

National illicit amphetamine consumption in Germany from wastewater: Bayesian source apportionment, hold-out-evaluated extrapolation and monitoring design

Phil Käding

philkaeding@web.de

Guglielmo Marconi University <https://orcid.org/0009-0001-9035-6216>

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National illicit amphetamine consumption in Germany from wastewater: Bayesian source apportionment, hold-out-evaluated extrapolation and monitoring design

Phil Käding^{a,*}

^a Independent researcher, Flensburg, Germany

* Corresponding author. E-mail: info@krautundklinik.info. ORCID: 0009-0001-9035-6216

Highlights

- Bayesian mass balance apportions amphetamine to illicit, medical and meth sources
- Amphetamine:methamphetamine ratio near 0.05 in German data, set by Chemnitz's record
- Illicit use 17 t/yr (95% CrI 7–58), a model-based extrapolation to all residents
- Held-out sites: median fold error 2.3; big cities alone underpredict twofold
- Five added small western catchments cut extrapolation uncertainty by 46%

Abstract

Wastewater-based epidemiology (WBE) yields city-level drug loads; national estimates require extrapolation to unmonitored populations and, for amphetamine, separation of the illicit signal from pharmaceutical amphetamine and from amphetamine excreted after methamphetamine use. We combined all German SCORE/EUDA data (16 catchments, 2013–2025, 95 site-weeks of daily amphetamine and methamphetamine loads) in a Bayesian mass-balance model with a hierarchical extrapolation to a frame of treatment-plant size classes by federal state built from the Destatis wastewater statistics. The methamphetamine cross-contribution ratio α was estimated from the data, with a site-specific extension; pharmaceutical d-amphetamine was quantified from prescription volumes; excretion, in-sewer stability and the spring-to-annual ratio were propagated as distributions. Predictive performance was assessed by holding out whole site histories and by predicting the nine catchments below 500,000 inhabitants from the seven largest. The posterior for α was 0.050 (95% CrI 0.034–0.066), set mainly by the Chemnitz record; fixing α at the Australian wastewater value of 0.09 fitted worse in leave-one-out cross-validation ($\Delta\text{elpd} -12$, SE 8, concentrated at Chemnitz) and implied a near-zero illicit load there. Illicit amphetamine accounted for 95% of the national amphetamine mass load, pharmaceutical amphetamine for 3.6% and methamphetamine-derived amphetamine for 1.1%. National illicit consumption in 2025 was 16.8 tonnes of pure amphetamine per year (95% CrI 6.8–57.6; 0.55 mg per resident per day); structural variants gave 14.1–19.5 tonnes. Held-out site-weeks were predicted with a median absolute fold error of 2.3 and 90% interval coverage of 89%; a model fitted to large cities alone underpredicted smaller catchments by a factor of 2.2. Extrapolation contributed 66% of the variance of the log estimate, and five

additional small western catchments would reduce the extrapolation standard deviation by 46%. Survey- and seizure-based figures are several-fold lower, an unresolved multimethod discrepancy.

Keywords: wastewater-based epidemiology; amphetamine; methamphetamine; Bayesian hierarchical model; source apportionment; Germany

1. Introduction

Wastewater-based epidemiology (WBE) measures drug residues in untreated municipal wastewater and converts them into population-normalised mass loads; it has become an established component of European drug monitoring (Zuccato et al., 2008; Castiglioni et al., 2014; Ort et al., 2014). The Sewage Analysis CORe group Europe (SCORE) and the European Union Drugs Agency (EUDA) have coordinated annual one-week campaigns since 2011, and the 2025 campaign covered about 115 cities in 25 countries, with several German sites among those with the highest amphetamine loads (EUDA, 2026a). The published values are city-level loads without excretion correction and, with few exceptions (ter Laak et al., 2025; Rapp-Wright et al., 2026), they have not been scaled to national consumption. A national figure for Germany would be useful for market sizing, for triangulation with survey and enforcement statistics, and for planning the monitoring network itself.

Two problems stand between city loads and a national estimate of illicit amphetamine. The first is source apportionment. Amphetamine is measured as the unchanged parent compound, so its load is the sum of illicitly consumed amphetamine, amphetamine excreted as a metabolite of methamphetamine, and pharmaceutical amphetamine, mainly d-amphetamine released from lisdexamfetamine prescribed for attention-deficit/hyperactivity disorder (ADHD), together with any directly disposed material (Gao et al., 2022; Estévez-Danta et al., 2021). The methamphetamine term matters in Germany because methamphetamine use is concentrated near the Czech border in Saxony, Thuringia, Saxony-Anhalt and northern Bavaria (Gomes de Matos et al., 2018; Oertel et al., 2023), where methamphetamine loads exceed amphetamine loads by up to an order of magnitude. Gao et al. (2022) derived a median amphetamine-to-methamphetamine wastewater ratio of 0.09 from Australian catchments and proposed subtracting this fraction; pharmacokinetic studies report that 2–7% of a methamphetamine dose is excreted as amphetamine and 18–54% unchanged, depending on urine pH (Caldwell et al., 1972; Cook et al., 1993; Oyler et al., 2002), which implies a mass ratio in urine of roughly 0.07–0.19. Whether either value applies to German sewers, where methamphetamine is predominantly taken orally or nasally rather than smoked, has not been tested. The pharmaceutical term has grown with adult ADHD prescribing (Bachmann et al., 2017) and, to our knowledge, has not been quantified in a national WBE estimate.

The second problem is extrapolation. SCORE sites are chosen by participating laboratories rather than sampled from a frame; German sites have been large cities and, in some years, a few smaller catchments. A national estimate therefore rests on an assumption about how per-capita load varies with catchment size and region. Dutch multi-plant data show no clear urbanity gradient for amphetamine (ter Laak et al., 2025), and a survey of ten plants in the Saarland found substantial amphetamine loads in villages as well as cities (Meyer et al.,

2015), but these findings have not been turned into a quantified extrapolation for Germany whose predictive performance has been tested against held-out catchments. Deterministic approaches that impute a typical city rate to the unmonitored population, including an earlier version of this analysis that used the 2025 campaign alone, cannot say how probable their scenario ranges are, and a truncated subtraction of the methamphetamine term produces an illicit load of exactly zero at Chemnitz, which is a property of the subtraction rather than of the city.

A third question follows from the second: given that extrapolation is the weak link, where should additional monitoring go? Recommendations to monitor small towns are common, but they are rarely quantified in terms of the reduction in national uncertainty that a specific addition to the network would buy, which is the quantity a monitoring agency needs when it chooses between candidate plants.

Here we address these questions with a single probabilistic model and report how well it predicts data it has not seen. The aims were (i) to estimate illicit, pharmaceutical and methamphetamine-derived amphetamine jointly in a mass-balance model in which α is learned from thirteen years of paired amphetamine and methamphetamine loads and may vary between sites; (ii) to extrapolate to a population frame of treatment-plant size classes by federal state that keeps monitored and unmonitored populations disjoint; (iii) to evaluate the extrapolation by predicting held-out site histories and small catchments from large ones in the space of the observed loads; (iv) to decompose the uncertainty of the national estimate and rank candidate additions to the network by the reduction in that uncertainty; and (v) to triangulate the estimate against survey, seizure and market figures and against the Dutch SCORE network. All numbers in this article are generated by an open pipeline from the public EUDA source data.

2. Materials and methods

2.1 Estimand and scope

We define four nested quantities for the reference year 2025. The first is the total mass of amphetamine (parent compound) entering the sewers of German municipal treatment plants per day. The second subtracts pharmaceutical d-amphetamine, the third subtracts amphetamine excreted after methamphetamine use, and the fourth converts the remaining illicit load into consumed pure amphetamine by back-calculation and scales it to all residents, including the 3.7% not connected to a central treatment plant, who are assumed to consume at the same per-capita rate. We refer to the first quantity as the total load and to the fourth as illicit consumption; we do not call the total load “consumption”. The extrapolation is model-based: it transfers the relation between per-capita load, catchment size and region observed within the monitored German catchments to unmonitored plants of the same size classes, and its credible intervals are conditional on that model. Section 2.8 describes how the transfer was tested.

2.2 Data

Daily population-normalised mass loads (PNML, mg per 1000 inhabitants per day) of amphetamine and methamphetamine for all German catchments in the SCORE/EUDA network were downloaded from the EUDA source-data release of 18 March 2026 (EUDA, 2026b), together with the site table (catchment population, coordinates). The release contains, for each site-year, seven consecutive daily values from a Wednesday-to-Tuesday week in spring and is uncorrected for excretion. Sixteen German catchments contributed amphetamine data between 2013 and 2025 (95 site-weeks, one sampling week per site and year, so that site-week and site-year denote the same unit; Table 1); thirteen participated in 2025 (catchment population 12.05 million, 14.4% of residents), and Dortmund, Saarbrücken and Dülmen contributed earlier years only. Berlin is reported under two site identifiers (four treatment plants) and was treated as one site. Four site-weeks with amphetamine reported as zero on all reported days were treated as not measured; methamphetamine reported as zero was retained as below the quantification limit. For each site-week we computed the arithmetic mean, the log-scale standard error from the daily values, the coefficient of variation and the number of days outside 1.5 interquartile ranges. Analytical performance in the network is monitored by annual inter-laboratory exercises (van Nuijs et al., 2018).

The population frame was built from the Destatis wastewater statistics for 2022: the annual mean population equivalents connected to public treatment plants and the number of plants by design size class and federal state (Destatis, 2025a, table 32213-07), and the residents connected to the public sewer network by federal state (Destatis, 2025b, table 32212-06), scaled to the population on 31 December 2024 (Zensus-2022 basis; 83.58 million residents; Destatis, 2025c) and from the 97.2% connected to sewers to the 96.3% connected to central treatment (Destatis, 2024), so that the frame counts 80.5 million residents connected to central treatment (“connected residents” below). Federal state, distance from the city centre to the nearest point of the Czech border (great-circle distance to a digitised border line) and municipal population were compiled for each site (Table 1). Sites in the new federal states and Berlin were coded as eastern.

