Corrigendum: Global analysis of urban surface water supply vulnerability (2014 Environ. Res. Lett. 9 104004)

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Abstract

Salem, Oregon was inadvertently included in the analysis, but it does not meet the study threshold population of 750,000 people. This reduces the number of cities in this study from 71 to 70. Changes to figure 1, and tables 1, 2 and 3 as well as the text are shown below. The changes do not affect the overall results or conclusions.

Online supplementary data available from stacks.iop.org/ERL/9/119501/mmedia

Abstract

This study presents a global analysis of urban water supply vulnerability in 70 surface water-supplied cities, with populations exceeding 750,000. Vulnerability represents the failure of an urban supply-basin to simultaneously meet demands from human, environmental and agricultural users. We assess a baseline (2010) condition and a future scenario (2040) that considers increased demand from urban population growth and projected agricultural demand under normal climate conditions. We do not account for climate change, which can potentially exacerbate or reduce urban supply vulnerability. In 2010, 36% of large cities are vulnerable as they compete with agricultural users. By 2040, without additional measures 44% of cities are vulnerable due to increased agricultural and urban demands. Of the vulnerable cities in 2040, the majority are river-supplied with mean flows so low that the cities experience ‘chronic water scarcity’ (12001 p−1 d−1). Reservoirs supply the majority of cities facing individual threats to future freshwater supply, revealing that constructed storage potentially provides tenuous water security. In 2040, of the 31 vulnerable cities, 13 would reduce their vulnerability via reallocating water by reducing environmental flows, and 15 would similarly benefit by transferring water from irrigated agriculture. Approximately half remain vulnerable under either potential remedy.

2.1. Criteria for inclusion and data sources

Paragraph 1:

Water vulnerability assessments were performed for all basins supporting cities with populations in excess of 750,000 that obtain water supplies solely from either (a) river withdrawals or (b) reservoirs (natural or man-made) that are not shared with another large city. In total, 70 cities in 39 countries were identified that meet these criteria. Information on the type and location of urban water sources was obtained from the City Water Map Initiative (McDonald et al 2014). Hydrologic data, including mean annual reliable basin discharge (GWSP 2008b), environmental flow requirements (GWSP 2008a), mean annual reservoir storage capacity (Lehner et al 2011, NID 2009), global potential evapotranspiration rates (Zomer et al 2007, 2008) and urban demand (FAO 2013) were obtained from global databases (see supplemental material). Available environmental flow requirements and discharge statistics for all supply basins were based on time series of monthly climate variables over the climate normal period 1961–1990. Estimates of future
vulnerability are based on urban growth projections developed in the UN World Urbanization Prospects (United Nations 2012). Basin boundaries for each urban water source were delineated using HydroSHEDS (Lehner et al. 2008), yielding 106 surface-water basins, with 48 cities relying on a single supply basin and 22 cities relying on more than one basin. Where a city uses more than one supply basin, that city’s supply basin refers to the combination of discharge from all of the supply basins used.

3.1. Baseline vulnerability and threats (2010)

Paragraph 1:

Each city was assessed according to the three vulnerability metrics defined in section 2. The status of each city, either vulnerable (red), threatened (yellow) or non-threatened (hollow) is shown on the global map in figure 1. The total
number of cities in each category is given in table 1. Of the 70 cities included in this study, 25 are classified as vulnerable in 2010, of which 23 are cities supplied solely by direct river withdrawals. These vulnerable river-supplied cities have significantly lower mean per capita flows (2700 l p⁻¹ d⁻¹) than those cities with sufficient water (200 200 l p⁻¹ d⁻¹), and fall within the range of water availability that Falkenmark et al. (1989) identify as having water management problems due to water stress (2700–4700 l p⁻¹ d⁻¹).

Also examined were ‘threatened’ cities, where ‘threatened’ means that one or two of the three metrics exceed their demand threshold. Of the 70 cities considered, 33 are threatened and represent the majority of reservoir-supplied systems (71%), but only 31% of river-supplied cities are threatened (table 1). Environmental demand was the only stressor for river-supplied cities, however reservoir-supplied cities revealed more varied sources of stress, suffering from a variety of environmental, human and storage-related threats (table 2). The number of threatened reservoir-supplied cities is ten times greater than those considered vulnerable, whereas the number of threatened river-supplied cities is approximately half of those found to be vulnerable (table 1).

