Exploring robust alternatives for future urban drainage

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ABSTRACT

The robustness of a range of alternatives for the management of urban drainage by 2050 is explored through scenario analysis and integrated modelling of the wastewater system. The concept of regret applied in the analysis permits a fairer and more transparent comparison of alternatives, as well as a richer picture of their performance. Both green infrastructure and piped solutions exhibit variable robustness overall and by individual scenario; however, observed trade-offs in river water quality and differing strengths and weaknesses associated to centralised and decentralised alternatives suggest that combined strategies may offer further potential to investigate more robust urban drainage options.

KEYWORDS

Green infrastructure, integrated urban drainage modelling, retrofit solutions, robust decision making, scenario analysis, sustainability.

INTRODUCTION

The pursuit of sustainability in urban drainage systems will generally require finding solutions that are not just valid now, but that are also able to accommodate to changing conditions in the future. This change could be due to short-term factors (e.g. incoming legislation) as well as to long-term threats, such as climate change or population growth. Indeed, this is a crucial consideration to ensure adequate performance and to minimise the vulnerability of the system now and in the future (Blackmore and Plant, 2008). The uncertain nature of these changes demands a more flexible and holistic approach to consider and evaluate the robustness of adaptation measures. In this context, scenario analysis may be particularly relevant to address sustainability in that its methodological approach permits to scan the future in a way that reflects the normative character of sustainability and incorporates different perspectives (Swart *et al.*, 2004).

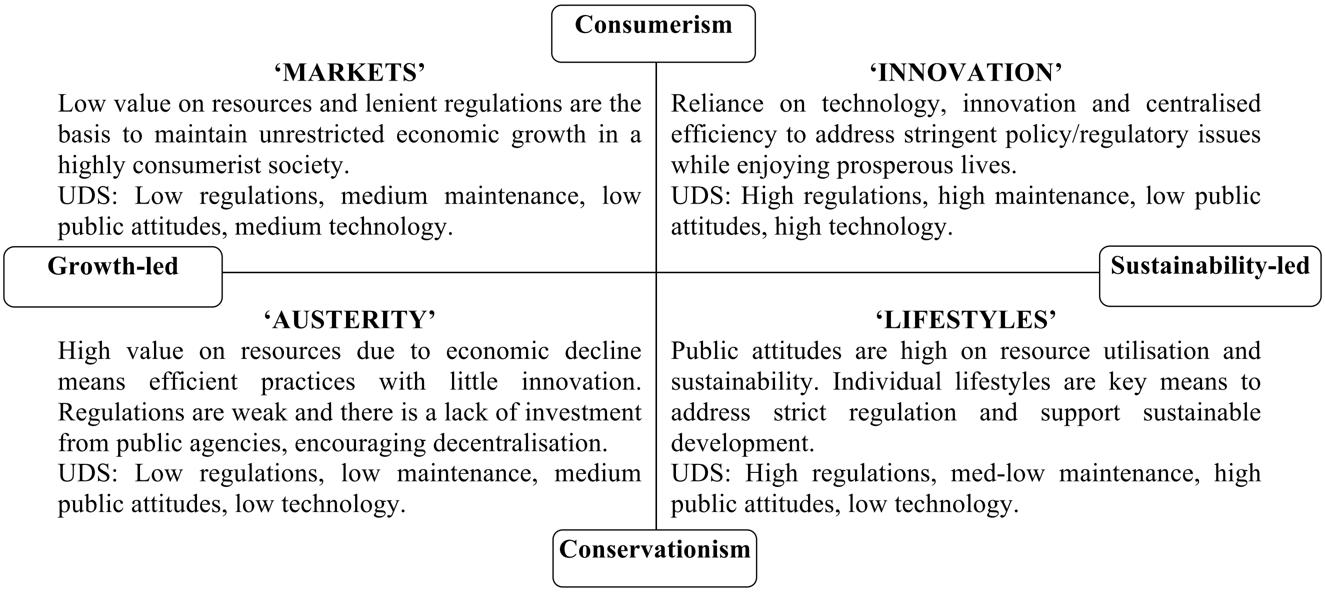
In order to propose alternatives that deliver satisfactory levels of service whilst coping with future demands, it is essential to validate them in an integrated manner (i.e. taking into account the subtle interactions between urban drainage subsystems), so that the system is considered on its entirety (Butler and Schütze, 2005).
Retrofit solutions, and particularly green infrastructure, offer great potential to simultaneously provide multiple benefits, whether these are environmental, economic or social in nature (Digman *et al.*, 2012). There is therefore a need to investigate the effect of such strategies in urban drainage systems from an integrated system perspective in the face of future change. There exist studies evaluating this from a water quantity (Zhou *et al.*, 2012; Stovin *et al.*, 2013) or a quality perspective (Freni *et al.*, 2010); however, very few incorporate multiple objectives which may be often required in long-term decision-making.

