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Low-cost monitoring systems for urban water management: Lessons from the field

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ABSTRACT

Sound urban water management relies on extensive and reliable monitoring of water infrastructure. As low-cost sensors and networks have become increasingly available for environmental monitoring, urban water researchers and practitioners must consider the benefits and disadvantages of such technologies. In this perspective paper, we highlight six technical and socio-technological considerations for low-cost monitoring technology to reach its full potential in the field of urban water management, including: technical barriers to implementation, complementarity with traditional sensing technologies, low-cost sensor reliability, added value of produced information, opportunities to democratize data collection, and economic and environmental costs of the technology. For each consideration, we present recent experiences from our own work and broader literature and identify future research needs to address current challenges. Our experience supports the strong potential of low-cost monitoring technology, in particular that it promotes extensive and innovative monitoring of urban water infrastructure. Future efforts should focus on more systematic documenting of experiences to lower barriers to designing, implementing, and testing of low-cost sensor networks, and on assessing the economic, social, and environmental costs and benefits of low-cost sensor deployments.

1. Introduction

In the bid for the Olympic Games, Paris made an ambitious promise: that the heavily polluted Seine River would be swimmable again in 2024. Beyond the political objective, this promise shed light on the water challenges faced by the city, with stormwater regularly overloading its combined sewer system, hence discharging wastewater to the river. The solution currently under implementation? More retention, promoted by the Plan ParisPluie launched in 2018 (Ville de Paris, 2018), and a giant tank to retain rainwater and slowly release it in dry weather.

This example is one amongst many in cities around the world facing the challenges of increased impervious areas and the associated flooding and water pollution. In response, urban water management has evolved over the past decades, embracing principles of integration – of the water supply, sanitation, and drainage systems – and decentralisation, with more treatment and retention “at source”, where runoff is generated. This is achieved with rainwater harvesting and a suite of blue-green infrastructure (e.g., swales, bioretention systems or constructed wetlands) (Lapointe et al., 2022).

The paradigm shift requires more spatially distributed monitoring to understand the performance of decentralized systems, especially in regions where blue-green infrastructure has been adopted only relatively recently (e.g., Hamel and Tan, 2021). The need for empirical evidence is reinforced by vegetated systems, which are more complex than concrete

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pipes and undergo more structural and functional changes over time. Yet, municipalities in charge of the maintenance and operation of urban water management systems typically have limited budget and know-how for monitoring (Abebe et al., 2021; Economic Development Research Group and Downstream Strategies, 2011; Kinney et al., 2023; Sharma et al., 2016; Tscheikner-Gratl et al., 2019). For small at-source systems such as raingardens, monitoring budgets including equipment and maintenance can easily surpass implementation costs, making it difficult for governmental agencies and operators to monitor post implementation (Strigaro et al., 2019). In addition, the setup and maintenance of a monitoring system requires a range of technical skills that staff do not necessarily have.

In this context, systems relying on low-cost sensing technology have recently gained in popularity in environmental monitoring, including for urban water management (Mao et al., 2019). These systems are cheaper than traditional ones due to the mass production of sensors and electrical components accompanying the IoT (Internet of Things) revolution, but also due to their leveraging of open-source and "DIY" (Do It Yourself) culture, and, often, lower quality assurance/quality control (QA/QC – Quality Assurance/Quality Control) (Fisher et al., 2015). Hereafter, we define "traditional monitoring systems" as sensors and components developed by specialised companies that invest significantly in QA/QC, which were the only readily available option until the 2000s. Beyond the cost savings, the low-cost technology offers other important advantages. Low-cost monitoring systems are modular, making them great technologies for non-conventional monitoring needs, including in research, and more effective to repair (piece-wise vs. whole system replacement) (Pearce, 2013). This modularity gives system designers full control over the design (e.g., Blaen et al., 2016; Chan et al., 2020): from the choice of the sensor, logger and measurement algorithm, communication technology, power supply and other desired features (Fig. 1). In addition, they offer multiple options for real-time communication and therefore high potential for real-time control across a network of centralised and decentralised systems. Moreover, they usually embrace open-source and open-data philosophies, making them great technologies for public information and empowerment, participatory projects and citizen science (Mao et al., 2019, 2020).