3.2. Future vulnerability and threats (2040)

In 2040, the number of vulnerable cities rises from 25 to 31, representing a 24% increase in urban areas facing serious water issues (table 1). Of these 31 cities, those that are river-supplied continue to make up the majority of those that are vulnerable. Our analysis provides a baseline estimate of vulnerability assuming near-term stationarity in urban surface water hydrologic systems. Even without accounting for potential changes in local hydrology due to climate change, as populations increase, mean per capita flows for vulnerable river-supplied cities drop over this 30 year period to 12001 p⁻¹ d⁻¹, creating ‘chronic water scarcity’ (Falkenmark et al. 1989). During this same period, the total number of vulnerable reservoir-supplied cities more than doubles, from 7% to 18%, as storage infrastructure loses its advantage as a supply buffer. When considering only the 31 vulnerable cities in 2040 (table 2), 17 (55%) cities had supply basins dominated by demand from the agricultural sector. The number cities with vulnerable supply basins dominated by demand from the urban sector increases from four (16%) in 2010 to eight (26%) in 2040.

Paragraph 2:

Although more cities become vulnerable in 2040, the percent of ‘threatened’ cities decreases from 47% in 2010 to 43% in 2040 (table 1). Similar to 2010, the majority of reservoir-supplied cities are those considered threatened (71%), however the relative difference between the numbers considered threatened versus vulnerable decreases. Environmental demands continue to be the only stressor for river-supplied cities, however, stress from storage over-allocation becomes the leading threat in reservoir-supplied cities, occurring in 15 of the 28 cities depending on this supply type (table 2). Although the ratio of reservoir- to river-supplied threatened cities increases, by 2040 all but three reservoir-supplied and six river-supplied cities remain unthreatened. Access to large sources of water combined with relatively low urban demand and/or environmental demands keeps these nine cities protected from water-supply compromise.

3.3. ‘Cities-of-concern’—locations threatened or vulnerable in the near future

Paragraph 1:

Between 2010 and 2040, nine ‘cities-of-concern’ were identified as becoming more susceptible, with conditions
Table 3. Number and percent of cities meeting demand and cities that are vulnerable under three reallocation strategies.

| Strategy                                      | Demand met-no reallocation | Demand met-after reallocation | Remaining vulnerable |
|-----------------------------------------------|----------------------------|-------------------------------|----------------------|
| Reallocation through environmental neglect to satisfy Urban demand only | 35 (50%)                   | 51 (73%)                     | 19 (27%)             |
| Reallocation through agricultural transfers to satisfy Urban demand only (% of all cities) | 35 (50%)                   | 50 (71%)                     | 20 (29%)             |
| Urban & environmental demand (% of all cities) | 18 (26%)                   | 28 (40%)                     | 42 (60%)             |
| Storage security (% of all cities)*            | 10 (14%)                   | 13 (19%)                     | 15 (21%)             |
| Reallocation through combined environmental neglect and agricultural transfers to satisfy Urban demand only (% of all cities) | 35 (50%)                   | 57 (81%)                     | 13 (19%)             |

* Percent totals for reallocation through agricultural transfers to satisfy storage security do not add to 100% since there are only 28 cities with reservoir storage.
worsening from a non-threatened to threatened status, or from threatened to vulnerable. In total, three of the cities identified as non-threatened in 2010 become threatened in 2040 (Accra, Ghana; Freetown, Sierra Leone; Panama City, Panama). Six cities-of-concern change from threatened to vulnerable status (Dublin, Ireland; Charlotte, USA; Ouagadougou, Burkina Faso; Guangzhou, Wuhan, and Nanjing, China; figure 1—insets). Three of these cities-of-concern (Charlotte, Ouagadougou, and Panama City), each transition from a system dominated by the environmental sector demand to one dominated by the urban sector demand, as none of their supply basins support significant irrigated agriculture. Of these nine total cities that show increased susceptibility by 2040, six are reservoir-supplied cities and three are river-supplied. This suggests that increased demand by 2040 puts at risk a significant number of both river-supplied and reservoir-supplied cities.

