Generating a Robust Global Dilution Factor Estimation from River Flow and Wastewater Effluent

Christopher M. Holmes[1*], Jillian LaRoe[1], Andre Roberts[2] and Juliet Hodges[2]
[1]Applied Analysis Solutions LLC, Winchester, VA, USA; [2] Unilever Safety & Environmental Assurance Centre, Sharnbrook, UK

Introduction

- Dilution factors (DFs) are critical for predicting environmental concentrations of contaminants discharged from wastewater treatment plants (WWTPs) into river systems.
- Currently, DFs used in chemical risk assessments do not take into account spatial and temporal resolution and lack transparent methodology.
- In many regulatory frameworks, a single default DF is applied.
- DFs for individual river segments vary due to natural variability in stream flow over time and spatially across a landscape underscoring the value of refinement of a single, simplistic default screening level DFs for refined ERAs.
- This work addresses these gaps by developing an up-to-date global DF dataset using high-temporal resolution hydro-environmental data and robust geospatial processing.

Materials and Methods

- Global datasets provide consistency and good spatial representation (Table 1).
- Representative points (FLO1K cells) were selected for each river using a median of cells within 500m of river lines (Figure 1).
- 56 years of mean annual and lowest monthly flow extracted for each representative point.
- WWTPs were spatially associated with closest river segment
- Next downstream segment assigned as the outfall location for each WWTP (Figure 2)
  - To avoid low-flow headwater reaches where FLO1K uncertainty is highest
- DF calculated annually for each WWTP

$$(DF) = \frac{(waste\ discharge\ [m^3/s] + river\ flow\ [m^3/s])}{waste\ discharge\ [m^3/s]}$$

- Three Levels of aggregated results
  - Level 1: individual WWTP-level distributions of river flow over 56 years
  - Level 2: temporally summarized river flows and WWTP DFs
  - Level 3: spatially summarized country-level distributions of DFs
- Figure 3 illustrates the overall process

Table 1. Data types, attributes and sources used in the study

Data	Dataset Name (Type)	Attributes	Year(s)	Reference
WWTPs	HydroWASTE (points) (n=58,502)	Location, Population served, Discharge flow	200x – 20xx (varies by country)	Ehalt Macedo et al., 2022
River flow	FLO1K (1km grid) (56 years)	Surface runoff for all grid cells. Mean annual and lowest monthly mean flow.	1960-2015	Barbarossa et al., 2018
Rivers	HydroRIVERS (lines)	Spatial path of river segments, hydrologic sequencing.	n/a - static	Lehner & Grill, 2013

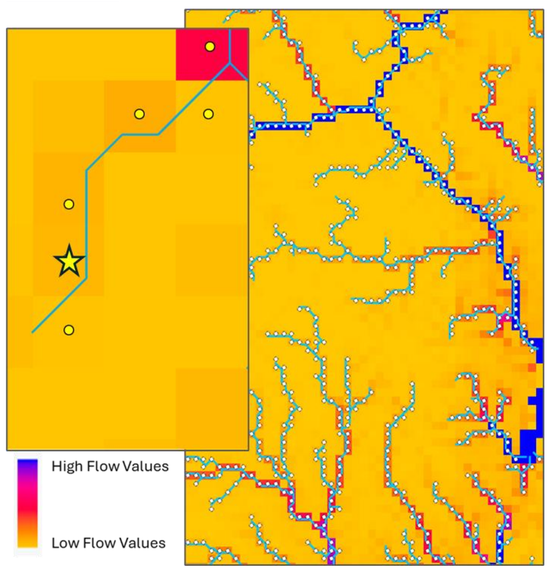

Figure 1. Selection or river segment representative point (star) for FLO1K extraction