2.3 Mass-balance observation model

Let A_{it} and M_{it} denote the weekly mean amphetamine and methamphetamine loads (mg per 1000 inhabitants per day) at site i in year t . The measured amphetamine load was modelled as

$$\log A_{it} \sim \mathcal{N}(\log(I_{it} + P_t + \alpha_i M_{it}), s_{it}^2 + \tau^2),$$

where I_{it} is the illicit amphetamine load, P_t the excreted pharmaceutical d-amphetamine load in year t , α_i the mass of amphetamine excreted per unit mass of methamphetamine excreted at site i , s_{it} the within-week standard error of the log weekly mean and $\tau = 0.15$ a fixed analytical error on the log scale, chosen from the inter-laboratory performance of the network (van Nuijs et al., 2018) and varied to 0.25 in sensitivity analysis. Because the sum in equation (1) is positive by construction and I_{it} is modelled on the log scale, the illicit load cannot become zero or negative; sites where methamphetamine-derived amphetamine

dominates receive a small positive illicit load with a wide credible interval instead of a truncated zero.

In the main model $\alpha_i = \alpha$ for all sites, with a lognormal prior of median 0.10 and log-scale standard deviation 0.35 (95% prior interval 0.05–0.20), derived from the urinary excretion data of Caldwell et al. (1972), Cook et al. (1993) and Oyler et al. (2002) after conversion to a mass ratio, with the Australian wastewater median of 0.09 (Gao et al., 2022) as an external reference point. Because urine pH, route of administration and in-sewer transformation may differ between catchments, a hierarchical extension (M8) allowed the ratio to vary between sites,

$$\alpha_i = \alpha \exp(\sigma_\alpha a_i), \quad a_i \sim \mathcal{N}(0,1), \quad \sigma_\alpha \sim \text{half-}\mathcal{N}(0, 0.3^2),$$

with σ_α also fixed at 0.2 and 0.5 (M8b, M8c) to show the effect of assumed heterogeneity. The ratio is written throughout as amphetamine relative to methamphetamine.

2.4 Pharmaceutical amphetamine

Prescription volumes of lisdexamfetamine in the statutory health insurance (GKV) were taken from the Arzneiverordnungs-Report: 6.8 million defined daily doses (DDD) in 2015, 23.1 million in 2022, 30.3 million in 2023 and 42.8 million in 2024, a 41% increase in the last year, with dexamfetamine at 1.0–1.3 million DDD (Schwabe and Paffrath, 2016; Ludwig et al., 2023, 2024, 2025). Prescribing of ADHD medicines shows a marked east–west gradient (0.42 DDD per insured person in Saxony-Anhalt versus 1.00 in Rhineland-Palatinate in the first half of 2024; GKV-Spitzenverband, 2024). With statutory insurance covering 88% of residents, WHO DDDs of 30 mg lisdexamfetamine dimesylate (8.9 mg d-amphetamine base) and 15 mg dexamfetamine (WHOC, 2026), the national consumption of prescribed d-amphetamine base in 2024 was about 449 kg per year, or 14.7 μg per resident per day. Multiplied by the median excretion fraction and in-sewer survival of Section 2.7 this gives an expected excreted load $\tilde{P}_{2024}$ of 4.1 mg per 1000 inhabitants per day; 2016–2021 were interpolated geometrically, 2013–2014 back-extrapolated, and 2025 was set at 125% of 2024, a damped continuation of the recent growth (Supplement S3). The term entered the model as

$$P_t = \tilde{P}_t \exp(\varepsilon_P), \quad \varepsilon_P \sim \mathcal{N}(0, 0.25^2),$$

where the single log-scale standard deviation of 0.25 covers the private-insurance scaling, the 2025 extrapolation and the excretion and survival parameters of the pharmaceutical fraction; these parameters are not drawn again in the back-calculation of the pharmaceutical term, so their uncertainty is counted once. Regional prescribing intensities were available only as extremes, so a national value was used at all sites; this understates the pharmaceutical share in the west and overstates it in the east.

2.5 Hierarchical model of the illicit load

The illicit load was modelled as

$$\log I_{it} = \mu + b_{\text{pop}} x_i + b_{\text{east}} e_i + u_i + v_t + \varepsilon_{it},$$

with $x_i = \log_{10}(\text{catchment population}/10^5)$, e_i an indicator for eastern sites, $u_i \sim \mathcal{N}(0, \sigma_u^2)$ site effects, $v_t \sim \mathcal{N}(0, \sigma_v^2)$ year effects and $\varepsilon_{it} \sim \mathcal{N}(0, \sigma_e^2)$ site-year deviations. Priors were weakly informative: $\mu \sim \mathcal{N}(\log 80, 1.5^2)$, $b_{\text{pop}} \sim \mathcal{N}(0, 0.5^2)$, $b_{\text{east}} \sim \mathcal{N}(0, 1)$, and half-normal priors with scales 0.7, 0.3 and 0.5 on σ_u , σ_v and σ_e (Table 2). A prior predictive check showed that these priors place the bulk of simulated loads within the range of the observations while allowing values well outside it (Supplement S4). In variant M6 the prior on b_{pop} was centred on the catchment-size gradient estimated from the rest of the European SCORE network: a regression of log amphetamine load on x with country-year fixed effects and site-clustered standard errors, excluding German sites and site-years with methamphetamine loads exceeding amphetamine loads, gave a slope of 0.08 (standard error 0.15) over 174 sites in 31 countries. Variant M7 added the state-level past-year prevalence of amphetamine use from the 2021 Epidemiological Survey of Substance Abuse (ESA) state report as a covariate, $z_s = \log(p_s/1.4)$, for the seven states with a state sample (Bavaria 1.5%, Berlin 3.2%, Bremen 1.4%, Hamburg 1.5%, North Rhine-Westphalia 1.2%, Saxony 0.7%, Saxony-Anhalt 0.8%; Olderbak et al., 2023) and zero, the national value, elsewhere.

2.6 Population frame and extrapolation

The population frame consisted of four treatment-plant size classes (design capacity above 100,000 population equivalents; 50,001–100,000; 10,001–50,000; 10,000 and below) crossed with the sixteen federal states. Within each state the share of connected population equivalents in each class was applied to the residents connected to central treatment, which assumes that the ratio of industrial to domestic load does not differ systematically between classes. Monitored catchments were removed from their class in their state (all sixteen are in the largest class except Dülmen, which is in the 10,001–50,000 class); the Berlin and Hamburg catchments exceed the connected residents of their city states because their plants also serve the surrounding state, and the excess was removed from the same class in Brandenburg and Schleswig-Holstein, so that monitored and unmonitored populations are disjoint and sum to the connected total. The remaining 67.8 million connected residents are served by 8,636 plants. For an unmonitored cell c the covariate x_c was set to the mean number of residents per remaining plant in its class (133,601 for the largest class, 37,272, 12,663 and 1,096 residents for the others) and e_c to its regional indicator, and its expected per-capita illicit load in 2025 was

$$r_c = \exp(\mu + b_{\text{pop}} x_c + b_{\text{east}} e_c + v_{2025}) \bar{m}, \quad \bar{m} = \frac{1}{n} \sum_{i=1}^n \exp(u_i),$$

where $\bar{m}$ is the arithmetic mean site-effect factor over the $n = 16$ monitored sites, an estimate that does not extrapolate the lognormal tail; the parametric alternative $\exp(\sigma_u^2/2)$ is reported as sensitivity S5. For monitored sites the fitted 2025 value r_i (or, for the three sites without a 2025 sample, a prediction with their own site effect) was used. The national illicit load entering sewers is

$$L_{\text{ill}} = \sum_i r_i N_i + \sum_c r_c N_c,$$

with N_i the catchment population and N_c the connected residents in cell c (both in thousands, so that L_{ill} is in mg per day). Because the frame counts connected residents, no further connection factor is applied to the load, and loads per 1000 connected residents are obtained by dividing by φ times the resident population. The formal structure is that of multilevel regression with poststratification (Park et al., 2004) applied to a purposive rather than a probability sample, so inference is model-based (Cochran, 1977). The methamphetamine-derived and pharmaceutical loads of the unmonitored population were obtained in the same way, using population-weighted eastern and western mean methamphetamine loads of the monitored sites and the national pharmaceutical term; they are reported for apportionment only and do not enter the illicit estimate.

2.7 Back-calculation and annualisation

Illicit consumption was obtained from the illicit load as

$$C = \frac{L_{\text{ill}}}{\varphi} \text{CF} \rho \frac{365.25}{10^9}, \quad \text{CF} = \frac{1}{f_{\text{excr}} S'}$$

in tonnes of pure amphetamine per year, where $\varphi = 0.963$ is the share of residents connected to central treatment, f_{excr} the urinary excretion fraction of unchanged amphetamine, S the in-sewer survival fraction and ρ the ratio of the annual mean to the spring-week load. Thirty per cent of an oral amphetamine dose is excreted unchanged in 24 h at uncontrolled urine pH (Dring et al., 1970); the fraction ranges from about 2% in alkaline to more than 70% in acidic urine (Beckett and Rowland, 1965; Golub et al., 2005), and Gracia-Lor et al. (2016) pooled the available studies for the correction factors used by SCORE. We used a logit-normal prior for f_{excr} with median 0.33 and 95% interval 0.20–0.49. Amphetamine is among the less stable biomarkers in sewers: in-sample stability is high but losses above 20% have been reported, and catchment-scale modelling suggests median in-sewer losses above 30% with very wide uncertainty (McCall et al., 2016, 2017; Li et al., 2018). We used a Beta(9.99, 1.76) prior for S (median 0.87, 95% interval 0.61–0.98). The resulting correction factor has median 3.59 (95% interval 2.26–6.46); the fixed value of 2.77 used by SCORE lies within this interval. Because all German samples are taken in one spring week, ρ was given a lognormal prior with median 1 and log-scale standard deviation 0.15 (95% interval 0.74–1.33), widened to 0.30 in sensitivity S6. Single-week estimates can differ appreciably from annual means (Goulding et al., 2020), and multi-year monitoring in Zagreb found lower stimulant loads in summer (Krizman-Matasic et al., 2019), so the prior is centred at one with no directional shift. The one German year-round series we are aware of, fifteen plants sampled from April 2020 to December 2021 (Oertel et al., 2023), reports loads aggregated by pandemic-restriction period rather than by month and without per-sample data, so it could not be used to estimate a seasonal amplitude. Parameters were drawn 6000 times, matched one-to-one with posterior draws, so that equation (7) yields a posterior for C that integrates over all sources of uncertainty.

