Protecting rivers by integrating supply-wastewater infrastructure planning and coordinating operational decisions

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Abstract

Placing water quality in rivers at the centre of water infrastructure planning and management is an important objective. In response there has been a range of 'whole system' analyses. Few studies, however, consider both abstraction (water removed from rivers) and discharge (water returned) to inform the future planning of water systems. In this work we present a systems approach to analysing future water planning options where system development prioritises the water quality of the receiving river. We provide a theoretical demonstration by integrating water supply and wastewater infrastructure, and downstream river water quality, on an open-source, stylised, systems model for London, UK, at a citywide scale. We show that models which consider either supply or wastewater separately will underestimate impacts of effluent on the water quality, in some cases by amounts that would require £1 billion worth of infrastructure equivalent to mitigate. We highlight the utility of the systems approach in evaluating integrated water infrastructure planning using both socio-economic and environmental indicators. Through this approach we find unintended impacts from planning options on downstream river quality; including benefits from water demand management and rainwater harvesting, and costs from wastewater reuse. Finally, we present a novel management planning option between supply and wastewater, which we refer to as Abstraction-Effluent Dilution (AED), that is, to reduce river abstractions during high precipitation events to dilute untreated sewer spills. The AED option is found to provide up to £200 million worth of equivalent infrastructure in river quality improvements and has minimal impact on the reliability of water supply while requiring only a change in operational decision making. This proof-of-concept study highlights that seeing our water systems differently with this holistic approach could fundamentally change the way we think about future water infrastructure planning so that it works both for people and the environment.

Introduction

The impact of water infrastructure on river quality has long been a key element in the wider discussion around water planning and management (Gleick, 2003; Vörösmarty et al., 2010). Without due consideration to environmental impacts, water infrastructure cannot be described as sustainable (Loucks, 2000). This desire to put the environment central to planning can be facilitated by a systems modelling approach (Coombes & Kuczera, 2002; Kasprzyk et al., 2018). When the planning focus

38 changes, specifically to the river quality in this work, the system boundaries may need to be expanded

39 (Vogel et al., 2015). There is a growing literature showing how the expanding of system boundaries

40 changes the behaviour of modelled processes in water systems (Coombes et al., 2016) and even to

41 the extent that would require a system to be managed differently (Dobson et al., 2019).

42 We look to the urban water system to illustrate this point. It covers rivers, groundwater, wastewater

43 and water supply systems. Each of these systems are typically managed separately yet most of them

44 are operationally connected; for example, water supply abstractions reduce river flows and thus

45 increase the concentration of wastewater effluent discharge in a river. To illustrate this, we show how

46 wastewater and water supply infrastructure interact in catchments across England and Wales in

47 Figure 1. It shows that over half of the catchments have large wastewater plants (serving >100,000

48 people) and water supply abstractions (>2Ml/d) along the same rivers.


49 (B)   (C)   (D)
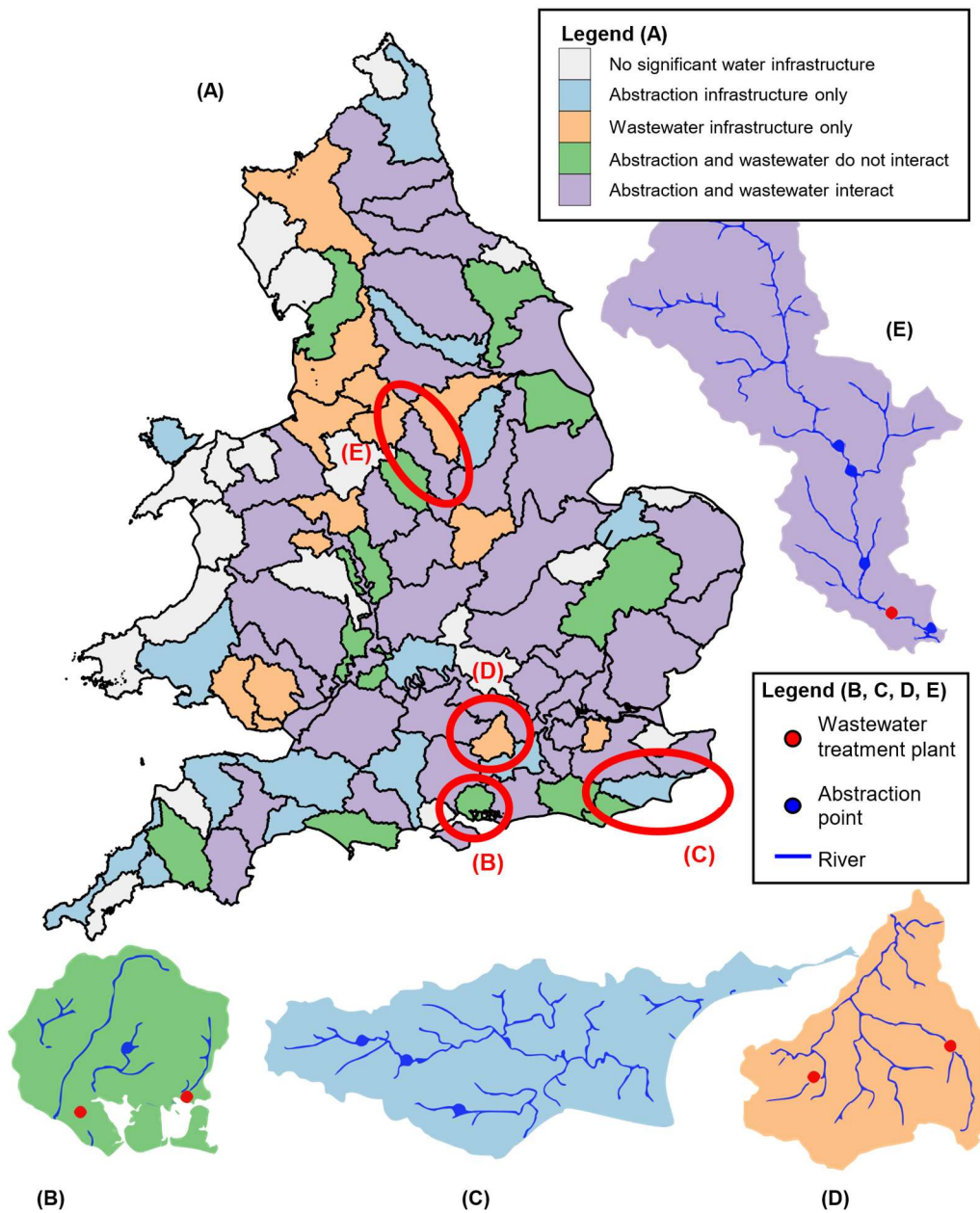
50   Figure 1. (A) A map depicting how different catchments (Environment Agency, 2019a) have different

