Response to Referee 2

Manuscript: egusphere-2026-3475

Title: A High-Resolution Water Resources Assessment Model (HyDRA version 1.0) for Industrial and Domestic Water Use: A regional application for the Gulf Cooperation Council (GCC) Countries and Jordan

Authors: Amr Al-Zu'bi and Yoshihide Wada

We sincerely thank the referee for a careful and constructive review. In response, we added a Discussion of what the 3-arcsecond grid can and cannot be used for, and a blueprint for applying the model elsewhere. We also added a table of data sources, spatial allocation and missing-data treatment for every subsector (Table S1), and an independent evaluation of the TEF in 119 countries. The industrial reconstruction is now compared with a single-sector benchmark.

Referee comments are shown in blue italics, followed by our response. Page and line numbers in the referee comments refer to the preprint; the page and line numbers given after each response refer to the revised manuscript and supplement. Section, figure, table and equation numbers refer to the revised manuscript unless marked "preprint". Two new figures were added (Fig. 6, production by subsector; Fig. 9, industrial consumption), so the domestic figures are now Figs. 10–13 (Figs. 8–11 of the preprint). The supplement has been reorganised to follow the order of the main text; supplementary sections, figures and tables are numbered as in the revised supplement.

Novelty and transferability

> *Overall, the model's methodology is based upon previous work, e.g., Wada et al., 2011; The model's novelty is associated with representing country-scale industrial water use as the aggregated water use of ten sub-sectors, and the explicit representation of infrastructure through the inclusion of connectivity to the water supply network and non-renewable water (e.g., supply system losses). Furthermore, the authors suggest that novelty is associated with the very high resolution of 3 arcseconds and indicate that unlike other regional models – the structure of this model 'can be extended to other regions, given appropriate socioeconomic inputs and harmonized statistical data.' (P. 1, lines 28–29). I find some gaps in the presentation of the novelty associated with the two latter points.*

Response:

We agree that both points needed more support. The revised Discussion explains what the 3-arcsecond allocation is for and where its limits lie and sets out what is needed to apply the model elsewhere. The new Table S1 gives, for every subsector, the sources of production data and locations, the allocation method and the treatment of missing data. Our detailed answers for the specific comments follow.

Location of changes. Revised manuscript: Sect. 4, p. 43, ll. 1–21. Supplement: Table S1, pp. 2–3.

Comment a – Why 3 arcseconds

> *First, while achieving a very-high resolution of 3 arcseconds is possible due to the resolution of the population grids and the use of point-data for industries – the reason for why such high resolution is needed remains unclear. The authors shall discuss the advantages and practical uses of such detailed dataset against the introduced uncertainties associated with downscaling. For LHMs, current state-*

of-the-art is at approximately 1 km resolution, and is already challenging computationally (Hoch et al., 2023) – yet the propose ~90 meters resolution is 10 times higher, and probably provides little, if any, benefits for water resources modeling. Further, choosing the high-resolution gridded population dataset should acknowledge the uncertainty in gridded population products (e.g., see Kuffer et al., 2022; Láng-Ritter et al., 2025). For utilities management and detailed planning – this data may be too uncertain, as all its structural components (households' size, NRW, GDP per capita) are based upon data at coarser resolution. This discrepancy may hide important spatial distinctions associated with very local urban elements affecting land value, development, and thus lifestyle and water use.

Response:

We agree that the purpose of the grid must be stated and that the gridded fields must not be read as local information. The 3-arcsecond grid is an allocation grid, not the resolution of the underlying information, and Sect. 2 now says so. We use it for the following reasons:

- The output can be aggregated, without re-gridding, to any target unit: river basins, aquifers, utility service areas, administrative regions, or the 1 km and 5 arcmin grids of large-scale hydrological models such as hyper-resolution PCR-GLOBWB (Hoch et al., 2023).
- Coastal plants that withdraw seawater stay separate from inland freshwater users, which coarser cells along the Gulf coast would merge.
- The model is also intended for use by government agencies, and showing what is possible at this resolution may encourage them to share more detailed data, which would make the results more accurate.
- The domestic fields follow the settlement pattern of the GHSL population grid.