This Perspective paper presents six considerations for deploying low-cost monitoring systems for urban water management and guide research in this field, with a focus that is both technical and socio-technological. We argue that there are not only technical challenges, such as those involved in the building, testing, and deployment of low-cost monitoring systems, but also key socio-technological aspects that are insufficiently studied, related to the diversity of water monitoring "users, scenarios, societies and communities" described by Mao et al. (2020). Filling these knowledge gaps is important for the technology to deliver its fullest potential.

2. "DIY… if you can": technical barriers to the deployment of low-cost monitoring systems

While the open science movement has improved access to low-cost monitoring system components and resources, implementing such technology still implies significant resources. A broad range of skills are needed for deploying monitoring systems, including coding, electrical and electronic engineering skills (Catsamas et al., 2023), experience with DIY (e.g., building an enclosure and fixing hardware in the field), metrology (how to measure a quantity and how to assess sensor performance through calibration, uncertainty assessment, repeatability and reproducibility experiments), and data analysis (e.g., data verification, Fig. 1) (Chan et al., 2020; Horsburgh et al., 2019). Without these skills, the implementation journey may be tedious despite the large number of resources available online (e.g., Github, Stack Overflow forum, or Hackster). This is because monitoring applications are extremely diverse in scope and purposes, ranging from operational monitoring to scientific research, system optimisation, and community development (Mao et al., 2020). Each has a different purpose, set of stakeholder requirements, or technical constraints, which all imply different technological solutions. As such, setting up a monitoring system is often a trial-and-error process, which requires significant economic and/or time resources (Chan et al., 2020).

The diverse skills needed to set up a low-cost monitoring system entail economic resources (see Section 7) or non-economic resources, depending on whether the project manager opts for paying salaries of qualified technicians, outsourcing the services to private companies (e.g., Fieldkit, Libellium) or using their own time to upskill. This level of resources will likely diminish rapidly in the future as more "off-the-shelf" low-cost monitoring systems become available and information is shared (e.g., maker's websites, fablabs). In addition, recent development in Artificial Intelligence can assist in writing code by suggesting