2.8 Inference, model comparison and predictive evaluation

Posteriors were sampled with the No-U-Turn sampler in NumPyro (Phan et al., 2019) using four chains of 1500 warm-up and 1500 retained iterations each (6000 draws), a target acceptance probability of 0.95 and a maximum tree depth of 12; convergence was assessed

by the split- $\hat{R}$, bulk and tail effective sample sizes and the number of divergent transitions for every variant (Table S10) and for the hold-out refits (Table S11). Model variants were: M1, the main model; M2, without methamphetamine correction ($\alpha = 0$); M3, without the size gradient; M4, without the pharmaceutical term; M5, with α fixed at 0.09; M6, with the European gradient prior; M7, with the state-level survey prevalence covariate; M8, M8b and M8c, with site-specific α ; and prior-sensitivity variants S1–S6 (Table 3). Variants were compared by Pareto-smoothed importance-sampling leave-one-out cross-validation (PSIS-LOO) on the observation likelihood of equation (1), with the standard error of each difference in expected log predictive density (elpd) computed from the pointwise differences, the number of site-weeks with Pareto shape parameter $k > 0.7$ reported as a reliability diagnostic, and stacking weights (Yao et al., 2018) computed as a further summary (Vehtari et al., 2017). In-sample posterior predictive checks compared the mean, standard deviation, maximum, minimum and 90th percentile of replicated log loads with the observed values, and examined residuals by catchment size, region, methamphetamine dominance and year (Supplement S5). The comparator is a deterministic median-imputation estimate of the kind used in earlier city-only estimates, reproduced on the present frame: the 2025 site loads corrected by a truncated subtraction of 0.09 times the methamphetamine load, converted with the fixed correction factor 2.77, and the median site rate imputed to all residents outside the 2025 catchments.

Predictive performance of the extrapolation was evaluated in the space of the observed loads, so that the reference is data rather than a fitted quantity. In the leave-one-site-out evaluation the model was refitted sixteen times with one site's entire history removed and the site's weekly mean amphetamine load in each of its years was predicted as for a new catchment of its size and region, drawing a new site effect, new site-year deviations and the observation noise:

$$\log \tilde{A}_{jt} = \log(\exp(\mu + b_{\text{pop}}x_j + b_{\text{east}}e_j + v_t + \tilde{u}_j + \tilde{\varepsilon}_{jt}) + P_t + \alpha M_{jt}) + \eta_{jt},$$

with $\tilde{u}_j \sim \mathcal{N}(0, \sigma_u^2)$, $\tilde{\varepsilon}_{jt} \sim \mathcal{N}(0, \sigma_e^2)$ and $\eta_{jt} \sim \mathcal{N}(0, s_{jt}^2 + \tau^2)$, where the methamphetamine load M_{jt} of the held-out site is treated as known because it is measured in the same sample. We report the mean and root-mean-square log error, the median absolute fold error, the coverage of 50%, 80%, 90% and 95% prediction intervals, the probability integral transform (PIT) and the mean log predictive density over all 95 held-out site-weeks and by subgroup. In the downward-extrapolation test the model was fitted to the seven catchments of at least 500,000 residents and used to predict all site-weeks of the nine smaller catchments, including Dülmen with 35,000 residents; the population-weighted ratio of observed to predicted loads (sum of observed load times catchment population over the same sum of predicted medians) measures the bias a network of large cities alone would incur; the unweighted ratio of mean observed to mean predicted load is also reported. A secondary comparison against the fitted values of the full model, which isolates the site-effect component from observation noise, is given in Supplement S6.

2.9 Uncertainty decomposition and monitoring design

The variance of the log national consumption was decomposed by fixing, in turn, the correction factor, the seasonal ratio and the posterior of the illicit load at their medians and recording the variance reduction; because the components interact multiplicatively, the

three reductions need not sum exactly to the total, and the sum is reported. For monitoring design, the regression part of equation (4) was approximated as a linear-Gaussian model with residual variance σ_u^2 and the priors of Table 2; the posterior covariance of $(\mu, b_{\text{pop}}, b_{\text{east}})$ was computed for the current design and for designs with k additional catchments in each frame cell, and propagated to the standard deviation of the log national unmonitored load through the population-weighted linearisation. This preposterior analysis treats a new site as an additional draw from the site distribution and holds the back-calculation uncertainty fixed, which cannot be reduced by monitoring.

2.10 Triangulation

The illicit estimate was compared with (i) past-year amphetamine users in the Epidemiological Survey of Substance Abuse 2021 and 2024 (Rauschert et al., 2022; Olderbak et al., 2025), expressed as the implied pure amount per user and, conversely, as survey-anchored consumption under illustrative per-user amounts of 1, 3 and 8 g pure amphetamine per year, which are assumptions chosen to span a plausible range rather than measured quantities; (ii) amphetamine seizures of 2,092 kg in 2024 and a mean retail purity of 11.8% amphetamine base (data of the Federal Criminal Police Office, BKA, reported by the REITOX national focal point; DHS, 2025), giving the model-implied street-product mass and the share of it seized; (iii) a model-implied retail value at 10.1 EUR per gram (DHS, 2025); and (iv) the population-weighted amphetamine loads at the Dutch SCORE sites in 2025 (EUDA, 2026b), a neighbouring market with multi-plant coverage (ter Laak et al., 2025).

2.11 Software and reproducibility

The pipeline (Python 3.11, NumPyro 0.21.0, ArviZ, GeoPandas) ingests the EUDA files, builds the frame, fits all variants, runs the predictive evaluation, design and triangulation, and writes every table, figure and number in this article from a single values file. Code, data extracts with checksums and retrieval dates, prior specifications, posterior draws and diagnostics are provided as Supplementary Material and in the accompanying repository.

3. Results

3.1 Data

The sixteen catchments and their characteristics are listed in Table 1. In 2025 the weekly mean amphetamine load ranged from 29.8 mg per 1000 inhabitants per day in Munich to 221.6 in Berlin (median 93.0). Methamphetamine exceeded amphetamine at Chemnitz, Dresden, Erfurt, Nuremberg and Magdeburg, all within 204 km of the Czech border, and was negligible beyond 250 km (Fig. 3b). The multi-year record (Fig. S1) shows amphetamine loads rising at most sites since 2013, most steeply at Berlin, Dortmund, Saarbrücken and Dülmen, the highest load in the whole record at Saarbrücken (2024) and, for a town of 35,000 residents, loads at Dülmen (2022) above those of any city of more than 500,000 residents in any year.

3.2 Sampling diagnostics and model checks

All variants converged (maximum $\hat{R}$ 1.010, minimum bulk effective sample size 958, minimum tail effective sample size 1163, no divergent transitions; Table S10); the sixteen leave-one-site-out refits and the seven-city refit of Section 3.7 met the same criteria (Table S11). Posterior predictive p-values for the mean, standard deviation, maximum and 90th percentile of the log loads were 0.58, 0.18, 0.41 and 0.35; the minimum had a p-value of 1.00, indicating that replicated data sets produce lower minima than the observed 6.3 mg per 1000 inhabitants per day, a consequence of the wide site-effect distribution rather than of a systematic misfit. Mean residuals were within ± 0.02 on the log scale by catchment-size class, region and methamphetamine dominance, and within ± 0.11 by year (Fig. S2, Table S9). Between 9 and 19 of the 95 site-weeks had Pareto $k > 0.7$ in the PSIS-LOO computation, mainly the earliest weeks of Berlin, Dortmund and Dülmen and single high-leverage weeks at Frankfurt, Mainz and Rostock (Table S7b), so the leave-one-out estimates for those observations are approximate and the elpd differences below should be read with that caveat.

3.3 The methamphetamine ratio

In the main model the posterior for α was 0.050 (95% CrI 0.034–0.066), below the prior median of 0.10 and below the Australian wastewater median of 0.09: the data favoured a lower effective wastewater ratio than either reference. The posterior sits at the lower edge of the prior, and with the wider prior of S1 it moved further down (0.041, 0.020–0.061), so the estimate is to be read as an upper range set by the data rather than as a value the prior was neutral about. The information comes from the paired time series at the methamphetamine-dominated sites, above all Chemnitz: there the amphetamine-to-methamphetamine load ratio was as low as 0.044 in 2019, so any α above that value would require a negative illicit load, which equation (1) does not permit, whereas the refit without Chemnitz gave $\alpha = 0.078$ (0.048–0.112; Table S11), an interval that includes 0.09; the evidence for a ratio below 0.09 therefore comes almost entirely from one site. Fixing α at 0.09 (M5) fitted worse in leave-one-out terms, although the difference is within two standard errors (elpd difference relative to M1 –11.6, standard error 8.3; Table S7), and inflated the between-site standard deviation from 1.06 to 1.35, because the sites near the border were pushed towards implausibly small illicit loads; the Chemnitz site-weeks account for the whole loss (–11.8 elpd units against a total of –11.6, the other sites netting to about zero; Table S7c). Omitting the correction (M2) fitted almost as well as M1 but is inconsistent with the excretion pharmacology. The case against a fixed 0.09 therefore rests on the Chemnitz record and the positivity of the illicit load rather than on the cross-validation score alone.

With site-specific ratios (M8) the population-level α was 0.063 (0.038–0.110) and the between-site standard deviation of $\log \alpha$ was 0.36 (0.04–0.82), so the data neither require nor exclude moderate heterogeneity. Only the methamphetamine-dominated sites carry information about their own ratio: Chemnitz had the lowest site-specific value (0.040, 0.016–0.061) and Dresden the highest (0.069, 0.034–0.116), while the western sites, where the methamphetamine term is negligible, returned the population distribution (Fig. S3, Table S8). Fixing σ_α at 0.2 or 0.5 moved the population-level α to 0.058 and 0.068. The national estimate was insensitive to this choice (16.9, 17.1 and 17.0 tonnes per year for M8,

M8b and M8c against 16.8 for M1), and PSIS-LOO did not separate M8 from M1 (elpd difference 0.6). The illicit load at Chemnitz rose from 5.2 to 8.2 mg per 1000 inhabitants per day under M8, within the credible interval of M1.