We also agree with the referee's two caveats. Within a country or Saudi region, the spatial information comes only from the population grid and the plant locations, because per-capita withdrawal, household size, connection rate and NRW vary only between countries and regions. Gridded population products are themselves uncertain and tend to underrepresent rural populations (Kuffer et al., 2022; Láng-Ritter et al., 2025). A new paragraph in the Discussion states both, and concludes that the gridded fields are suited to aggregation and regional assessments but not to utility-scale planning, which requires local information on consumers, networks and land use.

Location of changes. Revised manuscript: Sect. 2, p. 8, ll. 4–9; Sect. 4, p. 43, ll. 1–11.

Comment b – Transferring the model

Second, the authors do not provide sufficient detail of how to transfer the model to other locations. Gaps are mentioned below:

a. The authors suggest that the model structure could be replicated and transferred – but do not define the scope of such structure. For example, sub-sector selection seems biased towards a representation of the oil-economy – which is a cornerstone of the case-study; though, would it fit other areas where some of the aggregate other manufacturing category is dominant, e.g., Bangladesh (Ahaduzzaman et al., 2017), or data-center clusters?

Response:

We agree. The subsector set reflects the hydrocarbon-based economies of the study region, but the structure is not tied to it. Every subsector enters as production × baseline intensity × TEF, so any activity can be added in the same way. A new Discussion paragraph states that the industrial module can be

applied to other regions when the subsectors that dominate industrial water use there are represented explicitly, explains how water is allocated where plant locations are missing, and notes that the domestic module requires further refinement before it is transferred.

For Bangladesh, textiles would be added as an explicit subsector (Ahaduzzaman et al., 2017). The AI and data-centre subsector (Sect. 2.1.10), which is inactive in the historical runs, can be switched on where data-centre clusters are present.

Location of changes. Revised manuscript: Sect. 4, p. 43, ll. 12–17.

> *b. Sector selection (including sub-set of mining activities) is based only on water quantity – ignoring completely the impact of some sectors (e.g., textile industry, mining industry, etc.) on water quality. This is a shortcoming and shall be mentioned in the context of usability and transferability.*

Response:

We agree. The Discussion now states that HyDRA represents water quantity only. The effect of industries such as textiles, mining or chemicals on water quality is not represented, which limits its use where quality rather than quantity constrains availability. Water-quality implications will be addressed in future applications to countries where these subsectors are significant.

Location of changes. Revised manuscript: Sect. 4, p. 43, ll. 19–21.

> *c. The paper lacks sufficient description of the data processing (e.g., input harmonization) and sources to support reproduction (see Reproducibility section below).*
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> *d. While for some industries exact location is available globally (e.g., oil extraction, electricity generation), for most sectors data source used in this study, and required data for transferability remain unclear (e.g., paper, food processing, refining, chemicals, cement, metals, etc.).*

Response:

The new Supplementary Sect. S1 and Table S1 give, for every subsector, the source of the production data, the source of the locations, the method used to allocate water within each country and the treatment of missing data. Table 2 now refers to Table S1.

- Power plants, with their capacities and cooling types, come from Byers et al. (2018).
- Oil fields come from the Global Oil and Gas Extraction Tracker (GEM, 2026).
- Mining areas come from Maus et al. (2020).
- Refineries, petrochemical plants, steel plants, aluminium smelters, cement plants and the potash works were located individually. Their coordinates and annual capacities are provided by country in the HyDRA code and data archive (https://doi.org/10.5281/zenodo.24403901; folders Sub_Sectors/<subsector>/plant_capacity_location). The archive also lists the company reports, announcements and news from which the capacities were compiled (Sub_Sectors/References.xlsx).
- Food and beverage, paper and pulp and other manufacturing have no plant-level data. Their withdrawal is distributed over industrial areas in proportion to their extent.

Location of changes. Revised manuscript: Table 2 caption, p. 8, ll. 16–17. Supplement: Sect. S1, p. 1, l. 18 – p. 2, l. 5; Table S1, pp. 2–3.