This paper reports on a study examining the potential implications of a variety of standalone retrofit and non-retrofit alternatives in the future performance of urban drainage systems. The software platform SIMBA6 and the hydrodynamic sewer model SWMM5 are coupled to model the integrated urban drainage system (i.e. catchment, sewer network, wastewater treatment plant and river models) during one year of extended period simulation. A case study, as described by Butler *et al.* (2008), is used to assess performance impacts and analyse the robustness of alternatives under four different scenarios, which embody the uncertain nature of key factors likely to affect drainage systems by 2050.

METHOD

Definition of future scenarios

The equiprobable scenarios used for the purpose of this study are presented in Figure 1. They are characterised by two main drivers, namely: governance (growth-led vs. sustainability-led); and values (consumerism vs. conservationism). The selection of a 'two-axes' approach allows a richer representation of exploratory futures by defining two high-impact high-uncertainty drivers (Foresight Programme, 2009). Governance and values have been frequently considered as key driving factors for their ability to construct conceptual associations that permit to define a more diverse and transparent 'possibility space' (Berkhout and Hertin, 2002).



'MARKETS'
Low value on resources and lenient regulations are the basis to maintain unrestricted economic growth in a highly consumerist society.
UDS: Low regulations, medium maintenance, low public attitudes, medium technology.

'INNOVATION'
Reliance on technology, innovation and centralised efficiency to address stringent policy/regulatory issues while enjoying prosperous lives.
UDS: High regulations, high maintenance, low public attitudes, high technology.

'AUSTERITY'
High value on resources due to economic decline means efficient practices with little innovation. Regulations are weak and there is a lack of investment from public agencies, encouraging decentralisation.
UDS: Low regulations, low maintenance, medium public attitudes, low technology.

'LIFESTYLES'
Public attitudes are high on resource utilisation and sustainability. Individual lifestyles are key means to address strict regulation and support sustainable development.
UDS: High regulations, med-low maintenance, high public attitudes, low technology.

Figure 1. General description of 2050 scenarios used in this study and possible consequences for the urban drainage system (UDS).

In this context it is assumed that growth-led societies frequently rely on solutions that can be quickly implemented in order to address short-term issues, instead of considering far-reaching objectives like those encased in the definition of sustainability. Conversely, sustainability-led societies are therefore more concerned with the long-term implications of their actions by acknowledging the importance of environmental, economic and social gain altogether. Such integral benefits are rarely achieved in the short term, requiring careful planning where strict policy enforcement is crucial. Indeed, growth-oriented societies are more lenient on regulations, which could compromise growth by hindering a range of economic activities.

The vertical axis (‘consumerism-conservationism’) represents the dominant public attitudes regarding the use of resources and their valuation. This does not necessarily mean that a consumerist society is careless about environmental problems, but that they generally rely on public and private organisations to address these issues. In other words, it is assumed that consumerism promotes the centralisation of responsibilities, whereas conservationism encourages individual ones.

Based on these remarks and previous work on UK water-related scenario construction (Evans *et al.*, 2004; Environment Agency, 2010; Farmani *et al.*, 2012; Lombardi *et al.*, 2012) four scenarios have been defined: Markets, Austerity, Innovation and Lifestyles.

Table 1 presents different sources of uncertainty affecting the future performance of urban drainage systems and which are used to characterise each scenario. These factors intend to represent the physical implications of socio-economic conditions (e.g. regulatory climate, level of maintenance, public attitudes, and technological development) in the urban drainage system of study. The potential effect of climate change in precipitation is modelled by a 10% uplift to account for increased intensity of storms by 2050 (Defra, 2006). It is further assumed that this effect is independent of scenario conditions (i.e. uplift constant across scenarios) for simplicity and because it is considered appropriate for the purpose of this study.