51   levels of interaction between water supply and wastewater along rivers, indicated by colour. (B-E)

52   Catchments that illustrate different levels of interaction; rivers are shown as blue lines (Ordnance

53   Survey, 2019), wastewater treatment plants serving >100,000 people as red points (European

54   Commission, 2016) and water supply abstractions >2Ml/d as blue points (Environment Agency, 2015).

55   Despite the interdependency apparent in Figure 1, the UK's supply and wastewater planning

56   processes remain distinctly segregated. In water supply, infrastructure projects are currently

57   evaluated by their impact on continuity of supply, relying on licensed abstraction limits to account for

58   river quality (Cook et al., 2017). In wastewater, there is a focus on the occurrence and severity of both

59   volume and pollutant content of effluent discharges – rather than considering the waters that receive

60   them (Water UK, 2019). Biases in river quality estimation is to be expected for any water

61   infrastructure project if planning remains separate but the real system is connected. Some

62   infrastructure projects, such as wastewater reuse, to be accurately assessed will inherently require

63   conceptualisation over the entire urban water cycle (Behzadian & Kapelan, 2015).

64   Models that capture interactions between different water system processes fall broadly under

65   'integrated water management' models (Rahaman & Varis, 2005; Mitchell, 2006). These types of

66   models are most commonly found as joint sewerage network and urban runoff models (Bach et al.,

67   2014; Salvadore et al., 2015). However, other examples of integrated water management models

68   exist, for example: supply-drinking water quality (Mortazavi-Naeini et al., 2019), household waste-

69   sewerage-runoff (Bailey et al., 2019), supply-sewerage-runoff-treatment (Rozos & Makropoulos,

70   2013; Behzadian & Kapelan, 2015; Coombes et al., 2016), and supply-river quality (Paredes-Arquiola

71   et al., 2014). As more systems are included and larger geographical areas are covered, the

72   complexity of the system representations tends to be reduced, leading to a lumped "directed-graph"

73   approach to modelling urban water cycles. This approach was pioneered by the Aquacycle software

74   (Mitchell et al., 2001) and with recent implementations such as CityDrain3 (Burger et al., 2016),

75   however, these have been constrained to the wastewater system only.

76   In this paper we illustrate a case for a wider systems view of the urban water cycle in water planning

77   and management. We argue that unintended consequences can be incurred by the choice of

78   modelled processes resulting in bias for estimating river quality, and that unexpected benefits may be

79   revealed when the system is considered in an integrated fashion. This case is based on three

80   hypotheses. First, we assume that if a city's supply and wastewater systems abstract water and

81   discharge into connected rivers but are modelled separately, then their estimations of river quality will

82   be significantly different than if they had been modelled together. Next, we propose that reducing

83   water supply abstractions during high precipitation events will dilute sewer spills, reducing the

84   concentration of untreated effluent during spill events to an extent that it could complement

85   infrastructure-based options. The approach might also have interactions with flood risk, but this is

86   outside the scope of this study. Finally, we argue that water infrastructure planning options will impact

87   state variables across the wider water system revealing co-benefits and trade-offs in integrated water

88   planning. These hypotheses can only be tested in an integrated model that spans the urban water

89   system. Thus, we also present an open-source lumped water management model of a stylised,

90   London-based system.

91   **Methods**

92   *CityWat: an open-source water management model of London*

93   To investigate these hypotheses, a daily timestep, open-source lumped water management model of

94   a stylised, London-based system (CityWat hereafter) has been developed for this work – see

95   acknowledgements for its Python model code, with equations described in supporting material S1. We

96   note that, although targeted to London, CityWat is modular and can easily be rearranged and

97   generalised to a range of cities. The processes represented in CityWat for this study are depicted in

98   Figure 2A.
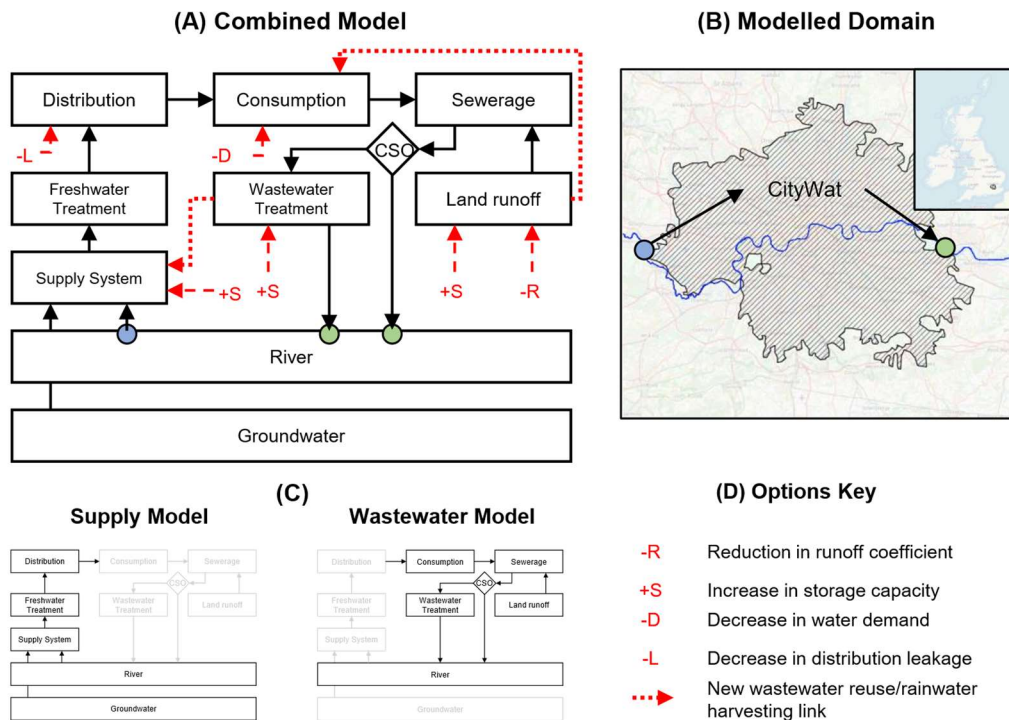
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100   Figure 2. (A, top left) In black is a schematic depicting the processes and data flow represented in

101   CityWat, planning options are highlighted in red. Abstraction and discharges points are indicated in

102   blue and green respectively (B, top right) The region represented by our model, with abstraction and

103   discharge locations indicated by circles. (C, bottom left) Two framings of the water system, a supply-

104   only model and wastewater-only model. (D, bottom right) The key for the different generic planning

105   options included in our study, which are linked into CityWat illustrated in red in Figure 2A.