> *The authors discuss the different stages (as shown in the conceptual figure 1, including scoping and data preparation), including the logic or reasoning behind different choices (e.g., in the discussion*

section, maybe proposing a blueprint for transferability). The authors shall provide more information regarding the decisions made during data harmonization – as other researchers shall go through the same challenges compiling data from different sources. Specifically, they shall disclose the methods used for interpolation of missing data (i.e., over time or across countries), as currently there are some pieces of information that do not form a clear understanding for the reader. Finally, they should indicate how to handle missing data – e.g., how to downscale industrial water use if high resolution industry's location is missing for some sectors.

Response:

We agree that these choices should be visible to anyone repeating the work. Table S1 now gives the treatment of missing data for each subsector and for the domestic inputs. Gaps over time were filled when the input tables were compiled: years before the first record were back-cast at constant growth rates, interior gaps were interpolated linearly, the last reported value was held where no newer data exist, and the latest years were extrapolated at fixed growth rates of 1–6 % per year. Supplementary Sect. S1 and Table S1 give the details by subsector. Proxies across countries are used in three places: household size and connection rate in the UAE are taken from Qatar; NRW in the UAE follows Qatar's trajectory (Sect. 2.2); and NRW is set to 30 % where no value is reported (2025, and Hail from 2023). Oil-field capacities are held constant over time because no time-varying field data exist (Sect. 2.1.8).

For missing locations, the transfer paragraph in the Discussion explains that withdrawal can be allocated to industrial or mining areas in proportion to their extent. This is what we did for food and beverage, paper and pulp, mining and other manufacturing.

Location of changes. Revised manuscript: Sect. 2.2.1, p. 24, ll. 16–17; Sect. 4, p. 43, ll. 15–17. Supplement: Sect. S1, p. 1, l. 18 – p. 2, l. 5; Table S1, pp. 2–3.

Validation and modeling improvement

The authors validate their country's scale and regional scale results in the GCC region as well as in European countries. The techno-economic factor (TEF) is validated by comparing the normalized observed and predicted water use intensity. Regional water use intensity is also compared for different regions. These sections require some additional input and clarifications.

Response:

We agree, and we have revised and extended the evaluation of both the industrial and the domestic results:

- Each panel of Fig. 3 now reports Pearson r, the concordance correlation coefficient and the median absolute percentage error, and all statistics exclude the 2020 reference year (Comment 4).
- Breaks in the reported records are identified from the observations alone, and Sect. 3.1.1 discusses what they mean for the evaluation (Comments 2 and 3).
- The TEF is evaluated independently in 119 countries, 82 of them with consistent records (Supplementary Sect. S5).
- The subsector test (Fig. 4) reports the error and bias of each subsector, and Supplementary Sect. S6 shows that the drivers of the test countries cover the TEF values of the study region.

- The full model is compared with a single-sector reconstruction driven by the same variables, and the change in industrial withdrawal is decomposed into economic growth, production mix and intensity (Sect. 3.1.3; Comment 7).
- The domestic evaluation reports the error, correlation and bias at national and regional scale, and the captions state the source of the observed ranges (Comments 1 and 6).

A new paragraph in the Discussion brings these tests together. It explains why several tests are needed, what they show, and how HyDRA differs from global models that scale aggregated industrial withdrawal with economic indicators. The Discussion also states which inputs limit the results most and what this implies for data-poor regions such as sub-Saharan Africa. Our answers to the specific points follow.

Location of changes. Revised manuscript: Sect. 4, p. 42, ll. 1–17; Sect. 4, p. 43, ll. 17–19.

Comment 1 – Source of the observed ranges

> *Observed data is shown as a median value +/- 1 s.d.; The source of the data and its treatment is unclear- why is observed data an array and not a single annual point? What is its source? This should be clarified by the relevant figures (3, 8, and 9).*

Response:

The observations are arrays because they combine reported water use with input data from several sources. In Fig. 3, the observed intensity is reported industrial withdrawal (AQUASTAT) divided by total energy use. Energy use is computed with each of the two energy-per-capita and two population datasets of Table 2, and the points and error bars are the median ± 1 s.d. over these four combinations. In the domestic figures (Figs. 10 and 11; Figs. 8 and 9 of the preprint), observed per-capita withdrawal comes from national statistics and AQUASTAT and is converted to per-capita values with several population datasets; the spread covers both. The captions of Figs. 3, 10, 11 and S4 now state this.