Table 1. Estimates of uncertain factors affecting UDSs by 2050 under each scenario.

	Baseline	**Markets**	**Innovation**	**Austerity**	**Lifestyles**
Misconnections (l/s)	-	7.8 (5%)	0.9 (1%)	4.1 (7%)	1.7 (3%)
Urban creep (ha)	-	87.7 (15%)	58.4 (10%)	70.1 (12%)	29.2 (5%)
Water use (l/h/d)	155	165	125	140	110
Infiltration (l/s)	52.4 (14%)	163.7 (30%)	40.5 (10%)	200.1 (50%)	151.2 (40%)
Siltation (*)	0.97	0.92	1	0.84	0.92
Population (inhabitants)	181,000	262,450	244,350	217,200	226,250
Area served by separate sewers (ha)	-	290	226	129	161
Precipitation uplift	-	10%	10%	10%	10%

(*) the effect of siltation in sewers is represented by full-pipe area reduction, 1: no reduction, 0: total reduction.

Definition of alternative strategies

Six different alternatives for the management of stormwater and/or wastewater are proposed within the catchment. The implementation of each alternative is considered in isolation from the others for simplicity and to fully realise the beneficial performance of one strategy relative to the others. Four of these alternatives only affect the management of stormwater in existing developments (retrofit solutions), namely: mitigation of urban creep (C_O, from now on); implementation of permeable pavement (PP); disconnection of residential roofs (R_O); and installation of separate sewers (SS). In addition to this, conventional grey infrastructure (GREY) and decentralised wastewater systems (OFF_GRID) are also considered as potential alternatives.

C_O is assumed to take place through strict planning permission applied by local authorities, who would regulate the provision of permeable pavement in driveways to be developed in front yards.

The PP alternative is modelled by retrofitting permeable pavement in half of the off-road hardstanding area of residential roads of the catchment as resurfacing is required, which is considered a conservative estimation of the retrofit potential of this technique (Environment Agency, 2007). This alternative approximately serves 21.5% of the impermeable area of the existing catchment, including adjacent pavements and roads.

Disconnection of residential roofs (R_O), which account for 34% of the total impermeable area of the catchment, is achieved through downpipe re-connection into retrofitted garden soakaways.

A retrofit separate sewer system (SS) affecting half of the existing urban area redirects the corresponding runoff flows directly into the receiving water body. In any of the considered alternatives, surface water from new developments is managed using separate sewers.

Rehabilitation of the combined sewer system serving the catchment (GREY alternative) is proposed by means of two simple measures: enlargement of sewer pipes and increase of centralised storm tank capacity. This alternative is designed to improve the carrying capacity of sewers while not increasing the annual number of untreated spills.

Finally, a decentralised wastewater system (OFF_GRID) is proposed for half of the new housing developments constructed between the baseline period and 2050 under each scenario. This is represented in the model as wastewater being treated on-site and discharged into the receiving water, bypassing the combined sewer system serving the rest of the catchment.

Performance assessment

The performance of alternatives is assessed using a variety of impact categories, which are considered the fundamental components of sustainability within this study. These include: sewer (pluvial) flooding, fluvial flooding, receiving water quality, greenhouse gas emissions, capital cost, health and aesthetics, and acceptability.

Annual sewer flooding is estimated as the total accumulated flood volume flowing out of surcharged manholes during the one-year extended period simulation. The impact of fluvial flooding in downstream developments is considered proportional to the magnitude of river peak flow 1 km from the last drainage discharge point.

The potential water quality impact of alternatives in the receiving water body is assessed through two physico-chemical indicators: minimum 6-hour dissolved oxygen concentration; and 99 percentile of total ammonia concentration. These indicators are particularly tailored to evaluate the performance of intermittent discharges which, because of their frequency and duration during wet weather, have a significant effect on aquatic life and could potentially compromise compliance with Water Framework Directive objectives (UKTAG, 2013).

GHG emissions are incorporated into the assessment as a measure of the operational energy required by the system to pump and treat sewage as well as the direct operational biological emissions arising from the activated sludge process.

The cost category is covered by the estimated capital cost of each alternative. Although other impact categories (e.g. flooding damage) are commonly monetised and sometimes combined with capital expenditure (i.e. cost-benefit analysis), it is the intention of this study to rather explore these impacts through multi-criteria analysis, which permits a more explicit and transparent consideration of objectives.