106   Each process in CityWat is represented by a lumped model at city scale), shown in Figure 2B. For

107   example, supply reservoirs are aggregated into one London-wide reservoir. This lumping ensures a

108   efficient and easy to understand water management model, and it also enables sharing of parameter

109   information openly without privacy or national security concerns. River flows and groundwater

110   availability are represented by data (detailed in Supplementary Material S2). We note that this is a

111   significant simplification of the real system. There are multiple abstractions and discharge points

112   within the modelled region that CityWat aggregates together as well as upstream processes that

113   model does not represent in detail. Thus, simulation results should be interpreted as a proof-of-

114   concept rather than assessment or critique of current system operation.

115   Water system parameters (e.g. capacities of reservoirs or treatment plants) can generally be found

116   openly at city-scale and are described in supporting material S2. Where this is not possible

117   reasonable estimates have been made. S2 indicates the reasoning behind, and supporting sources

118   for these estimates. Input data, i.e. flow and precipitation, have been sourced from the national river

119   flow archive (Centre for Ecology and Hydrology, 2020) and HadUK (Hollis et al., 2019) respectively.

120   London is fortunate in its environmental data records and so the simulation period spans the period

121   between 1903-2018. In the Experimental Setup, we verify how effectively the model simulates historic

122   data.

123   *Impact of water system boundaries on modelled river quality*

124   The first hypothesis in our case for expanding the model boundaries was that: if a city's supply and

125   wastewater systems abstract and discharge water into connected rivers but are modelled separately,

126   then their estimates of river quality at the downstream boundary will be significantly different than if

127   they had been modelled together. To test this, we treat different models of the system in question

128   each as a plausible representation of the system. Treating a model in this way can be referred to as a

129   'framing' of the system (Quinn et al., 2017). Thus, we formulate three framings of London's water

130   system. The first is the integrated water system, unchanged from Figure 2A. This combined framing

131   represents the systems view of the urban water cycle. The second is the supply-only portion of the

132   system including processes between the river and point of water consumption by customers, depicted

133   in Figure 2C, left. This is a water supply framing of the water cycle. The third is the wastewater-only

134   portion of the system including processes between the waste production of customers to wastewater

135   treatment work effluent, depicted in Figure 2C, right. This is a wastewater framing of the water cycle.
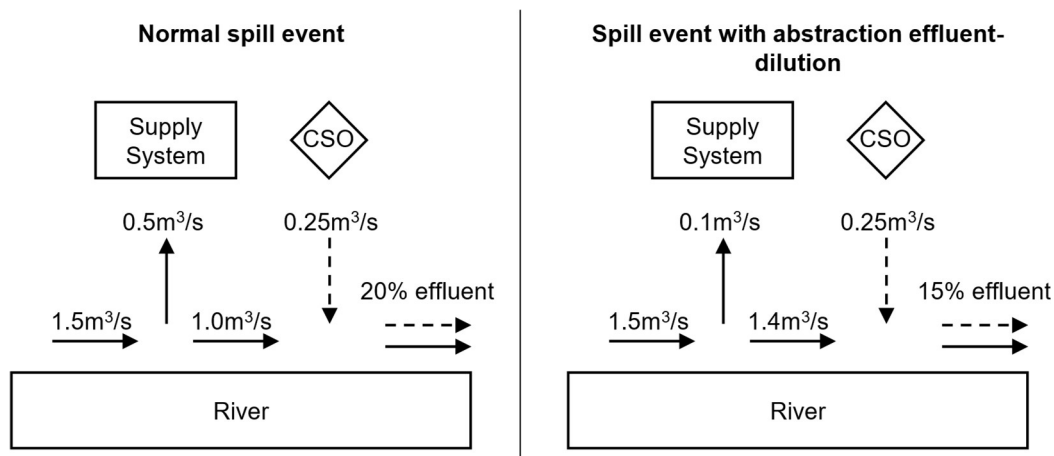
136   We hypothesise that downstream river water quality could be a key indicator to assess the

137   performance of the system as a whole. We propose concentration-based metrics formulated from the

138   proportion of downstream river flow. The raw river water, treated effluent and untreated effluent

139   proportions are used to illustrate differences in simulated river quality between framings. Given

140   CityWat's lumped scale, any metric that quantifies the impact of the urban water system on

141   downstream river quality will ultimately be some derivative of these three proportions. As an example

142   of this derivation, we also include phosphorus concentration, which is conceptualised as the

143   phosphorus concentration of raw river water, treated and untreated effluent blended in proportion to

144   their volumetric presence in the river. We chose phosphorus because it is a significant pollutant in the

145   River Thames and has high concentrations in sewage that are reduced significantly by treatment

146   (Jarvie et al., 2006).

147   To ensure that we consider socio-economic factors as well as environmental, we have also included

148   two metrics for reliability of water supply. These are total supply reservoir volume over time and the

149   level of water use restrictions (e.g. a level 3 restriction allows enforcement of hosepipe bans while a

150   level 4 restriction allows standpipe use). Water use restrictions are based on reservoir levels,

151   described in Mortazavi-Naeini et al. (2019). These metrics do not perfectly capture the complexity of

152   the water resources planning process in the UK (Cook et al., 2017), but we believe serve as an

153   adequate proxy in this proof-of-concept study.