Location of changes. Revised manuscript: Fig. 3 caption, p. 25, ll. 6–10; Fig. 10 caption, p. 36, ll. 1–2; Fig. 11 caption, p. 37, ll. 5–7. Supplement: Fig. S4 caption, p. 7, ll. 6–8.

Comment 2 – Breaks in the observed records

> *Additional discussion shall be dedicated to clear cuts in observed data – why do they occur? What do the mean for validation – e.g., Saudi Arabia and Bahrain.*

Response:

Section 3.1.1 now discusses the data breaks. Bahrain's reported intensity drops abruptly in 2004–2005 and again in 2014–2015. Qatar's rises sharply in 2014–2016, during the infrastructure expansion before the 2022 FIFA World Cup. The UAE's values of the 1990s are eight to fifteen times its 2020 value. Changes of this size within one or two years reflect changes in reporting rather than in efficiency. In Saudi Arabia and Oman, the reported intensity rises until about 2007 and 2016, respectively; the early records appear to omit some industrial subsectors, which lowers the early values and produces an apparent rise.

For validation, values on either side of a break are not comparable, so the statistics of Fig. 3 combine model error with reporting changes. This is why the TEF is also tested against an independent set of countries with consistent records. A screen based on the observations alone flags breaks in 37 of 119 countries, including Qatar and the UAE. The TEF is then evaluated in the remaining 82 countries (Supplementary Sect. S5; see Comment 4).

Location of changes. Revised manuscript: Sect. 3.1.1, p. 25, l. 19 – p. 26, l. 12.

Comment 3 – Kuwait and Bahrain

> *The authors indicate that some countries WWI (industrial) have considerable inconsistencies (P. 22, lines 17-18). They don't mention Kuwait and Bahrain, which seems to have similar inconsistencies with most other countries.*

Response:

Section 3.1.1 now names both. In Kuwait and Bahrain, the TEF follows the direction of the reported decline (r = 0.74 and 0.71). However, the reported intensities of the 1990s are two to three times their 2020 value, a steeper decline than the TEF reproduces. In Bahrain the record also contains the breaks described under Comment 2.

Location of changes. Revised manuscript: Sect. 3.1.1, p. 25, ll. 11–18.

Comment 4 – Support for the data-quality argument

> *The authors suggest that these inconsistencies occur in countries with 'limited, aggregated, or inconsistent data' (P. 22, line 15–17) – yet the figure or the text do not provide sufficient proof for this claim – instead it shows that the model fails to replicate historical dynamics for most countries' industrial water use intensity (4-6 out of 7). Figure S3 presents a better result, yet some countries are not performing so well. The authors shall improve their arguments regarding model performance and capacity to capture long-term dynamics, as it currently seems they are missing some structural element.*

Response:

We agree that the original sentence was not supported, and we have removed it. Each panel of Fig. 3 now reports r, CCC and MdAPE, and Sect. 3.1.1 discusses them. It states first where the TEF agrees with the reported intensity (Jordan, Kuwait, Bahrain and the UAE; r = 0.71–0.96), and then where it does not (Saudi Arabia, Oman and Qatar).

The data-quality argument is now supported by an independent test (Supplementary Sect. S5, Fig. S5). We compared the TEF with the observed intensity in the 119 countries with at least 15 years of records. A screen that uses only the observations flags breaks in 37 of them, including Qatar and the UAE. In the remaining 82 countries, the TEF reproduces the direction of change in 77 % of countries and predicts a significant decline in 50 of the 53 countries where one is observed. It also outperforms a no-change benchmark in 65 % of country-years. For Fig. S4, Fig. S5c now gives the per-country correlations: the median r is 0.67 in the screened countries, and 63 % of them exceed 0.5. The countries that perform less well are part of this distribution. Section S5 also notes that the TEF is smoother than the observations and does not reproduce year-to-year fluctuations.

On a missing structural element: Fig. 3 compares the TEF, which represents efficiency change only, with the intensity of the whole industrial sector, which also changes with the production mix. HyDRA represents the production mix through subsector production, and the single-sector benchmark in Fig. 5 isolates the effect of this term: without the production mix, the same drivers give a 1990 withdrawal 56–130 % higher in five of the seven countries (Sect. 3.1.3; see Comment 7).