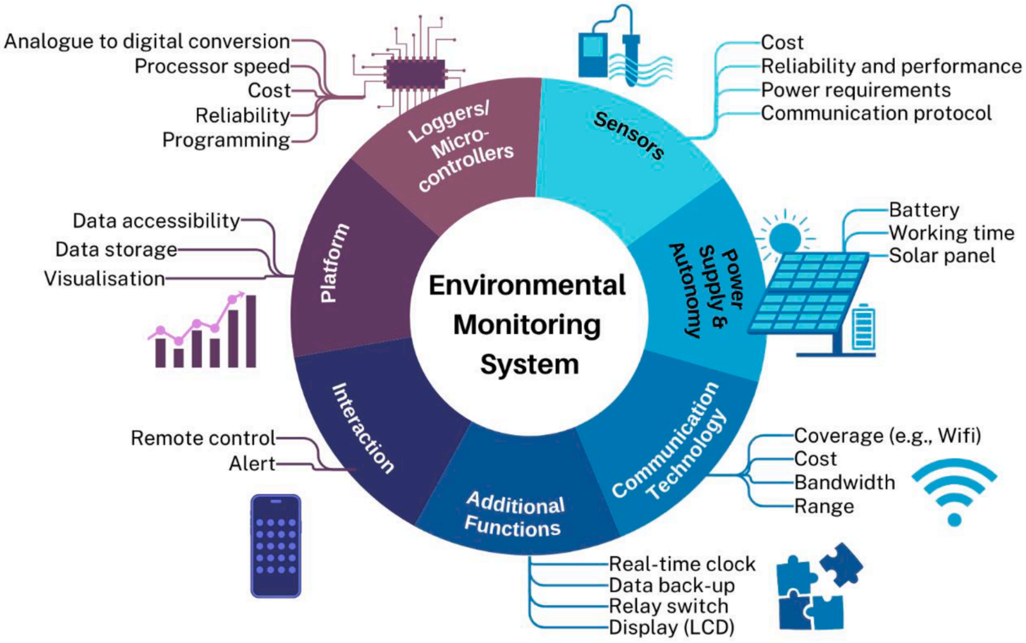

Fig. 1. Key elements of environmental monitoring system development and key factors driving their selection.

optimized algorithms and detecting errors, which greatly facilitates the coding process. Yet, for the next few years, we anticipate technical challenges to slow adoption and we call for systematic documentation of systems implementation and performance, in particular for scientific research (Beddows and Mallon, 2018). Training and education should also be offered to help build the capacity in the water sector to implement such technology.

3. “Test it yourself”: the hidden challenge

Thorough testing of low-cost monitoring systems is essential since their performance, particularly for water monitoring, is not well characterised (Zhu et al., 2023). Two complementary approaches are recommended to test low-cost monitoring systems (as it should be practiced with traditional sensors – unfortunately, this best practice metrology is still not systematically applied in the field of urban drainage). First, a controlled laboratory experiment comparing the low-cost sensor’s measurements to reference values will help qualify it and evaluate its performance, including range, accuracy, precision, reproducibility, and reliability (Cherqui et al., 2020; Shi et al., 2021). Second, before and during field implementation, testing, calibration and periodic verifications of the system in real field environmental conditions will help characterize actual performance (Catsamas et al., 2022;2023; Shi et al., 2021). Field performance may differ from laboratory conditions due to environmental factors outside the range of those tested in the lab (e.g., temperature or humidity conditions, sunlight), a possibly different electrical setup (e.g., fluctuating power supply, rewiring to accommodate field conditions), and, importantly, a possible drift over time that might not have been detected in short-term laboratory testing.

Despite the availability of open online resources, technicians conducting the system evaluation may face hidden challenges, in addition to the technical barriers highlighted above. The controlled experimental setup replicating key environmental conditions may be not trivial, e.g., when aiming to reproduce tropical temperature field conditions in a laboratory setting. In addition, each individual sensor should be tested: according to the authors’ experience, one out of seven low-cost sensors broke down during a test session for unknown reasons, suggesting that experiments should be run with several low-cost sensors to test their robustness. While these challenges are not unique to low-cost systems, the laboratory step may not be necessary with traditional sensors that have typically received sufficient QA/QC.

These challenges suggest that using low-cost monitoring systems for scientific-grade data may only be available to researchers or practitioners with the resources and knowledge to conduct extensive testing. This emphasizes how critical it is for researchers to produce and disseminate testing, calibration, and implementation protocols (including operation guides and codes) as well as maintenance instructions for field implementation (Bertrand-Krajewski et al., 2021). Researchers should aim to recommend sensors and systems which are robust, easy to use, have minimal calibration (i.e. time-stable) and minimal maintenance requirements.

4. Finding a sweet spot with hybrid systems

One important value add of low-cost components is their modularity. By leveraging the strengths and minimizing limitations of individual components, users can design optimal systems for their unique application. This may include finding off-the-shelf or conventional solutions for some part of the systems while retaining full modularity for the rest of the system. For example, one might design a system with low-cost microcontrollers and a communication system that fulfil the needs of a project, while investing in traditional (i.e. non-low-cost) sensors to lower the risk of sensor failures or low data quality – in the vast majority of cases where low-cost sensors have not undergone thorough, long-term testing. This was the case for recent projects developed by some of the authors,[1] with the use of BoSL loggers to circumvent issues with traditional loggers (costs, limited options to implement real-time control), while relying on established (“traditional”) monitoring sensors. Conversely, one might use conventional communication systems, e.g., relying on the global system for mobile communication (GSM) technology and infrastructure, but use low-cost sensors as was the case in an early warning system recently developed in Northern Thailand (Wannachai et al. 2022). The designers highlighted that their modular system reduced costs and maintenance issues, with a simple LED status system making it simple to diagnose faults and replace components.