154   *Evaluation of planning options from an environmental perspective*

155   It became clear when viewing the urban water cycle from a systems perspective, which the combined

156   CityWat framing provides, that there were potential opportunities to improve river quality through a

157   joint management approach. As anticipated in our second hypothesis, we have proposed using water

158   supply abstractions to manage untreated effluent spill events, which we term 'Abstraction Effluent-

159   Dilution' (AED). The working principle behind this option is illustrated in Figure 3. In the Experimental

160   Setup section, we perform a pilot experiment to design the implementation of this option.

Normal spill event | **Spill event with abstraction effluent-dilution**

Supply System   CSO

$0.5 m^3/s$ $0.25 m^3/s$

$1.5 m^3/s$ $1.0 m^3/s$ 20% effluent

River

Supply System   CSO

$0.1 m^3/s$ $0.25 m^3/s$

$1.5 m^3/s$ $1.4 m^3/s$ 15% effluent

River

161

162   Figure 3. A simplified system schematic that illustrates the working principle of abstraction effluent-

163   dilution, with the raw water flows (normal arrows) and untreated spill flows (dashed arrows)

164   represented for a normal spill event (left) and spill event with abstraction effluent-dilution (right). The

165   values shown are for illustrative purpose only and not representative of the case study.

166   Besides AED, we also examine conventional water infrastructure options. In the UK, the water supply

167   planning process (termed water resources management planning (Cook et al., 2017)) has been in

168   place since the privatisation of the water industry in 1985, with the feasibility of several project options

169   (e.g. new reservoirs, leakage reduction targets) already assessed. In contrast, the wastewater

170   planning process (termed drainage and wastewater management planning (Water UK, 2019)) is still

171   being developed. Thus, we select a range of feasible options for supply and commonly proposed

172   options for wastewater planning to test in CityWat alongside AED, which we summarise in Table 1.

Sector	Option	Description in model	Cost	Option impact
Integrated	Abstraction Effluent-Dilution	Minimise abstractions when precipitation is high and supply reservoirs are nearly full	Negligible	Dilutes untreated effluent from spill events
Supply	Wastewater Reuse	Allows treated effluent to be re-abstracted for supply	£2m/(Ml/d) (Environment Agency, 2019b)	Adds 150Ml/d in wastewater reuse capacity
Supply	New reservoir	Increase supply reservoir capacity	£12,500/Ml (Borgomeo et al., 2018)	24,000Ml increase in reservoir capacity
Supply	Demand reductions	Reduce per-household water demand	Negligible (in comparison to other options)	10% reduction in household consumption (achievable by 2035, (Environment Agency, 2019b))
Supply	Leakage reduction	Reduce level of leakage in the distribution network	£1.6m/(Ml/d) (NERA, 2019)	190Ml/d reduction in leakage (about 35%, achievable by 2035 (Environment Agency, 2019b))
Wastewater	Green roofs	Reduces equivalent impermeable area by green roof area multiplied by 50% (the assumed runoff reduction)	£100/m^2 (AECOM, 2017a)	3km^2 of green roofs installed, covering 2% of London's roof area
Wastewater	Rainwater harvesting	Creates volume that can store rainwater on roofs and be redirected to household demand	£280/(400L unit) (AECOM, 2017a)	Units installed on all of London's roofs, 700,000 units providing 280Ml of storage
Wastewater	Stormwater storage tanks	Increases storage for water that reaches treatment works but cannot be treated that day	£2m/Ml (AECOM, 2017b)	Increase temporary stormwater storage by 150Ml.

173   Table 1: A summary of the different options we test in CityWat using a historical demand scenario

174   (described in Supplemental Material S1), how they are implemented and at what scale.

175   In order to compare options from both sectors, we have gathered estimates of unit costs and

176   implement each option with a 'budget' of £300million. Some options are constrained by factors other

177   than cost (e.g. demand reductions, whose cost to implement is negligible in comparison with

178   infrastructure projects), thus we provide realistic estimates for these instead. The options we include

179   are illustrated in Figure 2A and 2D.

180   Our third hypothesis is that infrastructure options impact state variables in the systems they exist in,

181   but also those that they interact with, which could have implications for assessing systems level

182   benefits of proposed schemes. Thus, we compare all metrics for all options.

183   **Experimental Setup**

184   *Verification of the CityWat model*

185   CityWat is a stylised model and primarily illustrative, with parameter values estimated based on

186   openly available data to capture the behaviour of key system processes. We have performed a model

187   verification based on the supply reservoir volume data shared in Mortazavi-Naeini et al. (2019), Figure

188   4. We see that CityWat simulates reservoir volumes broadly in line with other, more complex models
189   of the London's supply system (Nash-Sutcliffe Efficiency = 0.85). The worst model performance is
190   during the 1976 drought. We expect this is due to the lack of emergency supply sources represented
191   in CityWat in contrast to the models it is being compared against. We do not include these emergency
192   supply sources since information about them cannot be made open-source for security reasons and
193   the complexity of decision-making during droughts is increased involving many factors that cannot be
194   modelled in CityWat.
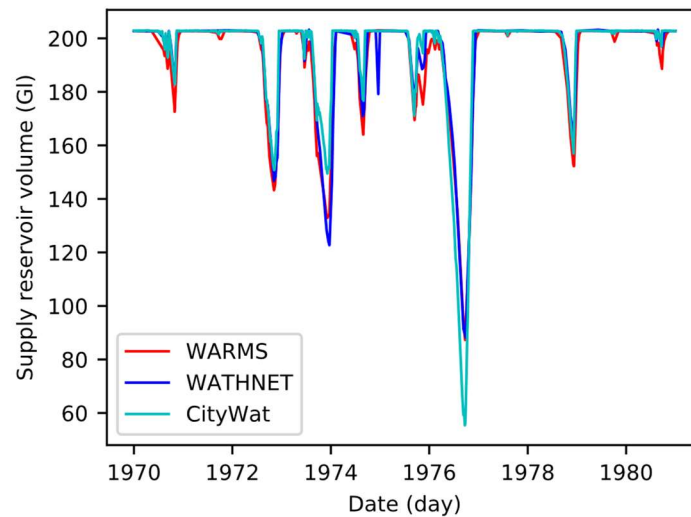
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196   Figure 4. A comparison of active supply reservoir volume for three different daily simulation models of
197   London's water supply. WARMS (red) is the water company model of the system. WATHNET (blue)
198   represents a research water supply model that has been based on WARMS, implemented in the
199   WATHNET supply simulation software (Kuczera, 1992). CityWat (cyan) is the model presented in this
200   study.

