

Urbanization under a Changing Climate—Impacts on Hydrology

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On a global scale, urbanization and climate change are two powerful forces that are reshaping ecosystems and their inhabitants. The scale and manner in which these two phenomena are changing the globe may differ, but any orchestrated response to one cannot be very effective without due consideration to the other. For all intents and purposes, anthropogenic response and adaptation are localized, disconnected, and single-purposed for various reasons including economic, social, political, and scientific. Thus, there remains a lack of understanding of how the holistic “sum” of these two forces can be assessed. This is not surprising, nor a criticism, but a simple fact that is difficult to manage. Researching the impacts of these two phenomena individually will likely only provide short-term results that are only marginally effective.

In many respects, urban hydrology is often framed in terms of increases in imperviousness, increases in peak flowrates, volumes and risk of flooding, increases in contamination, reduction to groundwater recharge, management via the end-of-pipe infrastructure, etc. Climate change impacts are often viewed in terms of changes to fundamental urban hydrological input parameters: changes to precipitation intensity, peaks, total volumes, frequency, duration [1], inter-event period length, minimum and maximum temperatures, and therefore, changes to response, planning and disaster mitigation (flooding or droughts). Stormwater management (i.e., our response to urban hydrology), has evolved over the last several decades to observe the need for sustainability—an often overly used term to convey anything “environmentally-conscious”; but here it is used to recognize that the needs of future generations are pivotal in its definition; and therefore, planning for a future that incorporates climate change is an integral part of all sustainable stormwater management. In urban hydrology, a technology that has been embraced in the name of sustainability is the Low Impact Development technology or LID. LID technology is designed to bring the post-development hydrograph back to its pre-developed state as much as possible. Thus, treatment involves reducing peak flowrates, prolonging timing and in many of these technologies, reducing and potentially eliminating contaminants arising in urban areas. Furthermore, urban water management aims to improve system resiliency and sustainability given that the principle of stationarity may be invalid under urbanization and climate change. An increasing role for LID in future planning that mitigates the effects of urbanization and climate change by impacting the fundamental hydrological parameters noted above, is apparent in this special issue of *Water*.

While at first glance the submissions to this special issue may seem disparate, they are however, all intimately connected to urban hydrology and most importantly, they span the wide range of scales of observation and consequences of urban hydrology. From the near microscopic scale [2] to meter scale [3,4] to km scale [5–8], this special issue effectively brings awareness and attention to the range of scales at which these phenomena manifest, and the responses that are necessary if societies are to truly become resilient. Spatial scale is not the only variant—temporal scales also vary across the study of urbanization and climate



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change impacts. Although often receiving less attention in observation and modelling than does spatial scaling, temporal scaling is no less important in truly sustainable responses.

In Zhao and Zhu [2], the authors provide a highly focused look at the leaching behaviours of zinc, lead, copper, and chromium; four highly problematic contaminating metals in urban runoff that are expected to increase in the future. The examination is focused on permeable pavements—a very popular and nearly pervasive LID in many parts of the globe. The authors found that while several fine-scale chemical, mechanical and physical processes within the pavement gave rise to their observations, they observed that in several instances, leaching concentrations changed with contact time (depending on the metal in question). This suggests that depending on the permeable pavement design, longer inter-event periods arising from climate change may lead to less incidents of flushing, and may in turn, lead to variability in metal contamination in stormwater at the end of the system. This can have adverse consequences for future planning and management.

At a slightly larger scale, outside the laboratory, but still focusing on LID technologies, Li et al. [4] examined the LID technology of bioretention cells for the curbside treatment of stormwater quantity and quality. Specifically looking at roadside bio-retention (RBR) facilities, the authors wanted to assess the influence of several fundamental assumptions involved in the design, and in particular, the importance of inlet hydraulics and how the spatial distribution of inflow along the RBR influence overall runoff control performance—something the authors note is rarely considered in LID modeling. The scale of focus here is from cm to meters, and this study included a very well written and concise literature on how RBR's function, and the corresponding research in the lab, field, and mathematical modelling. The important insight gained in their research include the fact that the effective length of an RBR, which depends upon the inflow rate as well as the perforation arrangement of the inflow distribution pipe, has an effect on the overall runoff control performance. In fact, the authors found that no matter how well an RBR is designed, the inlet dictated overall runoff control performance. Again, this can have serious consequences for future planning in stormwater management.