3.4 Fit of the illicit-load model

The between-site standard deviation of 1.06 on the log scale corresponds to a factor of about 8 between a site one standard deviation below and one above the mean; the year effects show a rise of about 75% from the 2013–2015 level to 2022–2025 (Table S2). The catchment-size gradient was not identified by the German data alone ($b_{\text{pop}} = -0.10$, 95% CrI -0.82 to 0.64 per log10 unit of population) and was close to zero with the European prior (0.06 , -0.23 to 0.36); eastern sites had lower illicit loads after correction ($b_{\text{east}} = -0.53$, -1.50 to 0.47), an estimate that is uncertain because it is carried by six sites. In M7 the survey-prevalence coefficient was positive but weakly identified ($b_{\text{esa}} = 1.05$, -0.25 to 2.27), so that a state with twice the national survey prevalence would be predicted to have about 2.1 times the illicit load.

3.5 Site-level source apportionment

Fig. 2 shows the 2025 illicit loads by site and Fig. 3a their apportionment. Illicit amphetamine made up more than 90% of the measured load at ten of sixteen sites. Methamphetamine-derived amphetamine accounted for 63% of the measured load at Chemnitz, 38% at Dresden, 29% at Erfurt, 17% at Nuremberg and 8% at Magdeburg. The illicit load at Chemnitz was 5.2 mg per 1000 inhabitants per day (95% CrI 1.1–11.7), the lowest in the network but not zero. Pharmaceutical d-amphetamine contributed 1.5% to 18.6% of the measured load, with the largest share at Munich, where the total load is low. The highest illicit loads were at Saarbrücken (predicted for 2025 from its 2017–2024 record), Mainz, Dortmund, Berlin, Rostock and Dülmen; the four largest cities other than Berlin (Hamburg, Munich, Frankfurt, Stuttgart) all lay below the network median.

3.6 National estimate

The national illicit amphetamine load entering sewered wastewater in 2025 was 11.9 kg per day (95% CrI 6.5–34.9), equivalent to 148 mg per 1000 connected residents per day (81–433); 88% of it is attributed to the unmonitored population. Pharmaceutical d-amphetamine added 0.46 kg per day and methamphetamine-derived amphetamine 0.15 kg per day, so illicit amphetamine constituted 95% (90%–98%) of the total amphetamine mass load of 12.5 kg per day. After back-calculation, illicit consumption was 46 kg of pure amphetamine per day (95% CrI 20–155), 16.8 tonnes per year (6.8–57.6; 50% CrI 12.0–24.4) and 0.55 mg per resident per day (Table 3, Fig. 4a).

The structural variants agree on the central value within about 20% and differ mainly in the width of the interval (Table 3). The European-informed gradient (M6) gives 14.1 tonnes per year (7.2–32.2) and the model without a gradient (M3) 14.8 (8.0–30.7); the wide upper tail of M1 comes from extrapolating a weakly identified gradient to plants of 50,000 population equivalents or less, which serve 40% of the unmonitored connected population. With the state-level survey prevalence as covariate (M7) the estimate is 19.5 tonnes per year (8.0–64.6). Omitting the methamphetamine correction raises the estimate by 9%, omitting the

pharmaceutical term by 6%; widening the seasonal prior (S6) leaves the median unchanged and widens the 95% interval to 6.0–62.4 tonnes. PSIS-LOO did not discriminate between the structural variants: M3, M8, M7, M1 and M6 lay within 0.9 elpd units of each other with standard errors of the differences between 0.5 and 1.3, and the stacking weights (0.41 for M3, 0.32 for M8, 0.16 for M2, 0.10 for M5, zero for M1, M6 and M7; Table S7) reflect this near-equivalence rather than a ranking that the data support. We therefore retain M1 as the main model on substantive grounds, because it imposes no assumed gradient and no external information and yields the widest interval of the structural variants, and report M3 and M6 as bounding cases.

The median-imputation comparator gives 7.3 tonnes per year, 2.3 times lower than the main estimate; 31% of the log difference is due to the correction factor (3.59 versus 2.77) and the remainder to the imputed per-capita load, because the median of the thirteen 2025 sites (81 mg per 1000 inhabitants per day after conversion) is dominated by large cities and border sites, whereas the arithmetic mean over all sixteen monitored catchments across the record is about 156.

Fixing the illicit-load posterior at its median reduced the variance of the log estimate by 66%, fixing the correction factor by 27% and fixing the seasonal ratio by 8% in M1 (the three reductions sum to 101% of the total variance; Fig. 4b shows their square roots in standard-deviation units); with the European gradient prior the extrapolation reduction falls to 33% and the correction factor becomes the largest single component.

3.7 Predictive evaluation of the extrapolation

Predicting the amphetamine load of a site whose whole history had been withheld gave a mean log error of -0.01 over the 95 held-out site-weeks, a root-mean-square log error of 1.04, a median absolute fold error of 2.3 and interval coverage of 36%, 78%, 89% and 92% for the 50%, 80%, 90% and 95% prediction intervals (Fig. 5a, c; Table S6). The 90% and 95% intervals are close to nominal and the 50% interval is too narrow, and the PIT histogram is bimodal rather than uniform (Fig. 5c), which is the expected signature of a between-site distribution that is wider than any single site's own variation: a new site tends to lie in one tail or the other of the population prediction. The mean log predictive density was -1.60 . Errors were not neutral with respect to size: sites of at least 500,000 residents were over-predicted (mean log error -0.38) and smaller sites under-predicted ($+0.24$), and the site-weeks in which methamphetamine exceeded amphetamine were over-predicted (-0.63 , 90% coverage 81%), and coverage was lower for eastern sites as a group (90% coverage 82% against 95% in the west), as expected when the regional effect for a held-out site is estimated from the five remaining eastern sites. Site-level prediction is therefore imprecise, as expected with a between-site standard deviation above one on the log scale, while the wider intervals are approximately calibrated.

The downward-extrapolation test is the more consequential result. A model fitted to the seven catchments of at least 500,000 residents under-predicted the 57 site-weeks of the nine smaller catchments by a population-weighted factor of 2.2 (unweighted 2.4; mean log error $+0.59$), with 90% interval coverage of 82% (Fig. 5b, Table S6): Saarbrücken, Rostock, Mainz, Dortmund, Magdeburg and Dülmen lay above the prediction in every sampled year, Erfurt close to it, and Chemnitz and Nuremberg below. A national estimate built from large

cities alone would therefore be biased downward by about a factor of two unless the smaller catchments already in the record are used, as they are here.

3.8 Monitoring design

Under the linear-Gaussian approximation the current network leaves a standard deviation of 0.52 on the log scale for the extrapolated national load. Adding five western plants of 50,000 population equivalents or less would reduce this to 0.28 (46%), ten to 0.22 and twenty to 0.18; five plants in the 10,001–50,000 class in the west alone would achieve 40%, five small eastern plants 28%, and five additional large western plants 16% (Fig. 6, Table S4). The ranking follows the product of unmonitored population and current uncertainty: western plants of 50,000 population equivalents or less serve 23 million residents with no monitored catchment except Dülmen.

3.9 Triangulation

Table 4 summarises the comparison. Dividing the WBE estimate by the 699 thousand past-year users of the 2021 survey gives 24 g of pure amphetamine per user per year (10–82), about 207 g of street product at 11.8% purity; with the 2024 survey, which reports half as many users, the figure doubles. Survey-anchored consumption under the illustrative per-user amounts of 1, 3 and 8 g per year would be 0.7, 2.1 and 5.6 tonnes per year, all below the 2.5th percentile of the WBE posterior. The model-implied street-product mass is 145 tonnes per year (51–530), of which the 2024 seizures represent 1.4% (0.4–4.1%), and the model-implied retail value is 1440 million EUR (490–5421). The Dutch SCORE sites carried a population-weighted total amphetamine load of 234 mg per 1000 inhabitants per day in 2025 against 121 at the monitored German sites, both uncorrected totals, so the monitored Dutch catchments carried about 93% more amphetamine per capita than the monitored German cities; the modelled German national illicit load of 148 (81–433) per 1000 connected residents is a different quantity, net of the pharmaceutical and methamphetamine terms and extrapolated to unmonitored plants, and is listed in Table 4 for reference only.

4. Discussion

4.1 Principal findings

Three results carry the paper. First, the methamphetamine cross-contribution can be estimated from the German data themselves, but the information is concentrated at one site. The estimate (0.05, 95% CrI 0.03–0.07) is about half the Australian wastewater median because the Chemnitz record cannot accommodate a larger ratio without a negative illicit load; without Chemnitz the ratio is compatible with 0.09, and fixing it at 0.09 pushes the illicit load at Chemnitz towards zero. A lower effective ratio may reflect the route of administration and urine pH of the user population, which govern the fractions excreted unchanged and as amphetamine (Cook et al., 1993; Oyler et al., 2002), but it may also absorb in-sewer differences and analytical bias, and it should be read as an effective wastewater ratio for the monitored German catchments rather than as a metabolic constant; allowing it to vary between sites changes neither the national estimate nor the

ranking of sites. Second, illicit consumption in 2025 was 17 tonnes of pure amphetamine (95% CrI 7–58), a model-based extrapolation from the monitored catchments to all residents, 2.3 times a median-imputation figure from the 2025 campaign alone, and the difference is not a matter of the correction factor alone: Saarbrücken, Mainz, Dortmund and Dülmen in the west, and Rostock and Magdeburg in the east, carry about two to five times the per-capita load of Frankfurt and Stuttgart and more relative to Hamburg and Munich (Fig. 2), and an extrapolation from large cities under-predicts them by about a factor of two in held-out data. Third, the remaining uncertainty is dominated by the extrapolation, and the design analysis converts the generic recommendation to monitor small towns into a ranked list in which five small western catchments reduce extrapolation uncertainty about 3 times as much as five additional large cities.