Location of changes. Revised manuscript: Fig. 3 caption, p. 25, ll. 6–10; Sect. 3.1.1, p. 25, ll. 11–18; Sect. 3.1.1, p. 25, l. 28 – p. 26, l. 12; Sect. 3.1.3, p. 29, l. 30 – p. 30, l. 5. Supplement: Sect. S5, p. 9, ll. 6–9.

Comment 5 – Demand-side policies

Specifically – TEF misses the human behavior aspects associated with national policies aimed for controlling water use – e.g., campaigns, water pricing, etc. This should be discussed.

Response:

We agree. The TEF represents efficiency change through GDP, energy intensity and electricity use. Demand-side measures such as tariff reforms, water-saving campaigns or discharge regulations therefore affect it only insofar as they change these indicators, and the Discussion now states this. For domestic use, the observed decline in Bahrain between 2000 and 2010, which the model does not reproduce, is a likely example (Sect. 3.2).

Location of changes. Revised manuscript: Sect. 3.2.2, p. 36, ll. 6–11; Sect. 4, p. 42, ll. 17–20.

Comment 6 – Domestic performance in Bahrain and Jordan

Domestic water performance is better – yet similar problem is evident in Bahrain and Jordan (Figure 9).

Response:

We agree. Section 3.2.1 now reports the bias for each country: it is negative in all five countries with observations and largest in Bahrain, Qatar and Jordan (−10 to −12 %). In Bahrain, the observed decline between 2000 and 2010 coincides with no comparable change in GDP per capita or household size, and the model does not reproduce it. Section 3.2 names possible causes outside the model: tariff reform, network rehabilitation and changes in reporting. In Jordan, the offset is confined to the years before about 2006: reported per-capita withdrawal stayed at 130–155 L cap^{-1} d^{-1} throughout, whereas the modelled value is lower in the 1990s because GDP per capita was lower and households were larger than in 2020; since 2006 the two agree within 8 %. Supply in Jordan is rationed and intermittent, so per-capita withdrawal is limited by supply rather than by demand, which the income and household-size terms do not represent. Section 3.2.1 now says so.

Location of changes. Revised manuscript: Sect. 3.2.1, p. 35, ll. 8–17; Sect. 3.2.2, p. 36, ll. 6–11.

Comment 7 – Restricted model version

To demonstrate improvement – the authors may consider running their models with a restricted version (e.g., lumped industrial sector) and compare with the current version and the observed data.

Response:

We thank the referee for this suggestion, which we have followed. Figure 5 now includes a single-sector reconstruction driven by the same variables: each country's 2020 total divided by the national TEF of each year, i.e. the TEF variables used directly as drivers of total withdrawal. In 1990 the two reconstructions differ by 56–130 % in five of the seven countries. The comparison shows that the subsector structure matters most where water-using industries grew at a different pace from these drivers, most of all in the UAE, Bahrain and Kuwait, and a decomposition of the industrial change into economic growth, production mix and intensity shows why (Sect. 3.1.3). We did not use the national records of total industrial withdrawal to rank the two versions, because they cover few years, contain breaks in reporting and include power-plant cooling water, which Fig. 5 excludes (Sect. 3.1.3). The model is tested against observations where the records are consistent: the TEF in Fig. 3 and Supplementary Sect. S5, and the subsector intensities in Fig. 4.

Location of changes. Revised manuscript: Sect. 3.1.3, p. 29, ll. 17–23; Sect. 3.1.3, p. 29, l. 30 – p. 30, l. 5; Fig. 5 caption, p. 30, ll. 20–25.

Reproducibility

Comment 1 – Geolocation of industries

Geolocation data of industries is not stated for all the sectors and is not clearly shown. To enhance reproducibility – the authors shall add a column with the references to table 3 or a relevant row to table 2.

Response:

Table 2 now refers to the new Table S1, which lists the location source and the allocation method for every subsector (see our answer to Comment b.c–d). The coordinates and annual capacities of every plant, field and works used in the model are provided by country in the code and data archive (https://doi.org/10.5281/zenodo.24403901), so the spatial allocation can be reproduced exactly.