The total annual volume of untreated spills (CSOs) discharged into the receiving water body is used as a surrogate indicator of both aesthetic pollution (e.g. litter, smell) and potential public health concerns (e.g. pathogenic organisms).

Finally, the acceptability of each alternative under each scenario is appraised using a simple scoring system (low-medium-high acceptability) which takes into account the assumed dominating public perceptions and managerial styles described in Figure 1.

Robustness criteria

A robustness approach, as compared to an optimal approach, should generally be considered when uncertainties are sufficiently deep and alternatives sufficiently rich (Lempert and Collins, 2007). In the context of this study, a robust alternative is understood as one that performs reasonably well compared to the others over a range of possible futures. This definition of robustness is embodied in the concept of regret, as described by Lempert *et al.* (2006) for the development of a robust decision making (RDM) method. A formal definition of regret of an alternative *a* in a future state *f* is given by

$$\text{Regret}_i(a,f) = \max_{a'}\left[\text{Performance}_i(a',f)\right] - \text{Performance}_i(a,f) \qquad (1)$$

where *a'* indexes through all the alternatives to present the one with the best performance (from performance category *i*) in the future state *f*. Thus, each performance category presented in the previous section has its own regret function associated with it, in the form expressed in equation (1). Indeed, low-regret alternatives are preferred to high-regret ones.

One of the main strengths of a regret-based approach to robustness (especially when compared to performance-based approaches) is that it can focus decision-makers' attention on those future states of the world most relevant to their decision (i.e. those in which positive or negative outcomes may strongly depend on decision-makers' choices) (Hall *et al.*, 2012). Further, the concept of regret is easy to grasp by a wider variety of audiences and facilitates communication and discussions taking place in the decision-making process.

Each category of regret is kept independent from the others, so that objectives can be compared in isolation and weighed by decision makers as required. In order to obtain an overall picture of the regret associated with each alternative across all plausible future states (i.e. scenarios), category regret functions are aggregated as follows,

$$\overline{\text{R}}_i(a) = \sum_f \text{Regret}_i(a,f)$$

where $\overline{\text{R}}_i(a)$ represents the cumulative regret associated with performance category *i* (e.g. sewer flooding) of alternative *a*.

RESULTS AND DISCUSSION

The performance of alternatives regarding water quantity control and receiving water quality impact is illustrated in Figure 2 ('do-nothing' options are presented in bold). All alternatives contribute to different degrees to reduce the volume of untreated spills and sewer flooding occurring under the defined scenarios. Taking the present baseline conditions as reference ('Base' in Figure 2), only SS consistently improves both quantity indicators throughout all the considered scenarios. R_O does so in two scenarios, whilst only reducing sewer flooding in the remaining two when compared to the baseline. PP and GREY significantly reduce flood volume, although the latter has a detrimental effect on annual CSO volume. Even though the number of annual CSOs is reduced (as anticipated by the design), the improved carrying capacity of the sewer system in GREY implies that more volume could be spilled during less time. This fact translates into an important degradation of river oxygen levels.

In general, R_O is the best alternative regarding river oxygen concentration, followed by OFF_GRID, PP, C_O and SS. The latter strategy is mostly damaging for oxygen concentrations due to untreated runoff being discharged to the receiving water through storm sewers, partly offsetting the beneficial effect of CSO reductions; however, SS outperforms other alternatives concerning ammonia concentration. Indeed, it is a generally observed tendency of R_O and other catchment interventions (C_O, PP) to have a more pronounced effect in river oxygen levels than ammonia, particularly in Markets and Austerity. This suggests that when the capacity of the system has been greatly exceeded, reducing storm flows entering the sewers will generally reduce pollution from CSOs (dominated by organic load), whereas the impact on river ammonia (dominated by the effect of the hydraulic load in the discharged effluent at the treatment plant) is less significantly affected. Further, only R_O under Lifestyles brings both river oxygen and ammonia back to baseline levels.