4.2 What the predictive evaluation does and does not show

The leave-one-site-out results describe how well the model predicts a German catchment it has never seen, given its size and region. A median absolute fold error of 2.3 and near-nominal 90% coverage mean that the model is honest about its own imprecision at the site level, not that it is precise; the bimodal PIT histogram and the under-coverage of the 50% intervals show that the population prediction is rarely close to a new site, because most of the between-site variance is not explained by size and region. For the national estimate this matters less than it appears, because the estimate is a population-weighted sum over many cells in which the site effects average out, and the quantity that matters is the mean site-effect factor $\bar{m}$ and the gradient, not any single site. The downward test speaks to exactly that quantity: the record's smaller catchments carry higher loads than the largest cities predict, so an extrapolation that ignored them would be biased low. What the evaluation cannot show is whether the sixteen monitored catchments, and in particular Dülmen, the only monitored catchment below 100,000 residents, are representative of the 40% of the unmonitored connected population served by plants of 50,000 population equivalents or less; no held-out German data exist for that class, which is why the design analysis ranks it first.

4.3 Choice of the main model

The structural variants M1, M3, M6, M7 and M8 are statistically indistinguishable by PSIS-LOO on the present data, and stacking assigns weight to M3 and M8 with M1 at zero, but the elpd differences are a fraction of their standard errors and several site-weeks have Pareto k above 0.7, so the stacking weights should not be read as evidence for one structure over another. We chose M1 as the main model because it imposes no assumed gradient and no external information, so that the width of its interval reflects what the German record alone can say about unmonitored plant classes; M3 and M6 make stronger assumptions (no gradient, or the European gradient) and are reported as bounding cases whose medians differ from M1 by –12% and –16%. A reader who accepts the European gradient as applicable to Germany may prefer M6, whose interval is half as wide.

4.4 Comparison with other national estimates

The Netherlands is the closest comparator in market and monitoring terms. Dutch plants serving both rural and urban populations show no urbanity gradient for amphetamine (ter

Laak et al., 2025), which matches the German posterior for the size gradient and the European regression, and the monitored Dutch catchments carried about 93% more amphetamine per capita in 2025 than the monitored German cities. England's national programme, with plants covering a large share of the population at high temporal resolution (Rapp-Wright et al., 2026), applies an amphetamine correction factor of 3.30, within our correction-factor interval. The Saarland survey of ten plants, from villages to Saarbrücken, found substantial amphetamine loads in all size classes in 2014 (Meyer et al., 2015), and Saarbrücken has the highest loads in the German SCORE record; the wastewater evidence from the Saarland is thus internally consistent and points to a regional market that the national campaign captures through one catchment. We are not aware of another national amphetamine estimate that separates pharmaceutical and methamphetamine-derived amphetamine, so the apportionment cannot be compared directly; its magnitude (pharmaceutical 3.6%, methamphetamine-derived 1.1% nationally) indicates that neither term changes the national figure much, while both change site-level interpretation near the Czech border and in low-load cities.

4.5 The gap to survey- and seizure-based figures

The WBE estimate implies about 24 g of pure amphetamine, or 207 g of street powder, per past-year user recorded in the 2021 survey, and survey-anchored consumption under the illustrative per-user scenarios examined here is several-fold lower. Seizures correspond to about 1.4% of the model-implied street-product mass. Both comparisons point in the same direction, and we regard the gap as an unresolved multimethod discrepancy rather than as evidence against either source. Household surveys with response rates of 22–35% under-cover heavy stimulant users and stigmatised use (Rauschert et al., 2022; Olderbak et al., 2025), and the near-halving of reported past-year users between 2021 and 2024 contrasts with rising wastewater loads at most German sites over the same period (Fig. S1), so the survey denominator may be too small. On the WBE side, the correction factor is the largest parametric uncertainty and, if urine pH in the user population were more acidic than assumed, the excretion fraction would be higher and consumption lower; direct disposal of unused drug or of production waste would inflate loads; and the arithmetic-mean extrapolation is sensitive to the three high western catchments. Enantiomeric profiling can distinguish pharmaceutical d-amphetamine from racemic illicit amphetamine and detect direct disposal (Estévez-Danta et al., 2021; Sharfudeen et al., 2023) and would narrow the gap from the WBE side; the Dutch approach of combining purity and price with wastewater loads (ter Laak et al., 2025) narrows it from the market side. The retail-value figure is an order-of-magnitude quantity conditional on the assumed purity and price distributions, not a market statistic.

4.6 Limitations

The limitations are listed with the direction in which each would move the national estimate, where a direction can be stated. (1) The German SCORE sites are purposively selected and the extrapolation is model-based; the predictive evaluation tests the transfer between monitored catchments, not the transfer to plant classes with no monitored member, and the direction of any resulting bias is unknown. (2) The smallest frame class lies below the smallest monitored catchment, and the covariate value assigned to each class is the mean residents per plant; the gradient variants bound but do not remove this

assumption (M3 and M6 lower the estimate). (3) The site-year deviations absorb residual variation, so fitted 2025 values differ from measured weeks by up to the analytical error, and three sites are predicted from their own history (no clear direction). (4) The seasonal ratio is a prior centred at one; if spring loads exceed the annual mean, as some multi-season series suggest for stimulants, the estimate would be lower. (5) The pharmaceutical term rests on statutory-insurance volumes scaled to all residents, an extrapolated 2025 volume and a national intensity; underestimating it would overstate illicit consumption slightly, and the effect is bounded by M4. (6) The in-sewer survival prior spans the literature but is not measured in German sewers; higher losses than assumed would raise the estimate. (7) The frame assumes the same industrial share of population equivalents across plant classes; if small plants carry a smaller industrial share, their connected residents are underestimated and the estimate is slightly low. (8) The methamphetamine ratio is an effective wastewater quantity; if it varies with route of administration, the border sites' illicit loads are the least certain, with little effect nationally. (9) The state-level survey covariate is available for seven states and weakly identified. (10) Catchment populations are the de jure figures reported to EUDA, not de facto populations; commuting and tourism inflate per-capita loads in city centres and would bias the monitored cities' rates upward. (11) The value-of-information analysis is a linear-Gaussian approximation that ranks options; the absolute reductions are indicative. (12) Direct disposal and production waste are not separable from consumption without enantiomeric data and would inflate the estimate.

4.7 Implications for monitoring

The German network already contains the information needed to correct the large-city bias, because Dortmund, Saarbrücken and Dülmen participated in earlier years; keeping such sites in the campaign is worth more for a national estimate than adding another million-city, and the design analysis quantifies by how much. A second implication concerns the methamphetamine correction: because α can be learned from paired amphetamine and methamphetamine time series at high-methamphetamine sites, campaigns in mixed markets should report both compounds at all sites and retain the daily values, which the EUDA release already does. Third, national estimates should be reported with credible intervals, a decomposition and an out-of-sample evaluation, so that users can see which part of the uncertainty is reducible by monitoring, which is not, and how far the model's predictions can be trusted for a catchment it has not seen.

5. Conclusions

A joint Bayesian mass-balance and extrapolation model applied to thirteen years of German SCORE data estimates illicit amphetamine consumption in 2025 at 17 tonnes of pure amphetamine per year (95% credible interval 7–58 tonnes), within the range 14–20 tonnes across structural variants, and attributes 95% of the national amphetamine mass load to illicit use, 3.6% to prescribed d-amphetamine and 1.1% to methamphetamine metabolism. The data favour an amphetamine-to-methamphetamine cross-contribution ratio near 0.05 for the monitored German catchments, lower than the Australian value of 0.09, which is difficult to reconcile with the Chemnitz record; the constraint rests on that one site. The estimate exceeds a median-imputation figure from the 2025 campaign alone by a factor of

2.3 because per-capita loads in medium-sized and small western catchments exceed those of the largest cities, a pattern that held when those catchments were predicted from the largest cities alone. Held-out sites were predicted with a median absolute fold error of 2.3 and approximately calibrated 90% intervals. Extrapolation remains the largest source of uncertainty, and adding a few small western catchments to the national campaign would reduce it more than any other change to the network. Survey- and seizure-based figures remain several-fold lower, an unresolved multimethod discrepancy that enantiomeric profiling and year-round sampling at small plants could narrow.

Declarations

CRedit authorship contribution statement. Phil Kading: Conceptualisation, Methodology, Software, Formal analysis, Data curation, Validation, Visualisation, Writing – original draft, Writing – review and editing.

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Data and code availability. The EUDA source data (data node 33337, version 5) are public; the extracted files with SHA-256 checksums and retrieval dates, the Destatis extracts, all auxiliary inputs with sources, the full pipeline, posterior draws and summaries, evaluation outputs and the values file used to fill this manuscript are provided in the Supplementary Material and in the repository accompanying this article [Zenodo DOI to be minted at submission].

Declaration of generative AI use. A large language model (Anthropic Claude) was used, under the author's direction, to draft analysis code, to assist with literature retrieval and to edit the text. The author designed the study, specified the models and priors, verified all references against Crossref records, all data against the primary sources and all numbers against the pipeline output, and takes full responsibility for the content.

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Tables

Table 1. Monitored German catchments in the SCORE/EUDA network with amphetamine data, 2013–2025. Catchment population as reported to EUDA; municipal population on 31 December 2024 (Zensus-2022 basis) from the statistical offices; distance is the great-circle distance from the city centre to the Czech border; ESA prevalence is the 12-month prevalence of amphetamine use in the state (18–64 years) in the 2021 Epidemiological Survey of Substance Abuse state report (n/a: state not surveyed). Flags for the latest week: M, methamphetamine load exceeds amphetamine load; O, at least one daily value outside 1.5 interquartile ranges; V, within-week coefficient of variation above 40%.