201   In Figure 5 we compare simulated downstream phosphorus from CityWat with 123 water quality
202   samples at two sampling sites downstream of the modelled region, using data from the WIMS archive
203   (Environment Agency, 2020). The agreement between modelled and sampled phosphorus indicates
204   that CityWat's estimates of treated effluent discharge are reasonable and therefore it is accurately
205   representing wastewater system processes. The two outliers, when CityWat simulates much higher
206   levels of phosphorus than the samples, occur during untreated spill events, which the samples do not
207   capture. When these spill events are removed the correlation coefficient with sample site 1 is 0.75
208   and 0.51 with sample site 2.

209
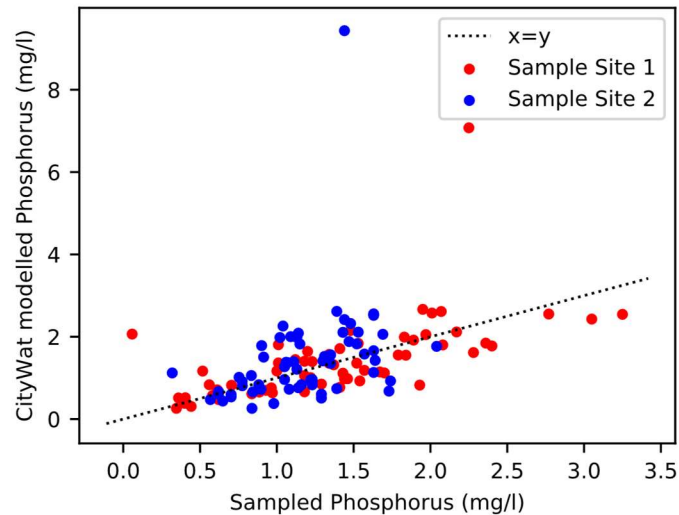
Figure 5. A comparison of phosphorus simulated by CityWat (y-axis) and 123 water quality samples (x-axis) at two different locations (indicated by colour) taken between 2000-2018.

The only openly available data on spill events that the authors could identify was that the average annual spill of untreated effluent is between 32-40Mm^3/y (Hamilton, 2013). CityWat spills 36Mm^3/y on average over the entire simulation period, within the estimated value.

Creating an Abstraction Effluent-Dilution rule

In the Methods section we introduced the concept of abstraction effluent-dilution (AED). We now provide a pilot experiment that examines when storm spill events occur to see if they follow any clear patterns to design an AED rule. In Figure 6 we plot the severity of simulated spills (indicated by proportion of river that is untreated effluent) against precipitation data and simulated supply reservoir volume. We note that, were AED tested in operational conditions, more complex design would be required than the heuristic we present here to safeguard supply security and prevent other risks such as flooding.
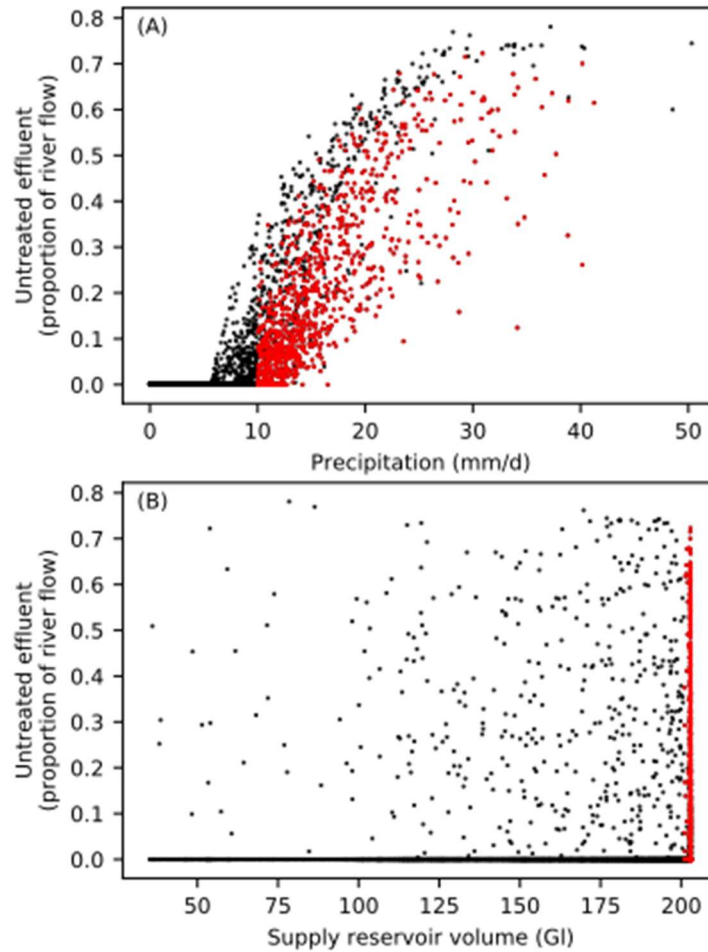
Figure 6. A scatter plot with daily climate data (A) and modelled storage (B), over the period 1903-2018, on the x-axis with modelled untreated effluent, as simulated by CityWat, on the y-axis. Red points are those that occur on days when both precipitation is greater than 10mm/d and supply reservoirs are greater than 99% full.

Inspecting precipitation, we see that severe spill events typically occur on days when precipitation is >10mm (upper panel, Figure 6, 80% of points that are greater than 0 on the y-axis occur with x-values greater than 10). We also see that most spill events are occurring when supply reservoirs are nearly full (lower panel, Figure 6, 70% of points that are greater than 0 on the y-axis occur with x-values greater than 200).

Thus, when the model is run using the 'abstraction effluent-dilution' (AED) option, water supply abstractions on the River Thames are minimized when both reservoirs are >99% full and precipitation is >10mm. We would not expect this to have a significant impact on reliability of water supply since there are few days (highlighted in red in Figure 6) that meet these criteria and if reservoirs are nearly full then under-abstracting is likely to be low risk. Yet abstraction can significantly reduce the flow (up to 5Gl/d), so we expect that 'leaving it in' could significantly dilute untreated effluent.

To test how effective AED is, we examine simulated phosphorus levels. We also test the water supply reliability metrics to check whether the option would put water supply at risk.