### 3.4. Water reallocation to reduce threats to cities in 2040

**Paragraph 3:**

Growing demand for freshwater will likely force human needs to be placed ahead of environmental requirements. As such, the first strategy is reallocation through environmental neglect in which cities divert all water available for maintaining minimum environmental flows to meet urban needs. Under this strategy agricultural demands are also met, such that neither the urban or agricultural sectors are threatened. Of the 70 cities included in this study, the number of cities that could support urban demands in 2040 increases from 35 to 51 when exercising environmental neglect reallocation (table 3). Urban sector threats alone are reduced in 13 otherwise vulnerable and 29 threatened cities, where nine cities remain non-threatened. Those aided by reallocation through environmental neglect include four of the six cities-of-concern likely to become vulnerable by 2040, with only Ouagadougou and Charlotte failing to benefit.

**Paragraph 4:**

The second strategy reallocates water from agriculture to urban use and shows similar benefits to reallocation by environmental neglect for 50 versus 51 cities. However, agricultural reallocation preserves environmental flows, and shows that roughly the same benefit can be gained without further damage to freshwater-dependent ecosystems. Under this strategy, urban sector threats are reduced in 15 otherwise vulnerable and 26 threatened cities, whereas nine cities remain non-threatened. Reallocation from agriculture leaves 29% of cities (including Ouagadougou, Charlotte, and Dublin) unable to meet urban demands. Additionally, under reallocation of irrigation water, the number of cities for which both urban and environmental demands are met increases from 18 to 28, and the number able to achieve reservoir storage security increases from 10 to 13 cities (table 3). Water available only from agricultural transfers could only support both urban and environmental demands in 3 of the 10 cities-of-concern (Guangzhou, Nanjing, Wuhan) that become more vulnerable between 2010 and 2040. A combination of environmental neglect and agricultural transfers would leave only Ouagadougou vulnerable in 2040.

### 4. Conclusions

**Paragraph 1:**

Cities here are considered ‘vulnerable’ when they exceed minimum thresholds for human, environmental, and storage requirements. Those cities exceeding some but not all three thresholds are considered ‘threatened’. The nature of urban vulnerability discussed here is exclusively focused on large cities judged most at risk for water scarcity because they lack source water diversity. By 2040, 31 of 70 large cities relying on surface water are predicted to become vulnerable. This represents an increase from 36% vulnerable in 2010 to 44% in 2040. In the majority of cases, the number of cities unable to meet human-based demands is likely to outstrip the number of cities for which minimum flow requirements of freshwater-dependent ecosystems are not met. The number of vulnerable river-supplied cities greatly exceeds reservoir-supplied cities in 2010 (tenfold) and 2040 (fivefold). Of large surface-water dependent cities in 2010, 83% are either vulnerable or threatened. This increases to 87% in 2040.

**Paragraph 2:**

Although the majority of threatened cities are reservoir-supplied, artificial storage currently offers far more security to cities using reservoirs. This is indicated by the substantially lower number of vulnerable reservoir-supplied (18%) versus river-supplied cities (62%) in 2040. In particular, reservoirs may have allowed some cities to delay vulnerability in the near future, but the high number of threatened cities suggest that the large financial investments made in the past to improve water security through reservoir storage may no longer be sufficient to prevent vulnerability. It is surprising that reservoir-supplied cities account for 6 of the 9 cities-of-concern showing an increase in vulnerability or threat status (susceptible cities) by 2040. This suggests that the temporal buffering capacity will no longer be adequate to meet both increasing urban and agricultural demands as well as accommodate environmental needs.

**Paragraph 3:**

Large cities can meet urban demand via reallocation by 2040. Reallocation through environmental neglect enables 51 of 70 cities to meet urban demand, and transfers of irrigation water enable 50 cities to meet urban demand. This compares favorably to just 35 cities meeting urban demand when no reallocation exists. Agricultural transfers have the benefit of
lessening urban sector threats while reducing the number of cities experiencing environmental and storage threats. However, reallocation of irrigation water by 2040 can enable both urban and environmental demands to be met in only an additional 14% of cities. Reallocation by environmental neglect enables an additional 23% of cities to meet demand. Of the nine cities-of-concern becoming vulnerable by 2040, only Ouagadougou, Burkina Faso, does not benefit from any reallocation method—even if both environmental and agricultural supplies are both transferred. Source diversification is essential in this and other regions.

**Supplemental Table Information**

Table S-2.1 has been corrected.