Site	Federal state	Region	Catchment population (10 ³)	Municipal population 2024 (10 ³)	ESA prevalence (%)	Distance to Czech border (km)	Years with amphetamine data	Amphetamine, latest week (mg/1000 inh/day, mean ± SD)	Methamphetamine, latest week	Latest year	Flags
Berlin	Berlin	East	3,948	3,685	3.2	175	6 (2014–2025)	221.6 ± 47.6	38.3	2025	O
Chemnitz	Sachsen	East	239	246	0.7	38	7 (2018–2025)	32.6 ± 9.1	381.6	2025	M
Dortmund	Nordrhein-Westfalen	West	404	603	1.2	364	11 (2013–2024)	262.2 ± 88.4	0.0	2024	O
Dresden	Sachsen	East	672	565	0.7	33	11 (2014–2025)	50.1 ± 5.8	327.2	2025	M O
Dülmen	Nordrhein-Westfalen	West	35	48	1.2	389	9 (2013–2022)	264.7 ± 230.4	0.0	2022	O V
Erfurt	Thüringen	East	215	219	n/a	118	7 (2018–2025)	97.3 ± 63.0	371.2	2025	M O V

Site	Federal state	Region	Catchment population (10 ³)	Municipal population 2024 (10 ³)	ESA 2021 state prevalence (%)	Distance to Czech border (km)	Years with amphetamine data	Amphetamine, latest week (mg/1000 inh/day, mean $\pm$ SD)	Methamphetamine, latest week	Latest year	Flags
Frankfurt	Hessen	West	1,158	756	n/a	254	2 (2017 – 2025)	82.9 $\pm$ 2.4	24.4	2025	–
Hamburg	Hamburg	West	2,050	1,863	1.5	394	3 (2017 – 2025)	75.2 $\pm$ 5.1	6.5	2025	–
Hannover	Niedersachsen	West	793	548	n/a	294	3 (2017 – 2025)	97.0 $\pm$ 7.5	0.6	2025	–
Magdeburg	Sachsen-Anhalt	East	281	238	0.8	204	6 (2017 – 2025)	182.9 $\pm$ 51.0	218.2	2025	MO
Mainz	Rheinland-Pfalz	West	223	225	n/a	284	2 (2017 – 2025)	171.7 $\pm$ 38.4	18.1	2025	–
Munich	Bayern	West	1,171	1,505	1.5	162	10 (2014 – 2025)	29.8 $\pm$ 3.0	10.9	2025	–
Nuremberg	Bayern	West	451	530	1.5	106	6 (2017 – 2025)	44.2 $\pm$ 3.9	166.5	2025	M
Rostock	Mecklenburg-Vorpommern	East	242	205	n/a	370	2 (2017 – 2025)	190.2 $\pm$ 7.9	3.4	2025	–
Saarlösche	Saarlösche	West	204	183	n/a	389	7 (2017	498.6 $\pm$ 27.7	0.0	2024	O

Site	Federal state	Region	Catchment population (10 ³)	Municipal population 2024 (10 ³)	ESA 2021 prevalence (%)	Distance to Czech border (km)	Years with amphetamine data	Amphetamine, latest week (mg/1000 inh/day, mean ± SD)	Methamphetamine, latest week	Latest year	Flags
n							– 2024)				
Stuttgart	Baden-Württemberg	West	609	609	n/a	263	3 (2017 – 2025)	93.0 ± 8.1	13.2	2025	0

Table 2. Prior distributions, fixed parameters and, where updated by the data, the corresponding posterior summaries of the main model (median and 95% quantile credible interval). Prior and posterior are labelled separately; parameters marked “not updated” enter the back-calculation only and retain their prior. N(m, s²) denotes a normal distribution with mean m and standard deviation s. CrI, credible interval; ESA, Epidemiological Survey of Substance Abuse; GKV, statutory health insurance.

Parameter	Distribution	Median [95 % interval]	Basis
f_excr (urinary excretion fraction of unchanged amphetamine)	logit-normal, median 0.33, sd 0.35 on logit scale	prior 0.33 [0.20–0.49] (not updated by the data)	Dring et al. 1970 (30 % unchanged, uncontrolled pH); Gracia-Lor et al. 2016 pooled value; pH dependence 20–70 % (Beckett & Rowland 1965; Ånggård et al. 1973 as cited in Golub et al. 2005)
S (in-sewer survival fraction)	Beta(9.99, 1.76)	prior 0.87 [0.61–0.98] (not updated)	McCall et al. 2016 (amphetamine variable, mostly stable in-sample); McCall et al. 2017 (modelled median loss >30 %, 5–100 %)
CF = 1/(f_excr · S)	derived	prior-derived 3.59 [2.26–6.46]	–
α (amphetamine : methamphetamine mass ratio in excreta after methamphetamine	lognormal(log 0.10, 0.35)	prior 0.10 [0.05–0.20]; posterior (M1) 0.050 [0.034–	Caldwell et al. 1972 (2–3 % as amphetamine, 18–27 % unchanged); Cook et al. 1993 (7 %, 37–45 %); Oyler et al. 2002 (4–7 %, 37–54 %); Gao et al. 2022

Parameter	Distribution	Median [95 % interval]	Basis
use)		0.066]	wastewater median 0.09
P_2025 (excreted pharmaceutical d-amphetamine load, mg/1000 inh/day)	lognormal(log 5.14, 0.25)	prior 5.14 [3.1–8.4]; posterior (M1) 5.7 [3.4–9.2]	Arzneiverordnungs-Report 2016/2023/2024/2025 (lisdexamfetamine 6.8, 23.1, 30.3, 42.8 million GKV DDD in 2015, 2022, 2023, 2024; dexamfetamine 1.0–1.3), WHO DDD, 8.9 mg d-amphetamine base per 30 mg lisdexamfetamine dimesylate
b_esa (M7 only; log state prevalence ratio)	$N(0, 1^2)$	posterior (M7): see Table S2	ESA 2021 state report (7 states)
σ_α (M8 only; between-site SD of log α)	half-normal(0.3^2); fixed 0.2 (M8b), 0.5 (M8c)	posterior (M8) 0.36 [0.04–0.82]	weakly informative; allows site-specific effective ratios
ρ (annual mean : spring-week ratio)	lognormal(0, 0.15)	prior 1.00 [0.74–1.33] (not updated)	Goulding et al. 2020 (single-week vs annual loads); Krizman-Matasic et al. 2019 (lower summer stimulant loads)
τ (analytical error, log-scale SD)	fixed 0.15 (sensitivity 0.25)	–	SCORE inter-laboratory exercises (van Nuijs et al. 2018)
$\sigma_u, \sigma_v, \sigma_e$ (site, year, site-year SD)	half-normal(0.7), half-normal(0.3), half-normal(0.5)	posterior (M1) 1.06 [0.75–1.57], 0.26 [0.16–0.44], 0.09 [0.00–0.18]	weakly informative
μ, b_{pop}, b_{east}	$N(\log 80, 1.5^2)$, $N(0, 0.5^2)$ [M6: $N(0.08, 0.15^2)$], $N(0, 1^2)$	posterior (M1) 4.42 [3.61–5.23], -0.10 [-0.82–0.64], -0.53 [-1.50–0.47]	weakly informative; M6: European SCORE gradient (this study)
Sewer connection	fixed 0.963	–	Destatis 2024 (reference year 2022)

Table 3. National illicit amphetamine estimates for 2025 by model variant (posterior median and 95% credible interval) and the deterministic median-imputation comparator reproduced on the present population frame. The daily figure is the spring-week

consumption rate; the annual figure applies the seasonal ratio ρ , so the two do not scale by 365.25 exactly.

Model variant	Illicit load into sewers (kg/day)	Illicit consumption, spring-week rate (kg pure/day)	Illicit consumption, annualised with ρ (t pure/year)	Per capita (mg/person/day)	50 % CrI (t/year)	Share from unmonitored population	Illicit share of total load
M1 main model	11.9 [6.5–34.9]	45.7 [20.0–154.9]	16.8 [6.8–57.6]	0.55 [0.24–1.85]	12.0–24.4	0.88	0.95 [0.90–0.98]
M6 EU-informed size gradient	10.1 [7.2–16.7]	38.6 [21.4–82.9]	14.1 [7.2–32.2]	0.46 [0.26–0.99]	11.1–18.2	0.86	0.94 [0.91–0.97]
M3 no size gradient	10.6 [8.6–15.8]	40.3 [24.0–78.5]	14.8 [8.0–30.7]	0.48 [0.29–0.94]	11.9–18.6	0.86	0.95 [0.92–0.97]
M2 no methamphetamine correction	13.2 [7.2–34.6]	50.3 [22.7–150.3]	18.3 [7.8–56.9]	0.60 [0.27–1.80]	13.3–26.1	0.88	0.97 [0.92–0.99]
M4 no pharmaceutical term	12.9 [6.9–36.2]	49.1 [21.8–155.3]	17.9 [7.6–58.9]	0.59 [0.26–1.86]	13.0–25.9	0.88	0.99 [0.98–1.00]
M5 α fixed at 0.09	11.8 [6.0–40.7]	45.4 [19.0–169.8]	16.7 [6.6–64.9]	0.54 [0.23–2.03]	11.6–24.9	0.88	0.95 [0.90–0.99]
M7 with ESA state prevalence covariate	14.1 [7.2–39.1]	53.3 [23.1–165.9]	19.5 [8.0–64.6]	0.64 [0.28–1.98]	13.9–28.2	0.90	0.96 [0.91–0.99]