241   **Results**

242   *Estimates of the impact of model boundaries on water quality*

243   In Figure 7A-D we plot river quality state variables at the point of downstream discharge estimated by

244   the different framings, showing distinct differences between them. We present a subsection of Figure

245   7A-D over a shorter period in Figure 7E-H to better observe patterns in the timeseries.
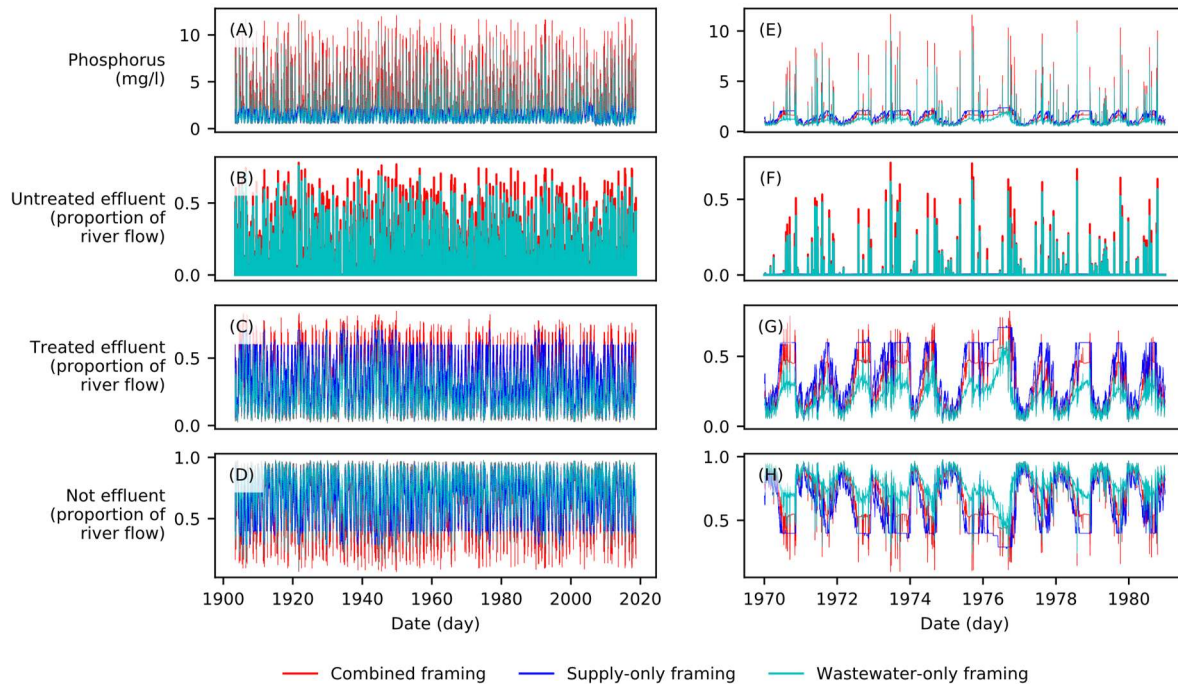

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247   Figure 7. (A-D) Downstream river quality represented by daily effluent and phosphorus concentration

248   timeseries under the three different model framings (represented by different colours) for the

249   simulation period (1903-2018). (E-H) the same as (A-D) but for a subsection of the simulation period

250   (1970-1980).

251   A significant discrepancy occurs in the supply-only framing. Since it does not represent storm spill

252   events it will not simulate any concentration of untreated effluent (Figure B, no blue) and so

253   underestimates phosphorus concentrations (Figure A, blue never rises above 1.5mg/l).

254   The wastewater-only framing overestimates downstream river quality in all metrics. By ignoring river

255   abstractions it underestimates treated and untreated effluent concentrations (cyan is lower than red in

256   Figures B, C) and overestimates raw river water concentration (Figure D). This results in

257   underestimating the impact of spill events, although not necessarily their occurrence (red and cyan

258   peaks to line up in Figures B, C). If this framing were used to inform future planning, the equivalent

259   stormwater storage required to reduce untreated effluent spills to these underestimated levels would

260   be 600Ml. Following Table 1, this could exceed £1billion of infrastructure investment.

261   *Abstraction effluent-dilution effectiveness*

262   In Figure 8 we plot phosphorus concentration and reservoir volume simulation results both without

263   and with abstraction effluent-dilution (AED).
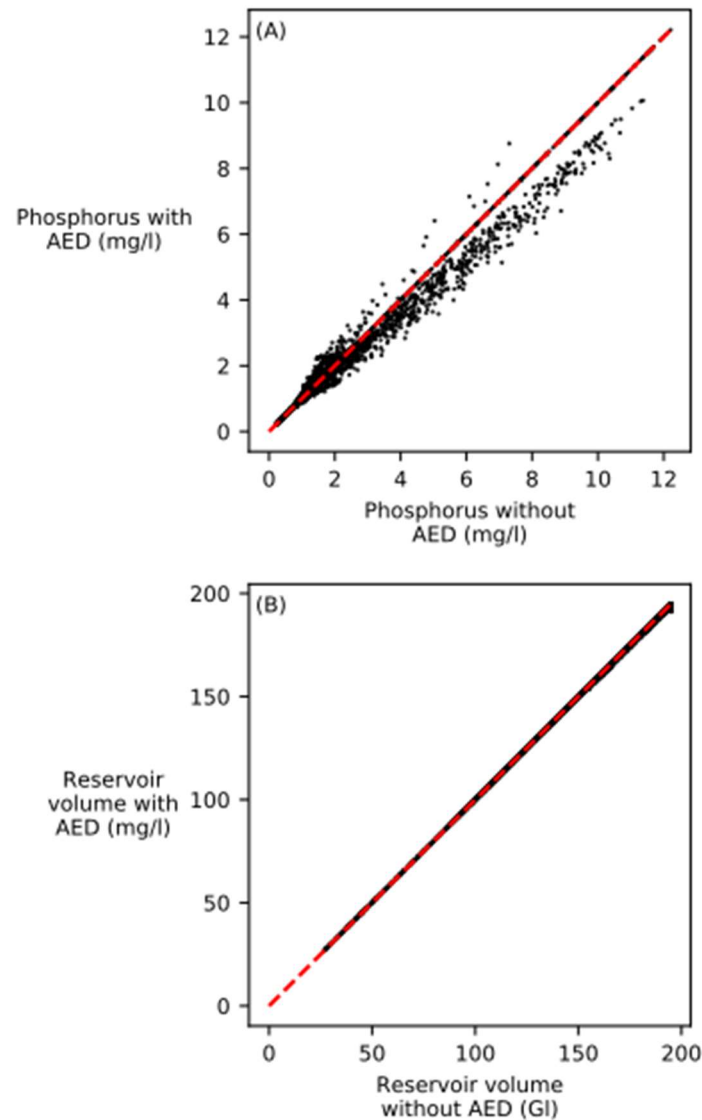
Figure 8. Downstream river quality represented by phosphorus concentration (upper) and water supply reliability represented by reservoir volume (lower) both with (y-axis) and without (x-axis) the abstraction effluent-dilution option (AED) for the simulation period (1903-2018). The red dashed line is x=y.