Communications and real-time data can be a strong driver to move to low-cost systems, which typically offer more versatility and technological solutions. For example, continuous development in the field of information technology allows easy access to LPWAN (Low-Power Wide Area Network) communication (Mekki et al., 2019), which enables long-range wireless connectivity while consuming minimal energy, facilitating the widespread deployment of affordable sensor networks for various applications. Yet this versatility comes at a price, with the range of technologies (e.g., long range, wide area networking protocol – LoRaWAN, narrowband Internet of Things – NB-IoT, long term evolution – LTE CAT-M1 or global system for Mobile communication – GSM) and systems (e.g., supervisory control and data acquisition, SCADA) rapidly becoming overwhelming. With communication technologies evolving rapidly, the challenge of identifying and implementing optimal solutions for a given application will likely remain in the future and again, efforts to document and standardize communication protocols could help lower technological barriers and guide innovation.

5. Understanding the value of information provided by low-cost monitoring systems

Greater affordability should in theory increase hydrometeorological information available to researchers and managers – making it an important driver for adoption of low-cost monitoring systems. With more sensors, more water management systems can be monitored, which is particularly useful in regions where empirical data are still scarce (Hamel and Tan, 2021). Hydrologic behaviour of complex catchments can also be better understood with more observations, with greater opportunities to track water flows spatially and temporally (Shi et al., 2022). In addition, real-time communication opens the door to maintenance on demand, greater information sharing with a range of audiences (see Section 6), and optimisation through real-time control for centralised and decentralised systems. For example, real-time controlled rainwater tanks can be deployed at the household scale, with operation controlled centrally to achieve outcomes relating to flood management, flow-regime regulation, in addition to their basic function of water supply (Xu et al., 2021, 2022).

Yet more data do not always mean more or better information, and there may be trade-offs in data quality and quantity. First, additional sensors need to be adequately located to provide additional value of information: for example, in an analysis in the Brue basin, in the United Kingdom, it was shown that more sensors would only increase the model skill if they were located in critical sub-watersheds (Mazzoleni et al., 2016); other locations did not result in improved model performance. In addition, given the larger uncertainty – or possible data gaps due to sensor failure – generally associated with low-cost sensors (Zhu et al., 2023), we posit that there is a tradeoff between the number of additional sensors and the information ultimately provided by the monitoring system. The scarcity of information on the long-term performance of low-cost monitoring systems means that these tradeoffs are rarely quantified. The emerging literature on low-cost sensors’ applications in

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[1] https://www.bosl.com.au/wiki/Connect_Commercial_Sensor_to_BoSL

the field, combined with theories of value of information (e.g., Bennett et al., 2018) can be mobilised to further understand these tradeoffs.

6. Valuing the collection of information with low-cost monitoring systems

Following Paul et al., (2018), we highlight here the distinction between information provision (Section 5) and information collection (this section). Low-cost monitoring systems, like all measurement technologies, are developed in response to societal issues. In the case of urban water, current metrology practices and data collection have emerged from a restricted group of experts, i.e., scientists, engineers from private company or managers, limited the current paradigm to their social representations of the environment (Callon et al., 2001). Therefore, low-cost monitoring systems offer an important opportunity for public information, education and empowerment of non-experts communities and stakeholders ignored by traditional knowledge generation processes (Paul et al., 2018), e.g., small institutions, NGOs, citizens and students (Paul et al., 2018). Similar to the development of Arduino® microcontrollers by Italian school teachers, low-cost monitoring systems can play a key role in environmental education for primary and secondary school levels by facilitating active and field-based teaching approaches (Otto, 2017). Higher education institutions can also take advantage of low-cost systems to emphasize field education in order to counterbalance the tendency towards of classroom-focussed learning (e.g., remote sensing or numerical modelling). Beyond formal education, such technology can also support the 'citizen science' approaches that have emerged as a promising direction in the provision of extensive, real-time information for risk management (Paul et al., 2018; Payan et al., 2020).