Model variant	Illicit load into sewers (kg/day)	Illicit consumption, spring-week rate (kg pure/day)	Illicit consumption, annualised with ρ (t pure/year)	Per capita (mg/person/day)	50 % CrI (t/year)	Share from unmonitored population	Illicit share of total load
S1 wider α prior	12.2 [6.6–33.7]	46.9 [21.1–146.7]	17.2 [7.2–54.7]	0.56 [0.25–1.76]	12.4–24.5	0.88	0.96 [0.91–0.98]
S2 tighter site-SD prior	12.5 [6.9–31.6]	47.6 [21.2–136.8]	17.7 [7.3–52.4]	0.57 [0.25–1.64]	12.9–24.5	0.88	0.96 [0.91–0.98]
S3 wider gradient prior	13.4 [5.8–70.4]	51.1 [19.2–293.8]	18.8 [6.6–108.7]	0.61 [0.23–3.51]	12.4–31.1	0.89	0.96 [0.89–0.99]
S4 analytical error 0.25	11.9 [6.2–35.1]	45.5 [19.5–153.0]	16.7 [6.8–59.2]	0.54 [0.23–1.83]	11.8–24.3	0.88	0.95 [0.90–0.98]
S5 lognormal site-effect mean	13.9 [6.1–47.5]	52.1 [20.1–199.4]	19.2 [6.9–73.8]	0.62 [0.24–2.39]	13.2–29.6	0.90	0.96 [0.90–0.99]
S6 wider seasonal ratio (sd 0.30)	11.9 [6.5–34.9]	45.4 [20.3–147.8]	16.6 [6.0–62.4]	0.54 [0.24–1.77]	11.5–24.9	0.88	0.95 [0.90–0.98]
M8 site-specific α (σ_α estimated)	12.2 [6.5–34.5]	46.5 [20.2–150.7]	16.9 [7.3–57.9]	0.56 [0.24–1.80]	12.1–24.4	0.88	0.95 [0.90–0.98]
M8b site-specific α (σ_α	12.1 [6.4–	46.7 [20.4–	17.1 [7.1–53.8]	0.56 [0.24–1.66]	12.4–24.5	0.88	0.95 [0.90–

Model variant	Illicit load into sewers (kg/day)	Illicit consumption, spring-week rate (kg pure/day)	Illicit consumption, annualised with ρ (t pure/year)	Per capita (mg/person/day)	50 % CrI (t/year)	Share from unmonitored population	Illicit share of total load
= 0.2)	32.7]	139.0]					0.98]
M8c site-specific α (σ_α = 0.5)	12.2 [6.5–33.3]	46.6 [20.5–145.2]	17.0 [7.1–54.1]	0.56 [0.25–1.74]	12.2–24.9	0.88	0.95 [0.89–0.98]
Comparator: deterministic median imputation, 2025 sites only, CF 2.77, α 0.09 with truncation at zero	7.2	20.0	7.3 (ρ = 1)	0.24	–	0.80	–

Table 4. Triangulation of the wastewater-based estimate against survey-, seizure-, market- and Netherlands-based figures. Intervals are 95% Monte Carlo intervals propagating the stated uncertainties; street-product mass and retail value are model-implied quantities conditional on the assumed purity and price distributions.

Quantity	Estimate [95 % interval]	Source / assumption
WBE illicit amphetamine consumption 2025 (t pure/year)	16.8 [6.8–57.6]	this study, M1
Past-year amphetamine users, ESA 2021 (18–64 y)	699 k [562–868 k]	Rauschert et al. 2022: 1.4 % [1.1–1.7]
Past-year amphetamine users, ESA 2024 (18–64 y)	382 k [261–568 k]	Olderbak et al. 2025: 0.7 % [0.5–1.1]
Implied pure amphetamine per past-year user (g/year), ESA 2021 denominator	24.1 [9.6–82.3]	WBE ÷ users
Implied pure amphetamine per past-year user (g/year), ESA 2024 denominator	44.0 [16.3–156.9]	WBE ÷ users
Survey-anchored consumption (t pure/year): 1 / 3 / 8 g per user-year	0.7 / 2.1 / 5.6	illustrative per-user scenarios examined here (assumptions, not measurements)
Model-implied street-product mass	145 [51–	purity 11.8 % base (REITOX

Quantity	Estimate [95 % interval]	Source / assumption
(t/year)	530]	2025), CV 25 %
Amphetamine seized in Germany 2024 (t)	2.09	BKA via REITOX 2025
2024 seizures as share of the model-implied street-product mass	1.4 % [0.4–4.1 %]	–
Model-implied retail value (million EUR/year)	1440 [490–5421]	10.1 EUR/g (REITOX 2025)
Population-weighted total amphetamine load (uncorrected), Dutch SCORE sites 2025 (mg/1000 inh/day)	234	EUDA 2026 source data, 5 sites
Population-weighted total amphetamine load (uncorrected), German SCORE sites 2025	121	EUDA 2026 source data, 13 sites
Modelled national illicit load per 1000 connected residents, Germany 2025 (different estimand: illicit only, extrapolated)	148 [81–433]	this study, M1

Figure legends

Fig. 1. Monitored catchments. Circle area is proportional to catchment population; fill colour gives the posterior median illicit amphetamine load in 2025; ring thickness is proportional to the methamphetamine-derived share of the measured load; dashed rings mark sites without a 2025 sample, for which the value is a model prediction. The dashed line is the former inner-German border; the thick line is the German–Czech border. Federal-state boundaries from the BKG VG2500 dataset; neighbouring countries from Natural Earth.

Fig. 2. Illicit amphetamine load in 2025 by site: posterior median with 50% (thick) and 95% (thin) credible intervals; circles are western and triangles eastern sites; open symbols are predictions for sites without a 2025 sample; open squares are the measured total amphetamine load of the site’s latest week. Fitted values differ from measured weeks by the analytical error and the site-year deviation. The band is the 95% credible interval of the national illicit load per 1000 connected residents. Flags as in Table 1; years in parentheses give the latest sampled year.

Fig. 3. Source apportionment. (a) Posterior median shares of illicit, methamphetamine-derived and pharmaceutical amphetamine in the measured load at each site, ordered by distance to the Czech border. (b) Methamphetamine-to-amphetamine load ratio (the inverse of the direction used for α) against distance to the Czech border for all site-years (grey) and 2025 (circles, western sites; triangles, eastern sites); the dashed line marks equal loads.

Fig. 4. National estimate. (a) Posterior densities of illicit amphetamine consumption in 2025 under the main model and five variants (line styles distinguish variants); the dotted

line is the median-imputation comparator. (b) Square root of the variance reduction of the log estimate when each component is fixed at its median (standard-deviation units), for the main model (solid) and the European-gradient variant (hatched).

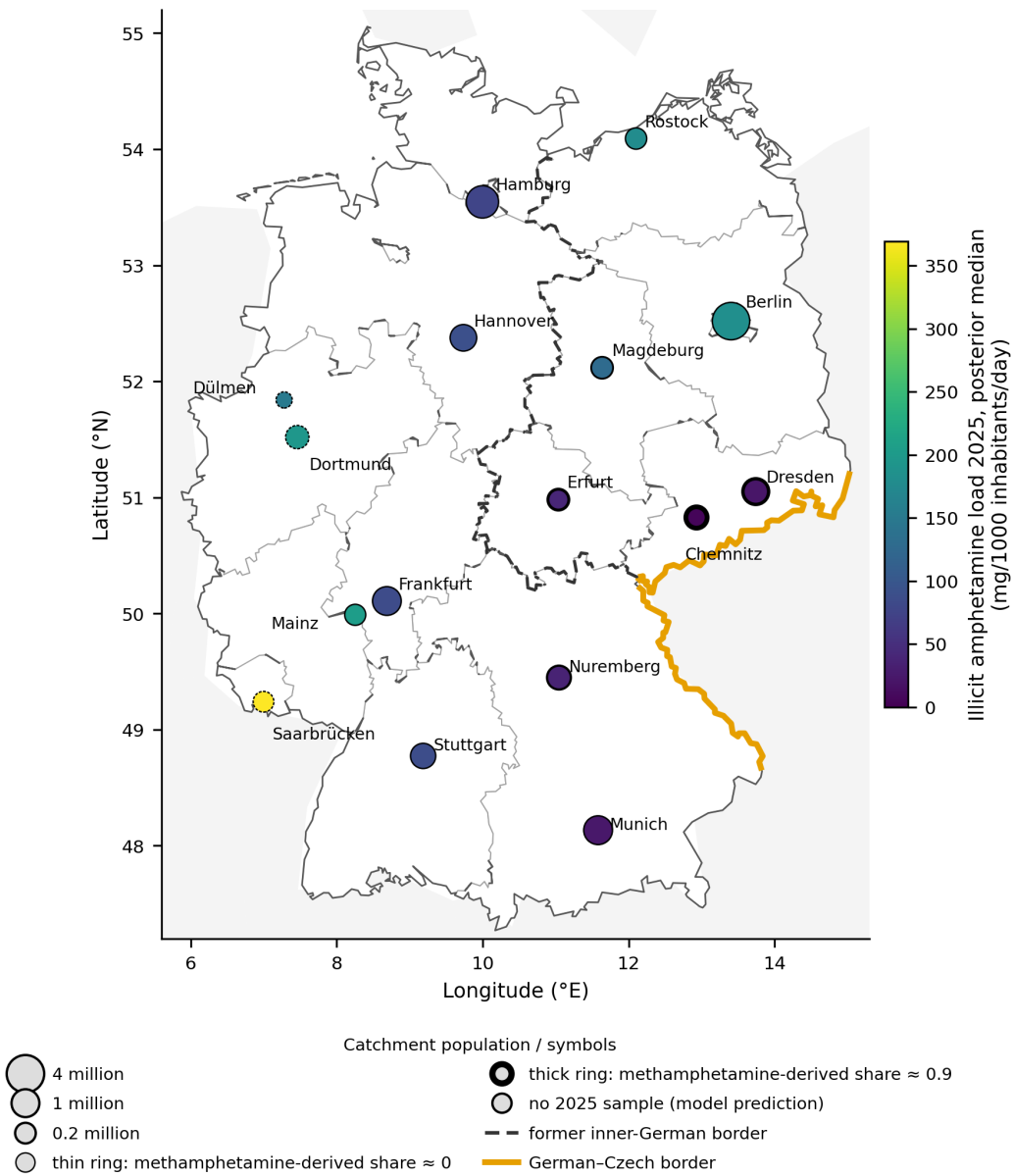
Fig. 5. Predictive evaluation in the space of the observed loads. (a) Leave-one-site-out prediction of each site's weekly mean amphetamine load in its latest sampled year (median and 90% prediction interval) against the observed value; circles, western sites; triangles, eastern sites; filled symbols, catchments of at least 500,000 residents; labels where the error exceeds a factor of 2.7. (b) Prediction of the latest week of each of the nine catchments below 500,000 residents from a model fitted to the seven largest catchments. The dashed line is the identity. (c) Probability integral transform of all 95 held-out site-weeks; the dashed line is the uniform expectation.