Location of changes. Revised manuscript: Table 2 caption, p. 8, ll. 16–17. Supplement: Table S1, pp. 2–3.

Comment 2 – Broken KAPSARC links

Some references associated with data associated to industrial water use/production are broken – specifically those directing to KAPSARC website. For example, the link to the metal production data (P.44, line 3) indicates a page stating, no results found', yet using the search box of the KAPSARC data yields 82 datasets. Other links lead to an error 404.

Response:

Thank you. Each KAPSARC dataset is now a separate reference that names its original source (BP, OAPEC or the British Geological Survey) and gives its own link; all links were checked. All production series used in the model, including those from KAPSARC, are also included in the code and data archive (Sub_Sectors/<subsector>/model_input_data), so the results do not depend on external links.

Location of changes. Revised manuscript: References (KAPSARC), p. 54, l. 19 – p. 55, l. 24.

Comment 3 – Urban and rural cells

Data used to distinguish urban from rural cells is not explicitly mentioned.

Response:

Section 2.2 now names the dataset. Urban and rural cells are distinguished with the GHSL settlement model (GHS-SMOD; Schiavina et al., 2023), resampled to the 3-arcsecond grid. The consumption fraction CF decreases linearly with the settlement class, from 0.50 in rural cells to 0.10 in urban centres.

Location of changes. Revised manuscript: Sect. 2.2.1, p. 24, ll. 5–12.

Comment 4 – Cooling water

The authors should clearly indicate how their model accounts for cooling water, as it is separated from WWI in table 3. Further, the authors shall not assume that all cooling water (e.g., in other areas) is seawater or other saline water.

Response:

Cooling water is computed separately from process withdrawal, using the cooling intensities of Table 3: 40 m^3 per m^3 of crude for refining, 80 $m^3\ t^{-1}$ for petrochemicals and 70 $m^3\ t^{-1}$ for basic metals. We agree that it should not be assumed to be seawater everywhere, and it is now assigned plant by plant. Plants within 10 km of the coastline are assumed to use once-through seawater cooling, and their cooling water is reported as seawater at the plant location. Inland plants, such as the refinery and steel plants in Jordan and the Riyadh refinery, are assumed to use recirculating cooling whose make-up water is part of their process withdrawal intensity, and are assigned no separate cooling water. Section 2.1 now states this and notes that applications elsewhere require the cooling source to be assigned plant by plant. Table S3 reports the cooling water separately from freshwater withdrawal (35 $km^3\ yr^{-1}$ in 2025, more than the 30 $km^3\ yr^{-1}$ withdrawn by power plants), and Table S1 describes the allocation.

Location of changes. Revised manuscript: Sect. 2.1, p. 11, ll. 7–14. Supplement: Table S1, pp. 2–3; Table S3 caption, p. 12, ll. 10–17.

Specific comments

P. 9, line 4

Florke et al (2013) uses economic metric manufacturing gross value added (GVA) and not GDP per capita as stated.

Response:

Corrected. Section 2.1 now states that Flörke et al. (2013) use manufacturing gross value added.

Location of changes. Revised manuscript: Sect. 2.1, p. 9, ll. 3–4.

P. 9, lines 8–9

I believe that the relationship between water use intensity and energy intensity was assumed by Shen et al., 2008, not by Hanaski et al., 2013 as mentioned).

Response:

Corrected. The relationship with energy intensity is now attributed to Shen et al. (2008).

Location of changes. Revised manuscript: Sect. 2.1, p. 9, ll. 7–9.

P. 13, lines 20–25

The electricity generation water requirements can include additional dynamic parameters – e.g., water temperature – as shown by Jones et al (2025) – should be mentioned in limitations.

Response:

Added to the limitations in the Discussion: cooling-water requirements vary with ambient and water temperature, which affect plant efficiency and the water needed per unit of electricity (Jones et al., 2025), and fixed intensities per MWh do not capture this.

Location of changes. Revised manuscript: Sect. 4, p. 41, ll. 19–20.

P. 13, line 31

'...to-heavy crude oils have ...' instead of had

Response:

Corrected.

Location of changes. Revised manuscript: Sect. 2.1.2, p. 14, l. 30.