We see in the phosphorus levels (upper panel) that AED reduces the severity of spill events (most points are either on or below x=y). Although AED does not alleviate spills completely, particularly when the reservoirs are at low levels, the volume of stormwater storage that would be required to achieve the same improvement is 200Ml, costing £100millions. When inspecting reservoir volumes (lower panel) we also see a small negative impact (points are slightly below x=y). These lower volumes increase the level of restrictions by an additional six days of level one restrictions over the entire simulation period. Since these do not cause actual disruptions, only representing awareness campaigns (Mortazavi-Naeini et al., 2019), we can consider this impact negligible.

277   *Systems assessment of water management options*

278   In Figure 9, we plot how the different options change state variables that indicate system performance

279   averaged over the entire timeseries. A greener colour indicates an improvement (e.g. reduction in

280   water-use restrictions or increase in proportion of downstream river flow that is not effluent), grey

281   indicates no change and pink indicates a worsening (e.g. increase in untreated effluent).
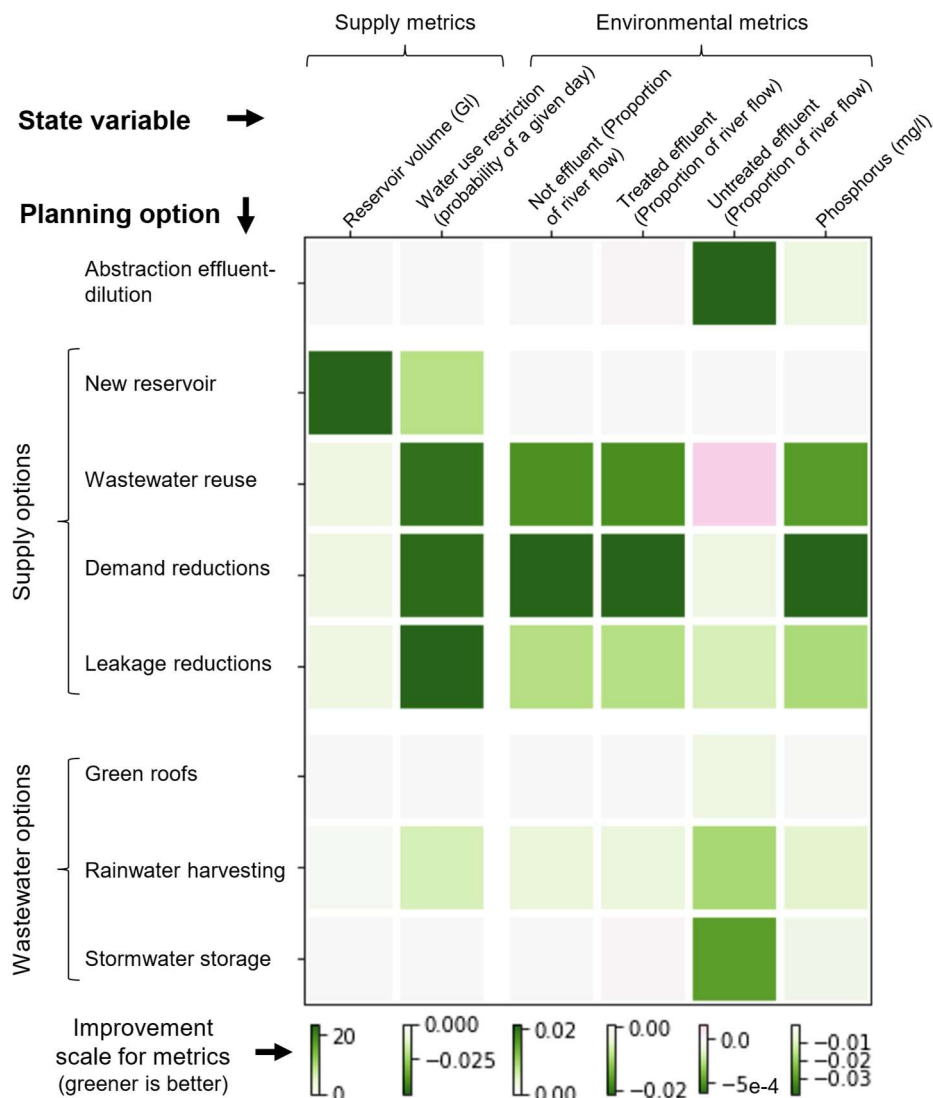
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283   Figure 9. Colour grid showing how different options compare to each other with respect to absolute

284   change various state variables averaged over the entire timeseries, 1903-2018, (greener indicates a

285   greater improvement while more pink indicates a decrease in performance).

286   In context, we see that the abstraction effluent-dilution option (first row) of minimizing abstraction

287   during high precipitation is an effective method to reduce untreated effluent concentration (i.e. first

288   row, fifth column is the deepest green).

289   Among the water supply options, we see improvement in all water supply metrics (first and second

290   columns), but also that they interact with water quality metrics. This interaction occurs through two

291   mechanisms: changing the amount of water abstracted and changing the amount of treated effluent

292 discharged. Each of wastewater reuse, demand reductions and leakage reductions interact with river
293 quality via these mechanisms, but they do so differently.