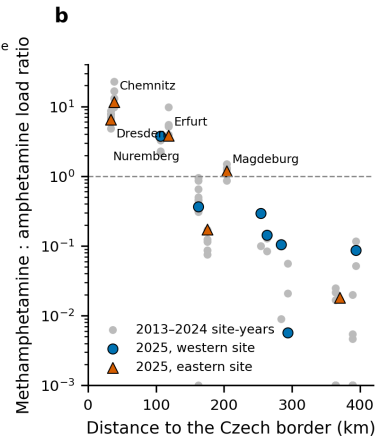
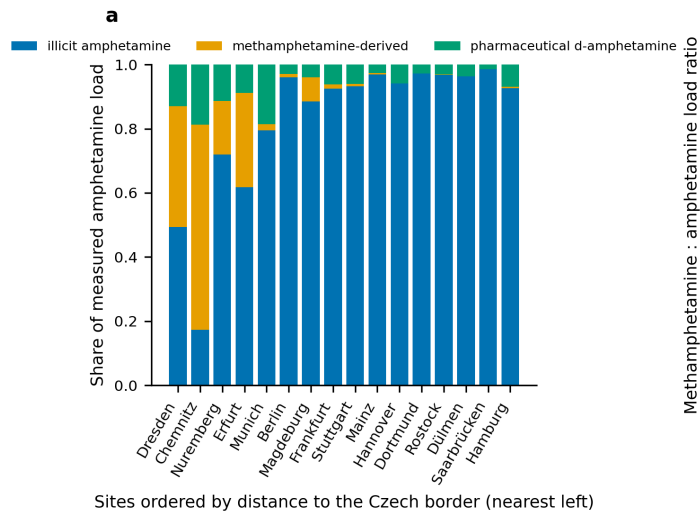
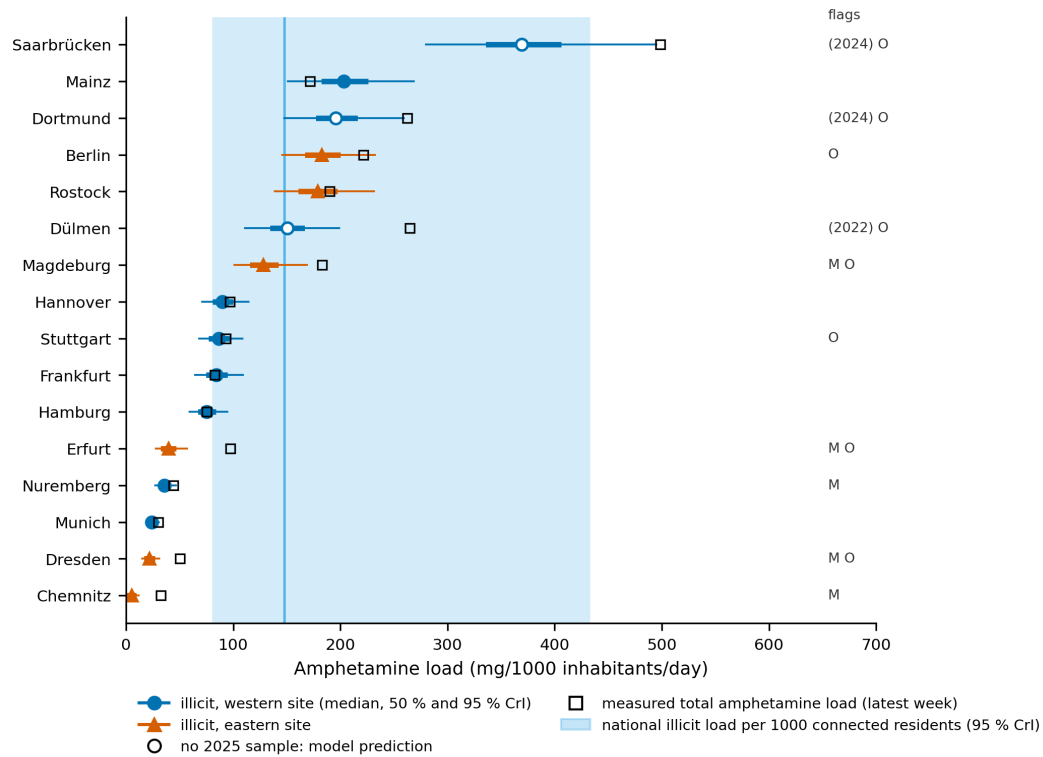
Fig. 6. Monitoring design (PE, population equivalents). (a) Standard deviation of the log national illicit load attributable to extrapolation as a function of the number of additional monitored catchments, by design option (linear-Gaussian preposterior approximation; markers and line styles distinguish options). (b) Reduction of that standard deviation from five additional catchments in each treatment-plant size class (population equivalents, PE) and region (hatched, East).

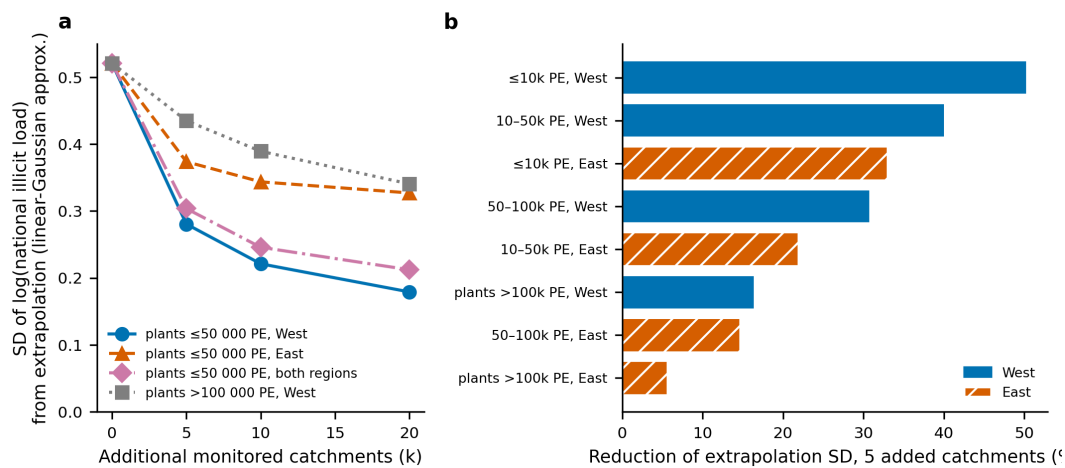
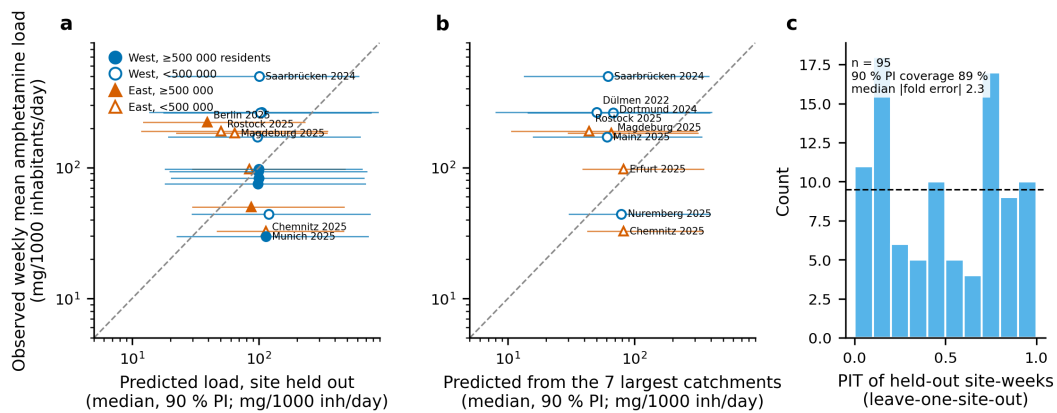
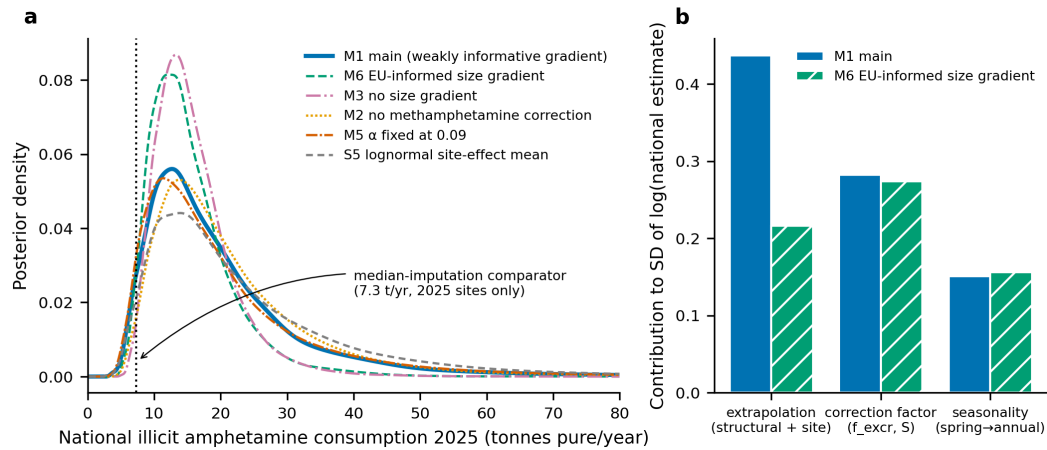
Supplementary material

Supplementary Material S1 (data and retrieval), S2 (population frame), S3 (pharmaceutical term), S4 (priors and prior predictive check), S5 (sampling diagnostics, posterior predictive checks and PSIS-LOO), S6 (predictive evaluation), S7 (site-specific methamphetamine ratio), S8 (value of information), S9 (triangulation inputs) and S10 (reproducibility package) accompany this article.

Figures







Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [FigS3.tif](#)
- [FigS2.tif](#)
- [FigS1.tif](#)