As such, low-cost monitoring systems interact with power relations and representations (Bouleau, 2014) and therefore with the processes of urban water governance. This raises ethical and socio-technological questions currently poorly addressed in the scientific literature: Which parameters should be measured and where, given the educational and social context? How to manage the data so that they are accessible but secure? Documentation of the rationale for technology selection therefore becomes as important as the technical protocols.

7. Net economic and environmental costs of low-cost monitoring systems

Notwithstanding the lower price tag of low-cost monitoring technology, there is still little information on the long-term economic savings they may deliver in reality – for example in the form of cost-benefit analyses. Economic tradeoffs may occur due to the significant human resources described in Section 2, meaning that installing low-cost systems may end up being much more costly when incorporating the additional "people-hours" into the budget (Chan et al., 2020). In our experience, where sensors are developed by a research group or management agency, there is likely at least one year of product engineering and testing required to achieve a working prototype. Importantly, this cost may be reduced by relying on existing open-source prototypes, and we argue that researchers have a key role to play in testing, validating, and disseminating information for other users to reduce such costs. Fostering an active low-cost monitoring community in the field of urban drainage is therefore necessary.

Another economic tradeoff may be due to the industrial quality of low-cost components, often lower due to lower QA/QC in their production, implying that low-cost sensors may need to be replaced more frequently. Yet such data are very scarce and to our knowledge, no comprehensive study has been published on these tradeoffs. On the other hand, innovation made possible by low-cost sensors could spur new business models (Xu et al., 2021), for example permitting businesses and householders to contribute to stormwater management objectives through the operation of real-time controlled stormwater control measures on their own property. Here also, the potential costs and benefits are scarcely studied and more consistent reporting (of total costs of implementation, of potential economic benefits) is needed to better understand the actual cost effectiveness of low-cost systems.

Evaluations of the environmental costs of low-cost monitoring systems are even scarcer than evaluations of their economic costs. A recent review concluded that eWaste was still a significant gap in the research on "Smart Earth" concepts (Bakker and Ritts, 2018) . Two key factors may lead to a higher environmental impact: the (often) lower industrial quality of sensors, already mentioned above, and the potential differences in energy usage. Energy usage could be higher for low-cost systems, assuming a larger number of sensors for a given application, but also reduced by innovative use of communication technologies and real-time control that help use power only when needed. Another confounding factor is the greater modularity of low-cost monitoring systems discussed above, which could reduce eWaste by allowing more recycling of individual components. With the imperative to factor environmental costs into economic decisions, it is high time for the low-cost monitoring community to document environmental impacts – in particular eWaste generation and power consumption – at the project level to understand the potential tradeoffs with the use of environmental sensors.

8. Conclusions

- Low-cost monitoring systems open new opportunities for urban water monitoring by enhancing the production and dissemination of spatial and temporal hydrological information.
- Technical barriers for implementation, testing and integration remain. Presently, advanced technical skills are still required to ensure scientific-grade quality of data for a given research or monitoring objective.
- The economic benefits of low-cost systems are promising but they remain poorly documented. The environmental costs of such systems are poorly understood.
- To address these limitations, we call for better documentation of system's design process and performance for the community of practice to learn effectively from each other.
- While there are broader socio-technological challenges associated with low-cost monitoring technology – e.g., data management, communication, cybersecurity – the considerations highlighted in this article provide a guide for technology to reach its full potential.