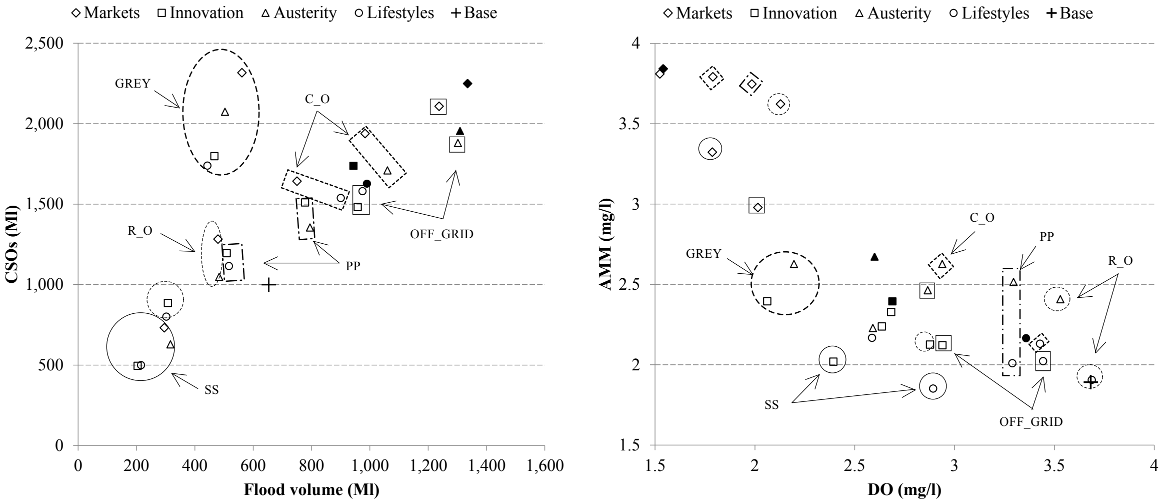


Figure 2. Performance of alternatives regarding total CSO spill and flood volume (left), and total ammonia and dissolved oxygen in the receiving water (right) under different scenarios.

The contribution of OFF_GRID to river water quality is rather significant across scenarios, regardless its limited role in reducing CSO spills. Certainly, the effect of this intervention is twofold: reducing the wastewater load conveyed by combined sewers which could be potentially spilled during storms; and reducing misconnected and infiltrated flows causing background pollution in the receiving water body.

Water quantity and quality objectives are evaluated together with the remaining criteria (acceptability, capital cost, fluvial flooding, and GHG emissions) through regret functions and robustness analysis. The regret of each alternative across and for each scenario is shown in Figure 3. The total regret presented in the bar chart is calculated as the sum of the individual cumulative regrets of each impact category (i.e. Total regret = $\sum_i \overline{R}_i(a)$).

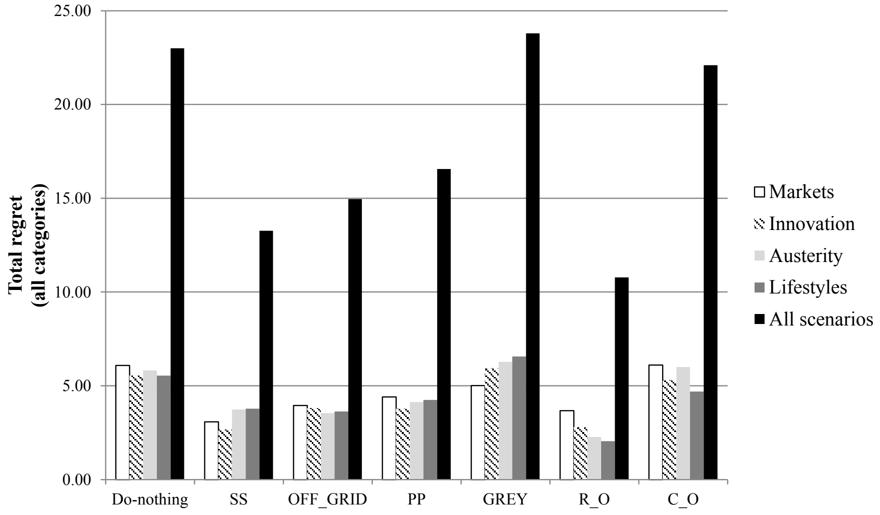


Figure 3. Total regret of alternatives across scenarios and total regret overall (black bar).

Overall, ‘Do-nothing’ and GREY alternatives result in very similar levels of total regret. The latter is the most regrettable option in three scenarios, with C_O making the top in Markets.