294 Wastewater reuse (third row) improves quality metrics (except during spill events) by reducing treated
295 effluent discharge and reducing the need for river abstraction. It does, however, also increase the
296 concentration of untreated effluent during storm spill events (i.e. third row, fifth column is pink). This
297 occurs because a portion of treated stormwater is being directed to the supply system rather than
298 diluting the untreated storm spill effluent.

299 Demand reductions (fourth row) improve downstream river quality outside of spill events in the same
300 way – reducing household effluent and reducing river abstractions. Demand reductions do not change
301 untreated effluent concentration since the amount of treated stormwater discharged during spill
302 events is unchanged.

303 Leakage reductions (fifth row) reduce river abstractions but do not change treated effluent output.
304 Therefore, their impact on raw water, treated effluent and phosphorus is not as strong as demand
305 reduction or wastewater reuse (i.e. third, fourth and sixth columns in the fifth row are less green than
306 in the third and fourth rows). However, leakage reductions do interact with spill events due to reduced
307 abstractions and unchanged treated effluent output, diluting untreated effluent during spills (i.e. fifth
308 column is light green).

309 A new reservoir simulated with historical water demand (second row) does not change abstractions or
310 effluent discharge so does not interact with water quality downstream of the CityWat model domain.

311 Wastewater planning options have less impact on the wider urban water cycle – targeting primarily
312 untreated effluent concentration.

313 The exception is rainwater harvesting, which impacts both supply and wastewater metrics (seventh
314 row, green in all columns). If implemented at a city scale, it may reduce water use restrictions by
315 supplying 90% of outdoor water demand not met by rainfall. However, this supply occurs
316 disproportionately outside of drought conditions since harvesting tanks dry up during severe droughts,
317 so the impact is not as significant as it might be. This repurposing of rainfall reduces river abstractions
318 and treated effluent discharge so improves river quality outside of spill events. The impact on
319 untreated effluent is smaller than we might expect, given the large storage capacity provided, since
320 the storage is often full when storms that trigger spill events occur.

321 Green roofs (sixth row) reduce untreated effluent by reducing runoff from roofs that would go to
322 sewers; however, this impact is relatively small compared to other options because the proposed area
323 is small (2% of London's rooftop area, compared to 100% for rainwater harvesting, Table 1).

324 Stormwater storage (eighth row) behaves as expected, reducing untreated effluent but without wider
325 impacts beyond that.

Discussion

327 Our case for a wider systems view of the urban water cycle in planning and management was based
328 on three hypotheses. The first was that abstracting and discharging into the same river while planning
329 wastewater and supply separately will induce model errors in estimating downstream river quality. In

330 our proof-of-concept analysis (Figure 7) we find this error to be significant. We believe this provides

331 evidence that by explicitly accounting for the river state, we can identify unforeseen environmental

332 risks. Abstraction licences for water suppliers are intended to safeguard UK rivers, however, as

333 Figure 1 highlights, water quality on most rivers is not solely dependent on supply-side actions.

334 Meanwhile, proposed metrics for wastewater system performance in Water UK (2019), typically only

335 consider the time of year when discharges are made, not accounting for flows in their receiving waters

336 nor the operation of the supply system. The results presented here provide evidence that the use of

337 in-river water quality metrics are required to account for the environment in water planning.

338 The second hypothesis was that our proposed joint management option, abstraction effluent-dilution

339 (AED), could significantly reduce the concentration of spilled untreated effluent. Our results in Figures

340 8 and 9 show that it achieves a performance comparable to infrastructure-based options, despite only

341 being a new channel for information in operations. In Figure 8 we see that it attains these gains

342 without reducing supply reliability, even though it occasionally limits abstraction. We also highlight that

343 a water company has complete control of this option, unlike some of the other analysed options (e.g.

344 demand reductions or rainwater harvesting). Thus, we argue that AED could be added to the water

345 companies' portfolio of future interventions, albeit with more nuanced design than the simple heuristic

346 presented here to account for factors such as flood risk management.

347 The final hypothesis was that planning options will impact state variables across the wider urban

348 water cycle. Figure 9 shows evidence of this. We see how supply-side options may improve river

349 quality by reducing abstractions. We also see that wastewater reuse may worsen the impact of

350 untreated effluent spills by redirecting stormwater that would be released as treated effluent (diluting

351 the spill) back into the supply system. Accounting for these systems level interactions in cost-benefit

352 analysis could have a significant impact on long-term planning decisions for water infrastructure.

353 **Future direction and concluding remarks**

354 This work demonstrates the case for integration and provides a proof-of-concept for achieving it.

355 However, we recognise the presented top-down approach is not a panacea for water planning and

356 management, nor that the planning options assessment we perform should be taken as literal

357 recommendations for future investment. Although CityWat's model simulations have been compared

358 against historic reservoir volume and river samples of phosphorus (Figures 4, 5) showing good

359 agreement considering the model's simplicity, the field of integrated modelling research has yet to

360 converge on a suitable technique to reliably validate these types of models (Voinov & Shugart, 2013;

361 Belete et al., 2017; Tscheikner-Gratl et al., 2019). Additionally, we use simplistic representations of

362 any individual modelled process in comparison to the state-of-the-art.

363 CityWat's lumped approach also assumes homogeneity in a heterogeneous system. This prevents

364 assessment of small-scale interventions, impacts of upstream water quality on abstractions and the

365 role of options that improve system connectivity, such as the Thames Tideway Tunnel project (Loftus

366 & March, 2019). This project will link up London's storm spill overflows to its largest wastewater

367 treatment works, and so cannot be represented by a city-scale lumped model.

368   In addition, our assessment is based on water management criteria only, and the approach should be

369   extended to include wider benefits of multifunctional infrastructure such as green roofs (Ossa-Moreno

370   et al., 2017; Hattab et al., 2020). Finally, the modelling approach is yet to be tested on how it could be

371   used for flood risk management (Rezazadeh Helmi et al., 2019) and planning under deep uncertainty

372   (Erfani et al., 2018; Babovic & Mijic, 2019).

373   In a survey of water managers, Höllermann & Evers (2017) found that model boundaries were the

374   most commonly cited source of uncertainty. We hope that the scientific and wider communities

375   interested in the sustainability of water systems will continue to build evidence for the importance of

376   system boundaries on model simulations, and study how best to carry out integrated modelling to

377   support the water industry in a future with fewer boundaries and one in which the environment is

378   placed central to planning and management.

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