CRediT authorship contribution statement

Perrine Hamel: Supervision, Funding acquisition, Writing – original draft, Conceptualization, Writing – review & editing. **Ning Ding:** Writing – original draft, Conceptualization, Writing – review & editing. **Frederic Cherqui:** Supervision, Funding acquisition, Writing – original draft, Conceptualization, Writing – review & editing. **Qingchuan Zhu:** Writing – original draft, Conceptualization, Writing – review & editing. **Nicolas Walcker:** Conceptualization, Writing – review & editing. **Jean-Luc Bertrand-Krajewski:** Conceptualization, Writing – review & editing. **Paskorn Champrasert:** Conceptualization, Writing – review & editing. **Tim D. Fletcher:** Conceptualization, Writing – review & editing. **David T. McCarthy:** Conceptualization, Writing – review & editing. **Oldrich Navratil:** Writing – original draft, Conceptualization, Writing – review & editing. **Baiqian Shi:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Perrine Hamel and Frederic Cherqui reports financial support was provided by MERLION (French embassy in Singapore and Nanyang Technological University). Perrine Hamel reports financial support was provided by Singapore National Research Foundation. Frederic Cherqui

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Data availability

No data was used for the research described in the article.

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References

Abebe, Y., Adey, B.T., Tesfamariam, S., 2021. Sustainable funding strategies for stormwater infrastructure management: a system dynamics model. Sustain. Cities Soc. 64, 102485 https://doi.org/10.1016/J.SCS.2020.102485.

Bakker, K., Ritts, M., 2018. Smart Earth: a meta-review and implications for environmental governance. Glob. Environ. Chang. 52, 201–211. https://doi.org/10.1016/J.GLOENVCHA.2018.07.011.

Beddows, P.A., Mallon, E.K., 2018. Cave pearl data logger: a flexible arduino-based logging platform for long-term monitoring in harsh environments. Sensors 18 (2), 1–26. https://doi.org/10.3390/s18020530.

Bennett, J.R., Maxwell, S.L., Martin, A.E., Chadès, I., Fahrig, L., Gilbert, B., 2018. When to monitor and when to act: value of information theory for multiple management units and limited budgets. J. Appl. Ecol. 55 (5), 2102–2113. https://doi.org/10.1111/1365-2664.13132.

Bertrand-Krajewski, J.L., Clemens-Meyer, F.H.L.R., & Lepot, M. (2021). Metrology in Urban Drainage and Stormwater Management: Plug & Pray. In: Bertrand-Krajewski, J.-L., Clemens-Meyer F.H.L.R., Lepot M. (Eds.), IWA Publishing.

Blaen, P.J., Khamis, K., Lloyd, C.E.M., Bradley, C., Hannah, D., Krause, S., 2016. Real-time monitoring of nutrients and dissolved organic matter in rivers: capturing event dynamics, technological opportunities and future directions. Sci. Total Environ. 569–570, 647–660. https://doi.org/10.1016/j.scitotenv.2016.06.116.

Bouleau, G., 2014. The co-production of science and waterscapes: the case of the Seine and the Rhône Rivers, France. Geoforum 57, 248–257. https://doi.org/10.1016/j.geoforum.2013.01.009.

Callon, M., Lascoumes, P., & Barthe, Y. (2001). Acting in an Uncertain World: An Essay On Technical Democracy. In: Bijker, W. E., Carlson, B.W., Pinch, T. (Eds.), MIT Press.

Catsamas, S., Shi, B., Deletic, B., Wang, M., McCarthy, D.T., 2022. A low-cost, low-power water velocity sensor utilizing acoustic doppler measurement. Sensors 22 (19), 7451. https://doi.org/10.3390/S22197451/S1.

Catsamas, S., Shi, B., Wang, M., Xiao, J., Kolotelo, P., McCarthy, D., 2023. A low-cost radar-based IoT sensor for noncontact measurements of water surface velocity and depth. Sensors 23 (14), 6314. https://doi.org/10.3390/S23146314/S1.