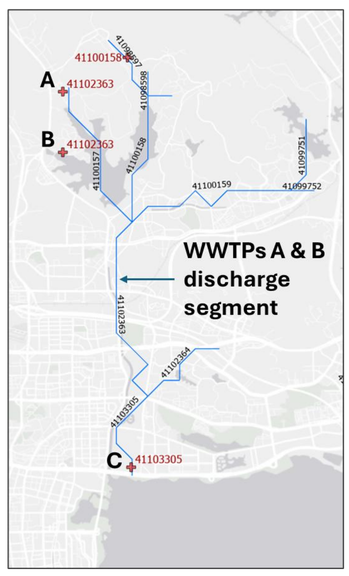

Figure 2. Selection of WWTP discharge river segment

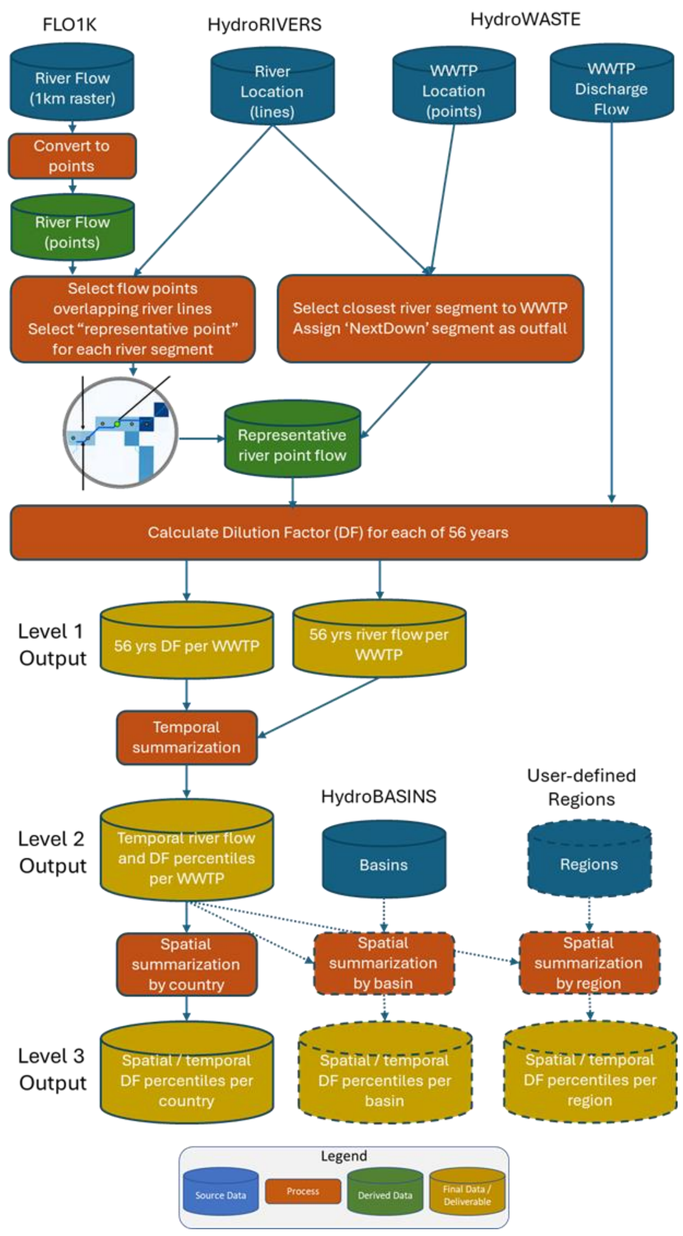

Figure 3. Overview of the source data (blue), processing steps (orange), derived datasets (green) and outputs (brown).

Results

- Empirically derived Level 3 DFs (FLO1K annual mean flow dataset) span several orders of magnitude globally (Figure 4). The country-level medians (using 56-year temporal median for each WWTP) range from <5 in arid regions to >1,000 where large river flows dominate, compared to the widely used default of 10.
- Temporal variability (Level 2) captures 56 years of hydrological variability per WWTP (Table 2 & Figure 5). Users select context-appropriate percentiles, e.g., temporal median of mean flow for typical conditions, temporal 10th %ile of mean flow as a conservative quasi-low-flow proxy.
- Level 2 results can be used for user-defined DF distributions based on HydroBASINS or custom area (Figure 6).
- Country-level (Level 3) summaries for 175 countries include % sewer connectivity and % treated by WWTP increasing applicability.