Sewer flooding alleviation of GREY do not compensate for lower CSO performance, lower river water quality, and induced fluvial flooding of the solution in those scenarios when compared to ‘Do-nothing’. High regrets associated with C_O highlight the high cost of this solution relative to the small beneficial effect obtained under most scenarios.

The most robust alternative is R_O, which also outperformed the rest of alternatives across all scenarios except in Markets and Innovation, where SS had a lower total regret. This can be explained by the better performance of SS regarding total ammonia concentration and its higher acceptability under these scenarios. In this sense, the high acceptability of ‘piped strategies’ (e.g. GREY and SS) in ‘consumerist’ scenarios contributed to lower regrets when compared to ‘conservationist’ worlds. The greater variance of total regret observed across alternatives in Austerity and Lifestyles suggests a deeper impact of decisions under these scenarios.

Figure 4 permits explicit consideration of objectives and visualization of the strengths and weaknesses of individual alternatives. The external octagon represents ‘complete regret’ in all categories, so that alternatives are preferred to be closer to the inner octagon (‘no-regrets’ level). Results from Figure 3 can be now better understood and interpreted: R_O presents a less eccentric pattern across impact categories (i.e. less regret), whereas SS weaknesses lie on the large regret associated with fluvial flooding downstream, its lower acceptability and a poorer dissolved oxygen performance. The radar charts in Figure 4 also show how alternatives with similar total regret (OFF_GRID and SS) may benefit very different objectives (SS main strengths are those associated with flooding, ammonia, aesthetics and cost, while OFF_GRID lower regrets relate to dissolved oxygen, acceptability and GHG emissions).

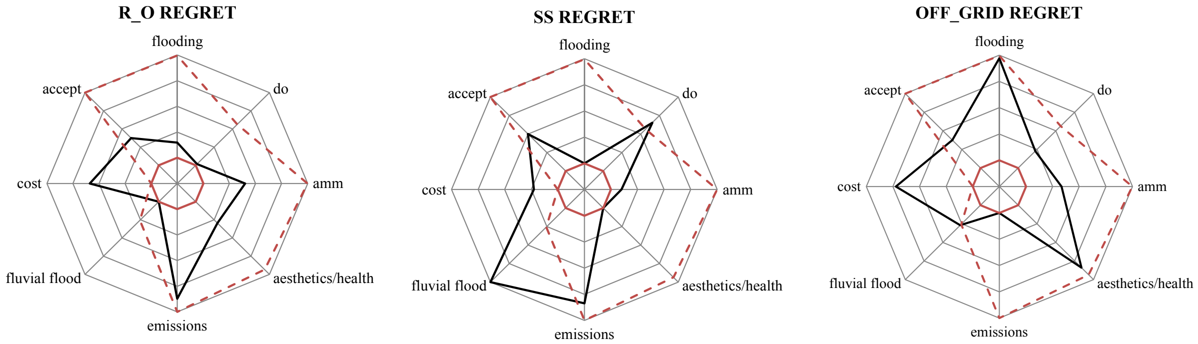


Figure 4. Cumulative regret by impact category of top performing alternatives (black line). The dashed line denotes regrets of the ‘do-nothing’ alternative.

CONCLUSIONS

Uncertain changes in the future may have differing implications for urban drainage systems. Finding robust alternatives with low regrets spanning across a variety of scenarios and objectives is crucial to plan more sustainable drainage solutions. The application of such approach in this study permitted identifying states of the world where decisions may have greater consequences (i.e. Austerity and Lifestyles), as well as realising the relative merits and demerits of alternatives throughout.

The variable robustness of retrofit green infrastructure interventions importantly depends on the cost of solutions relative to the total area served, and thereby the total benefit obtained. In this sense, creep control may prove significantly more robust if cheaper solutions (e.g. gravel) or more inclusive alternatives (e.g. partial disconnection of roofs to permeable pavement used to prevent creep) are considered. Additionally, the acceptability of options may play a crucial role in ranking preferred alternatives in individual scenarios. Performance trade-offs (e.g. oxygen and ammonia concentration in the river) and differences observed across regret categories for alternatives suggest that the combination of centralised and decentralised strategies may have a mutually beneficial effect, potentially delivering more robust solutions.

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