Chan, K., Schillereff, D.N., Baas, A.C.W., Chadwick, M.A., Main, B., Mulligan, M., O'Shea, F.T., Pearce, R., Smith, T.E.L., van Soesbergen, A., Tebbs, E., Thompson, J, 2020. Low-cost electronic sensors for environmental research: pitfalls and opportunities. Prog. Phys. Geogr.: Earth Environ. 45 (3), 305–338. https://doi.org/10.1177/0309133320956567.

Cherqui, F., James, R., Poelsma, P., Burns, M.J., Szota, C., Fletcher, T., Bertrand-Krajewski, J.L., 2020. A platform and protocol to standardise the test and selection low-cost sensors for water level monitoring. H2 Open J. 3 (1), 437–456. https://doi.org/10.2166/H2OJ.2020.050.

Economic Development Research Group, & Downstream Strategies., 2011. Failure to act: the economic impact of current investment trends in water and wastewater treatment infrastructure. Failure to Act. American Society of Civil Engineers. https://doi.org/10.1061/9780784478813.

Fisher, R., Ledwaba, L., Hancke, G., Kruger, C., 2015. Open hardware: a role to play in wireless sensor networks? Sensors 15 (3), 6818–6844. https://doi.org/10.3390/s150306818.

Hamel, P., Tan, L., 2021. Blue–Green Infrastructure for flood and water quality management in Southeast Asia: evidence and knowledge gaps. Environ. Manage. 69 (4), 699–718. https://doi.org/10.1007/S00267-021-01467-W. *2021 69:4*.

Horsburgh, J.S., Caraballo, J., Ramírez, M., Aufdenkampe, A.K., Arscott, D.B., Damiano, S.G., 2019. Low-cost, open-source, and low-power: but what to do with the data? Front. Earth Sci. 7. https://www.frontiersin.org/articles/10.3389/feart.2019.00067.

Kinney, A., Evrard, R., Bogue, K., James, C.A., 2023. Filling the gap: a comparative analysis of stormwater utility fees and stormwater program budgets in the Puget Sound watershed. JAWRA J. Am. Water Resour. Assoc. 59 (5), 1128–1145. https://doi.org/10.1111/1752-1688.13123.

Lapointe, M., Rochman, C.M., Tufenkji, N., 2022. Sustainable strategies to treat urban runoff needed. Nat. Sustain. 5 (5), 366–369. https://doi.org/10.1038/s41893-022-00853-4.

Mao, F., Khamis, K., Clark, J., Krause, S., Buytaert, W., Ochoa-Tocachi, B.F., Hannah, D. M., 2020. Moving beyond the technology: a socio-technical roadmap for low-cost water sensor network applications. In: Environmental Science and Technology, 54. American Chemical Society, pp. 9145–9158. https://doi.org/10.1021/acs.est.9b07125.

Mao, F., Khamis, K., Krause, S., Clark, J., Hannah, D.M., 2019. Low-cost environmental sensor networks: recent advances and future directions. Front. Earth Sci. 7. https://www.frontiersin.org/articles/10.3389/feart.2019.00221.

Mazzoleni, M., Alfonso, L., Solomatine, D., 2016. Influence of spatial distribution of sensors and observation accuracy on the assimilation of distributed streamflow data in hydrological modelling. Hydrol. Sci. J. 62 (3), 389–407. https://doi.org/10.1080/02626667.2016.1247211.

Mekki, K., Bajic, E., Chaxel, F., Meyer, F., 2019. A comparative study of LPWAN technologies for large-scale IoT deployment. ICT Express 5 (1), 1–7. https://doi.org/10.1016/J.ICTE.2017.12.005.

Otto, S.E.K., 2017. From Past to Present. The Handbook of Technology and Second Language Teaching and Learning, pp. 10–25. https://doi.org/10.1002/9781118914069.ch2.