Table 2. Example of Level 2 output table showing attributes and DF percentiles

	A	B	C	D	E	F	G	J	S	T	U	V	W	X	Y
1	WASTE_ID	COUNTRY	CNTRY_ISO	POP_SERVED	WASTE_DIS_CMS	DISCHARGE HYRIV_ID	COAST_ 10KM	PFAF_ID	DF_5th_5 6yrs	DF_10th_ 56yrs	DF_25th_ 56yrs	DF_50th_ 56yrs	DF_75th_ 56yrs	DF_90th_ 56yrs	DF_95th_ 56yrs
16761	20228	Germany	DEU	37,600	0.14075	20380161	0	232640360200	8.7	9.9	14	18	23	23	26
16762	20229	Germany	DEU	2,545	0.01676	20382991	0	232640360300	34	40	55	69	88	94	104
16763	20230	Germany	DEU	45,000	0.09378	20370663	0	232640310200	7.6	8.1	11	13	15	17	17
16764	20231	Germany	DEU	70,979	0.14842	20372185	0	232640310100	3.4	3.6	4.3	4.8	5.4	5.8	6.2
16765	20232	Germany	DEU	8,822	0.02526	20370464	0	232640310300	3318	4247	5582	6926	8923	10001	11315
16766	20233	Germany	DEU	7,384	0.02206	20371641	0	232640330100	3585	4594	6047	7535	9664	10807	12277

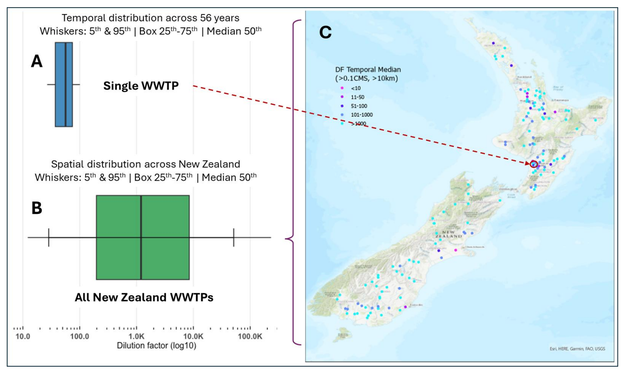

Figure 5. For New Zealand, (A) the Level 2 temporal distribution of a single WWTP, (B) the Level 3 spatial distribution of DFs using t50mean, and (C) the spatial locations of all 139 WWTPs

Table 3. Level 3 DF distributions (50th temporal percentile of mean annual flow) shown with % population connected to sewer and % sewer treated by WWTP.

Country	Count of WWTPs	5th	10th	25th	50th	75th	90th	95th	% of waste-water to sewer	% sewer treated by WWTP
Algeria	64	4	7	12	55	153	301	331	89.5	77.4
Argentina	106	4	8	37	130	715	3,700	73,788	57.4	87.7
Australia	593	7	15	56	228	1,335	6,424	18,354	94.1	100
Austria	624	37	58	161	477	2,804	26,665	73,831	92.7	100
Bangladesh	11	7	8	12	41	105	176	412	7.6	0.0