At a larger scale, but still focusing on LID technologies, Mahmoodzadeh et al. [3] examined green roofs as a means for affecting the energy budget of school buildings across a variety of North American climates and cities. Using a popular energy modelling software, the authors evaluated the relevance of green roof vegetation characteristics (such as leaf albedo, for example) on the roof's ability to maintain or improve the insulative value of the school building. This was done for four different climate areas spanning a range of temperatures and humidity levels. The authors found that even with the simplifying assumptions arising from the model, in climates where vegetation is active (outside of winter seasons where vegetation is in senescence), leaf area index had a major influence on cooling load reduction in all four cities. While optimal vegetation characteristics could be determined with the model, they were certainly climate dependent. The study highlighted the fact that increasing vegetation biomass in urban areas can help to reduce aspects of the heat island effect, and the role of vegetation in LID may become more pronounced as climate change impacts amplify.

Expanding the spatial scale even further, two articles ([5,7]) looked at locating LIDs in urban areas by creating a new approach to identify optimal locations for LIDs. Kaykhosravi et al. [7] presented a highly novel approach on how to incorporate LID in planning through a useable, simple, but rigorous index for determining the optimal location of an LID. The authors proposed a geospatial, physically-based framework integrated with a multi-criteria decision-making model that considered both environmental and socioeconomic factors. The LID Demand Index, or LIDDI, was able to effectively determine the optimal locations for LID demand across a large Canadian city (Toronto, Canada) to help reduce the risk of flooding and at the same time, provide the socioeconomic and environmental benefits of LID. This incredible new tool allows decision-makers to conduct future land-use planning quickly and holistically, in order to make landscape and infrastructure planning under a changing climate more resilient and effective.

At the municipal city scale, Kaykhosravi et al. [5] provided an examination of how climate change and urbanization combine to increase the risk of flooding in urban areas and how the demand for the stormwater mitigating benefits of LIDs will improve or change under these changing conditions. This seminal work shows conclusively using a variety of scenarios for both urbanization and climate change, that demand for LIDs will increase and how; and most importantly, shows how the demand varies depending on the climate, and of course, the nature of the increase in urbanization and urban form.

Further increasing the spatial scale is an examination of the impacts of climate and land-use on bacterial concentrations in stormwater. Xu, et al. [6] looked at the relationship between observations of fecal coliform concentrations in urban stormwater runoff from the lower Vancouver Island region in Canada. The work demonstrated a clear relationship historically between increases in fecal coliform (FC) concentrations and minimum temperatures (positive), antecedent dry period (positive), and higher urban area proportions (positive,) and with negative relationships to precipitation volumes. Using data driven modelling techniques, the study demonstrated that increasing urbanization leads to increases in FC but that conversely to other studies, longer periods of drier weather will likely lead to an increase in bacterial loadings from urban watersheds. Longer, drier periods with increasing daily temperature minimums may lead to higher growth in FC levels. Precipitation that normally dilutes and washes-off bacteria loadings and tends to reduce FC observations in stormwater may be altered. If future climate change scenarios suggest a combination of longer, drier inter-event periods with changes to precipitation volumes at the same time, urban regions may see increases in FC levels in stormwater in the future.

At the largest spatial scale in this special issue of *Water*, Mohanavelu et al. [8] used statistics on a large database of point-scale well observations to examine the influence of both climate change and urbanization on groundwater levels from several cities in India. Recognizing that large aquifers are the predominant water source for many urban areas in India, the authors undertook to determine the signal in dropping groundwater levels arising from both climate and the rapid urbanization being experienced across the country. The authors found that non-stationarity was observed across seasons suggesting water levels are related to land use changes (in turn related to increasing urbanization) and, potentially, climate variability. The authors carefully noted that historical, irreversible aquifer depletion caused by a high rate of pumping over a long time could have rendered the effects of climate variability and land use changes as negligible. Less interdependence between seasonality (based on monsoon) and groundwater levels was observed, which might have been caused by the impact of climate variability on groundwater recharge. The research suggests that rainfall–groundwater level relationships have been seriously affected across all the studied cities and possibly due to reductions in monsoon rainfall, which may have resulted from climate change.

Overall, this special issue of *Water* was very successful in highlighting the need for incorporating both urbanization and climate change in tandem in future planning, future research, and problem-solving, at all the relevant spatial and temporal scales.

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