Paul, J.D., Buytaert, W., Allen, S., Ballesteros-Cánovas, J.A., Bhusal, J., Cieslik, K., Clark, J., Dugar, S., Hannah, D.M., Stoffel, M., Dewulf, A., Dhital, M.R., Liu, W., Nayaval, J.L., Neupane, B., Schiller, A., Smith, P.J., Supper, R., 2018. Citizen science for hydrological risk reduction and resilience building. WIREs Water 5 (1), e1262. https://doi.org/10.1002/wat2.1262.

Payan, S., Turcati, L., Hornung, J., 2020. Sensors and citizen science: insights from the SENCIS seminar, April 2019. La Météorologie - N 111.

Pearce, J., 2013. Open-Source Lab: How to Build Your Own Hardware and Reduce Research Costs. Elsevier.

Sharma, A.K., Pezzaniti, D., Myers, B., Cook, S., Tjandraatmadja, G., Chacko, P., Chavoshi, S., Kemp, D., Leonard, R., Koth, B., Walton, A., 2016. Water sensitive urban design: an investigation of current systems, implementation drivers, community perceptions and potential to supplement urban water services. Water (Basel) 8 (7), 272. https://doi.org/10.3390/W8070272. *2016, Vol. 8, Page 272*.

Shi, B., Catsamas, S., Deletic, B., Wang, M., Bach, P.M., Lintern, A., Deletic, A., McCarthy, D.T., 2022. Illicit discharge detection in stormwater drains using an Arduino-based low-cost sensor network. Water Sci. Technol. 85 (5), 1372–1383. https://doi.org/10.2166/WST.2022.034.

Shi, B., Catsamas, S., Kolotelo, P., Wang, M., Lintern, A., Jovanovic, D., Bach, P.M., Deletic, A., McCarthy, D.T., 2021. A low-cost water depth and electrical conductivity sensor for detecting inputs into urban stormwater networks. Sensors 2021 21 (9), 3056. https://doi.org/10.3390/S21093056. *Vol. 21, Page 3056*.

Strigaro, D., Cannata, M., Antonovic, M., 2019. Boosting a weather monitoring system in low income economies using open and non-conventional systems: data quality analysis. Sensors (Basel) 19 (5). https://doi.org/10.3390/S19051185.

Tscheikner-Gratl, F., Caradot, N., Cherqui, F., Leitão, J.P., Ahmadi, M., Langeveld, J.G., Le Gat, Y., Scholten, L., Roghani, B., Rodríguez, J.P., Lepot, M., Stegeman, B., Heinrichsen, A., Kropp, I., Kerres, K., Almeida, M.do C., Bach, P.M., Moy de Vitry, M., Sá Marques, A., Clemens, F., 2019. Sewer asset management–state of the art and research needs. Urban Water J. 16 (9), 662–675. https://doi.org/10.1080/1573062X.2020.1713382.

Ville de, P., 2018. Zonage D'assainissement De La Ville De Paris – Règlement – Pièce 1.b. Paris (France): Mairie de Paris, Direction de la propreté et de l'eau, Service technique de l'eau et de l'assainissement, Mars 2018. https://cdn.paris.fr/paris/2020/02/26/7ac5e7527bf2bdc541d73767fc67bb36.ai. visited on 24 Nov. 2023.

Xu, W.D., Burns, M.J., Cherqui, F., Fletcher, T.D., 2021. Enhancing stormwater control measures using real-time control technology: a review. Urban Water J. 18 (2), 101–114. https://doi.org/10.1080/1573062X.2020.1857797.

Xu, W.D., Burns, M.J., Cherqui, F., Smith-Miles, K., Fletcher, T.D., 2022. Coordinated control can deliver synergies across multiple rainwater storages. Water Resour. Res. 58 (2), e2021WR030266 https://doi.org/10.1029/2021WR030266.

Zhu, Q., Cherqui, F., Bertrand-Krajewski, J.L., 2023. End-user perspective of low-cost sensors for urban stormwater monitoring: a review. Water Sci. Technol. 87 (11), 2648–2684. https://doi.org/10.2166/WST.2023.142.