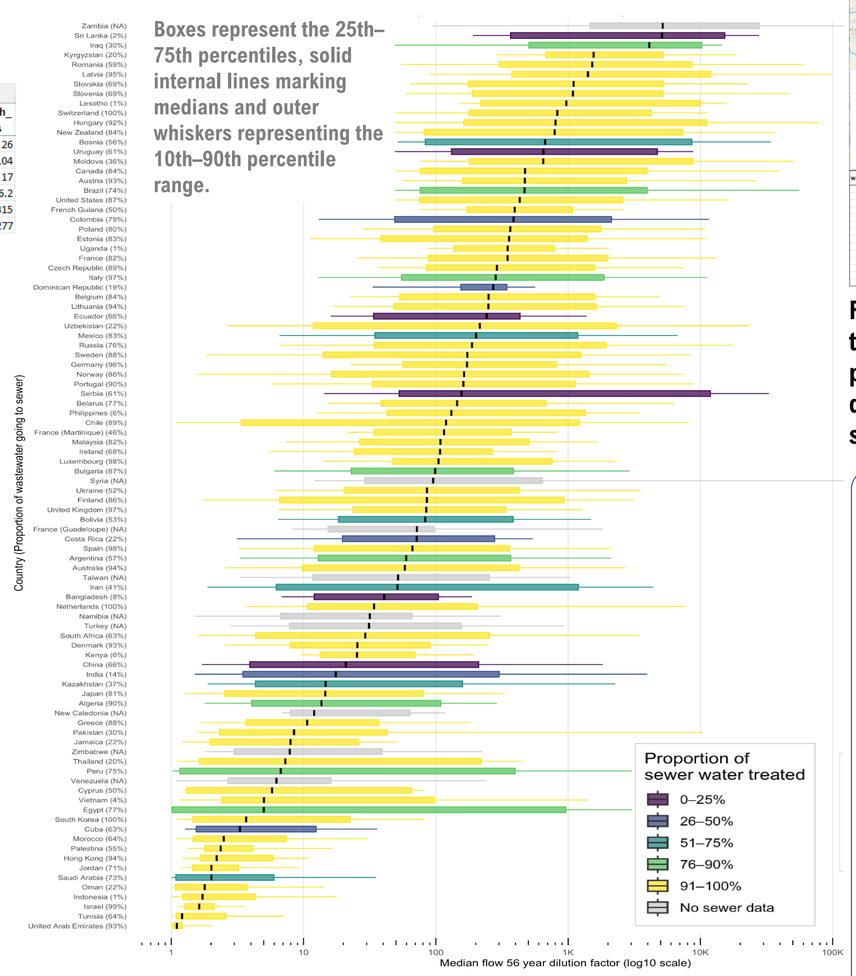

Figure 4. Spatial variability of 56-year temporal median DFs for each country (mean flow data). Country labels include the proportion of population connected to sewers and bar colors denote the proportion of sewer water treated by WWTPs (WHO, 2023).

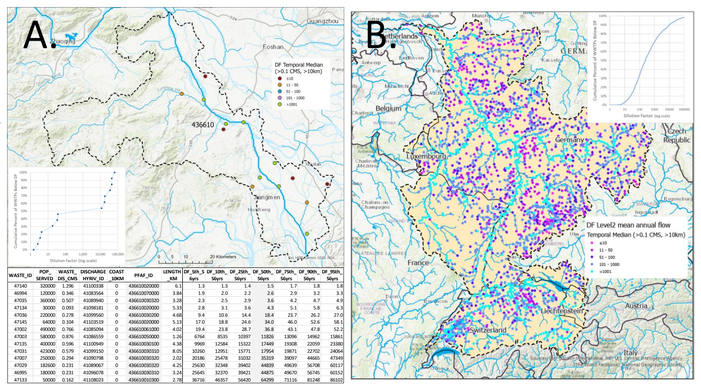

Figure 6. (A) DF results for a Level 6 HydroBASIN at the end of the Pearl River selected tabularly based on the Pfafstetter code present in the study output files. (B) Level 2 results for a user-defined study area (Rhine River WFD River Basin District) spatially selected within a GIS.

Conclusions

- This represents a step change over other DF approaches:
  - 1-km vs ~55km resolution
  - Individual WWTP-level outputs in addition to country percentiles
  - 56-year temporal distributions vs a single time-period
- The three-level output structure enables applications from site-specific probabilistic ERA to global screening.
- Direct integration with HydroBASINS allows DF summarization for any river basin or user-defined study area.

Barbarossa, V., Huijbregts, M.A.J., Beusen, A.H.W., Beck, H.E., King, H., Schipper, A.M., 2018. FLO1K, global maps of mean, maximum and minimum annual streamflow at 1 km resolution from 1960 through 2015. Sci Data 5, 180052
Ehalt Macedo, H., Lehner, B., Nicell, J., Grill, G., Li, J., Limtong, A., & Shakya, R. (2022). Distribution and characteristics of wastewater treatment plants within the global river network. Earth System Science Data, 14(2), 559–577
Lehner, B., Grill G. (2013). Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. Hydrological Processes, 27(15): 2171–2186
WHO/UNICEF Joint Monitoring Programme (JMP) for Water Supply, Sanitation and Hygiene (2023), Progress on household drinking water, sanitation and hygiene 2000–2022: Special focus on gender, World Health Organization (WHO) and the United Nations Children's Fund (UNICEF)

For more information contact
ChrisHolmes@AppliedAnalysis.solutions
or Juliet.Hodges@Unilever.com

APPLIED ANALYSIS SOLUTIONS LLC