P. 13, line 34 – P. 14, line 1

Figures seem to be associated with light-to-medium and not medium-to-heavy.

Response:

We agree. The values quoted (1.5, 0.96 and 40 m^3 per m^3 of oil) are those for light-to-medium crude, which dominates in the region. The text and Table 3 now say so and list the medium-to-heavy range (2.24–3.47 $m^3\ m^{-3}$) separately.

Location of changes. Revised manuscript: Table 3, pp. 12–13; Sect. 2.1.2, p. 14, ll. 28–30.

P. 15, line 31

The use of 42% to indicate consumption-to-withdrawal is not completely justified. Some evidence may be found in material flow analysis of water footprint accounting papers. For example, Henningsson et al. 2001 – suggest that 70% of the water use in the F&B sector end up as wastewater. Authors shall also check other cases where an average approach was applied.

Response:

Thank you for the reference. Henningsson et al. (2001) imply that about 30 % of the water used in food and drink processing is consumed, which is less than the 42 % used here. The 42 % is the mean consumption-to-withdrawal ratio of the other subsectors, since no consumption data exist for food and beverage in the study countries. Section 2.1.6 now cites Henningsson et al. (2001) and states that food-and-beverage consumption is therefore likely an upper estimate. The same 42 % is used for other manufacturing (Sect. 2.1.11), and Sect. 3.1.4 notes that both values are assumptions.

Location of changes. Revised manuscript: Sect. 2.1.6, p. 16, l. 33 – p. 17, l. 1; Sect. 2.1.11, p. 21, ll. 10–15; Sect. 3.1.4, p. 34, ll. 18–19.

P. 16, Section 2.1.8

Additional explanation of the model used for oil extraction could be useful – as it is very specific application (in a broader paper) and it includes a lot of technical language. E.g., what does surface oil and produced water production rates – some clarification regarding production process would be good.

Response:

We have added a short description of the production process at the start of Sect. 2.1.8. Reservoir pressure is maintained by injecting water to replace the volume of fluids withdrawn. The oil reaches the surface together with formation water (produced water), whose ratio to the oil volume, the water–oil ratio (WOR), increases as fields mature. Part of the produced water is treated and reinjected, and the

rest of the injection demand is met with water from outside the field. Formation volume factors convert surface volumes to volumes at reservoir pressure and temperature.

Location of changes. Revised manuscript: Sect. 2.1.8, p. 17, ll. 16–21.

P. 17, lines 14–29

Sensitivity analysis of selected parameters B0, Bw, and WOR shall be advanced to shed light on the uncertainty associated with researcher choice of representative value.

Response:

Withdrawal per unit of oil follows Eq. (12), $W/Q_o = B_o/B_w + WOR(1 - \eta)$. Because the equation is linear in its parameters, its sensitivity can be given directly, and Sect. 2.1.8 now reports it. With the other parameters fixed, Bo over 1.05–1.60 changes the withdrawal intensity by −13 % to +16 %, and Bw over 1.00–1.06 by less than 3 %. WOR over its regional range of 0.01–1.5 gives 1.27–1.70 $m^3\ m^{-3}$, and the global average of about 4 gives 2.42 $m^3\ m^{-3}$. Consumption equals withdrawal (Sect. 2.1.8) and has the same sensitivity. Oil extraction accounted for about a third of regional industrial withdrawal excluding electricity in 2025, so a WOR between 0.01 and 4 changes that total by about ±10 %.

Location of changes. Revised manuscript: Sect. 2.1.8, p. 19, ll. 12–17.

P. 20, line 12

Which countries did not have DWW? Further (line 13) – the choice of 50 l/cap/day is either prescriptive or assuming some initial development status. This assumption would is not suitable in other regions, e.g., SSA. The details are important for transferability. There are areas in the world (e.g., in SSA) where water withdrawal is far below 50 l/cap/day – the choice of this minimum value is normative, whereas a descriptive approach is probably better for this model. Furter – is the 500 l/cap/day justified – why is it restricted to the local

Response:

Kuwait and Oman have no observed domestic withdrawal. The curve is used only to set their reference-year values, and Sect. 2.2 now names them. We agree that the bounds are normative. The lower bound of 50 L $cap^{-1}\ d^{-1}$ is the basic water requirement of Gleick (1996) and the lower end of the 50–100 L $cap^{-1}\ d^{-1}$ recommended for the human right to water (OHCHR, 2010). The upper bound of 500 L $cap^{-1}\ d^{-1}$ lies slightly above the highest per-capita withdrawal observed in the region, which is why it is a regional value. Both bounds affect only Kuwait and Oman, whose GDP per capita lies within the fitted range. Section 2.2 now states that in regions where withdrawal falls below 50 L $cap^{-1}\ d^{-1}$, such as parts of sub-Saharan Africa, the bounds should be estimated from observations rather than prescribed.

Location of changes. Revised manuscript: Sect. 2.2.1, p. 22, ll. 5–22.

P. 21, line 20

The authors used a fixed water consumption fraction (CF) to represent urban and rural areas (0.1 and 0.5, respectively). In a previous work Wada et al (2010) argued that these fractions (termed recycling ratios -> 1 – CF), are expected to change with country development. Yet, this information is lacking in this paper, and readers may think that the indicated fractions are globally applicable.

Response:

We agree. Section 2.2 now states that the two end values, 0.10 for urban centres and 0.50 for rural cells, are regional values and are not meant to apply globally. The consumption fraction of a cell is not fixed over time, however. It is set by the cell's degree of urbanization in the GHSL settlement grid (GHS-SMOD), which is available at five-year intervals and was interpolated to annual grids, so the national consumption fraction changes as the population urbanizes. What is held constant is the value assigned to each settlement class. Section 2.2 also states that applications to regions with expanding sanitation and wastewater infrastructure should let these values change with development, as in Wada et al. (2011).

Location of changes. Revised manuscript: Sect. 2.2.1, p. 24, ll. 5–12.

P. 26, line 17

You have probable meant figure 6

Response:

Correct. The paragraph has been rewritten and now refers to the right figures.

Location of changes. Revised manuscript: Sect. 3.1.3, p. 29, ll. 24–29; Sect. 3.1.3, p. 30, ll. 14–17.

P. 26–28

Currently Figure 6 is not referenced in the text – following my last comment – make sure all figures (6 & 7) are referred to from the text.

Response:

All figures are now referred to in the text. Figure 6 of the preprint (power-plant withdrawal) is now Fig. 7, and Fig. 7 of the preprint (map) is now Fig. 8; both are referred to in the paragraph on the coastal concentration of industry (Sect. 3.1.3). The new Fig. 6 (production by subsector) is referred to in the same section, and Fig. 13 (gridded domestic withdrawal) in Sect. 3.2.2.

Location of changes. Revised manuscript: Sect. 3.1.3, p. 29, ll. 24–29; Sect. 3.1.3, p. 30, ll. 14–17; Sect. 3.2.2, p. 36, ll. 24–30.

P. 30, lines 3–10

The distinction of what drives national water withdrawal and consumption is presented as a result – but the observation that national fluctuation in withdrawal closely follow economic growth and changes in household size, and that consumption is related to network efficiency and urbanization – is rooted in the modeling framework – this is not a result, rather an outcome of the model design.

Response:

We agree, and the paragraph has been removed. Section 3.2 now reports a decomposition of the domestic change, which cannot be read from the equations. Population growth accounts for almost 90 % of the increase in regional domestic withdrawal between 1990 and 2025, and the decline in household size for most of the rest. Income and household size mainly shape the differences between countries (Fig. 12).

Location of changes. Revised manuscript: Sect. 3.2.2, p. 36, ll. 24–30.

P. 33, line 14

The use of monetary water intensities instead of physical units in the F&B sector is presented as a limitation. Yet it is also an opportunity to be used with widely/globally available input-output tables (IOT) and to be linked to IAMs to inform projected water withdrawal at a sectoral level. These should be acknowledged.

Response:

We agree and have added this to the Discussion. The monetary formulation links the subsector directly to input–output tables that are available worldwide, such as GLORIA (Lenzen et al., 2017, 2022), and that are used in integrated assessment models. Food-and-beverage withdrawal can therefore be projected consistently with economic scenarios.

Location of changes. Revised manuscript: Sect. 4, p. 41, ll. 29–32.