in a single wastewater stream and treated on-site for non-potable reuse inside and outside individual buildings (e.g. toilet flushing, irrigation, and/or infiltration for aquifer recharge). Sludge is collected by trucks and treated in centralized sludge treatment plants. Rainwater is harvested and used for toilet flushing. (b) Hamburg, Jenfelder Au, Germany: 23 small-grid systems for groups of individual buildings with different pipes for source-separated wastewater streams. Blackwater and greywater are collected and treated separately in decentralized treatment plants. Treated greywater is reused outside buildings. Energy is recovered from blackwater as heat and electricity and used in buildings. Sludge is collected by trucks and treated in centralized sludge treatment plants. (c) Eawag, Zurich, Switzerland: 27 hybrid systems integrate non-grid and small-grid solutions into a grid-dominated system. Brownwater (e.g. from toilets, but without urine) and greywater is collected in a single wastewater stream and treated in a centralized wastewater

treatment plant. Urine is collected through urine-diverting toilets and treated on-site. Urine is transformed into fertilizer for reuse in urban agriculture⁴⁴. Rainwater is harvested and used for toilet flushing.

179x245mm (300 x 300 DPI)