

# Applying the Parameter “Irreducible Concentration” in Modelling of Stormwater Treatment Facilities

Thomas Larm and Anna Wahlsten

*StormTac Corporation, Närkesgatan 8, Stockholm 116 40, Sweden*

**Abstract:** To design stormwater treatment facilities (STFs), we recommend the use of a model that should include the calculation of runoff quality, to be based on a detailed land use specification, include site-specific design parameters, calculated outflow concentrations and loads of specified pollutants of relevance for the receiving water. This study compiles minimum outflow concentrations from stormwater databases of different types of STFs (e.g. swales, wet ponds, wetlands, biofilters and underground retention basins with filters). These data are used for the suggested values of specific “irreducible concentrations” ( $C_{irr}$ ). Suggested  $C_{irr}$  for phosphorus (P) varies from 20-82  $\mu\text{g/L}$  depending on facility type, for copper (Cu) 1.1-3.7  $\mu\text{g/L}$ , for zinc (Zn) 2.0-17  $\mu\text{g/L}$  and for total suspended solids (TSS) 2,900-5,700  $\mu\text{g/L}$ . Corresponding data for 70 substances are compiled in the StormTac database and employed in the model StormTac Web.  $C_{irr}$  has significant impact regarding the choice of facility type and its calculated dimensions. This design parameter and the calculated outflow concentrations can be used to investigate the need for combined serial facilities or complemented design elements with more planted vegetation or installed filters. Such elements can be required to decrease  $C_{irr}$  and thereby reach project specific limit outflow concentrations and loads.

**Key words:** Irreducible concentration, stormwater, treatment, swale, wet pond, wetland, biofilter.

## 1. Introduction

Stormwater management is required to meet specific objectives considering site-specific as well as receiving water conditions, instead of using general percent removal rates [1]. Effluent (outflow) concentrations and loads need to be calculated. In urban drainage modelling, designers therefore need to apply design methods that include parameters such as areal or volumetric relations to the reduced watershed area (area  $\times$  volume runoff coefficient), inflow concentrations, vegetated area, flow detention and the minimum outflow concentrations [2]. These parameters have great impact on the design and resulted outflow quality.

The minimum outflow concentrations or “irreducible concentrations” ( $C_{irr}$ ) refer to a stormwater treatment facility’s (STF’s) inability to reduce pollutant concentrations below a certain level.

Consequently, if the inflow concentrations are close to  $C_{irr}$ , no further reduction is likely. If they are equal to or fall below  $C_{irr}$  there could even be a negative removal [3]. This important design parameter is further studied here for different types of STFs.  $C_{irr}$  is affected by incoming content and internal processes in facilities. Examples are decomposition of plants, leakage from the bottom due to lack of oxygen, the exchange with sediment, stirring sediment because of benthic animals in wet ponds (Fig. 1), background content of materials in filter materials and vegetation beds [3, 4].

There are high-performance stormwater controls. However, high performance may not be consistently achieved due to specific design criteria (e.g. too small dimensions, no vegetation, no filter or poor maintenance). The focus here is to show how low concentrations that can be reached with different types of STFs. The design methods must be complemented with e.g. inflow and outflow concentrations and share of vegetation.

---

**Corresponding author:** Thomas Larm, Ph.D., research fields: stormwater, and surface water.



Fig. 1 A wet pond with shallow wetland areas.

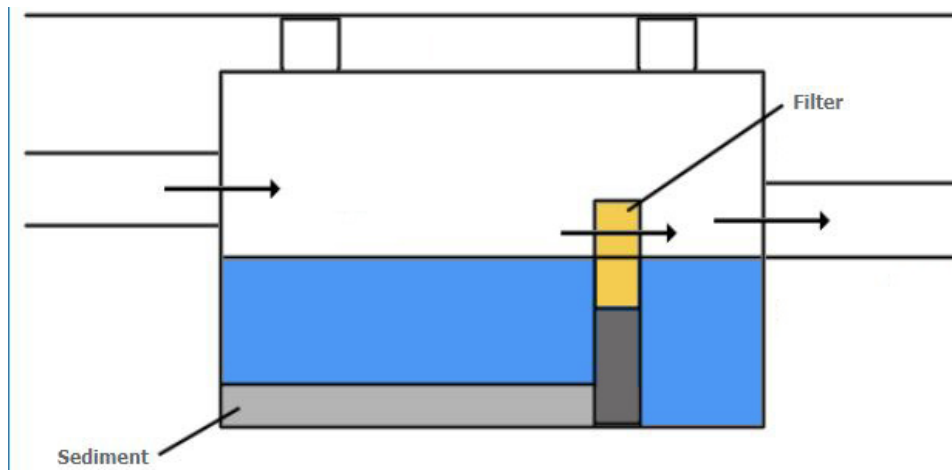


Fig. 2 An underground retention basin with filter cassette.

A general design to e.g. have 80% removal of TSS is not recommended. If inflow TSS concentrations are extremely low, say 20 000  $\mu\text{g/L}$ , for an 80% reduction the effluent would need to be 4,000  $\mu\text{g/L}$ , which may not be possible to reach. The findings of Refs. [5, 6] suggest a lowest reachable outflow concentration for TSS around 10,000-20,000  $\mu\text{g/L}$ , for facilities relying primarily in sedimentation. Given an inflow concentration of 20,000  $\mu\text{g/L}$  and the same irreducible concentration, the expectation for percent removal is zero.

There is a limit to sedimentation basins efficiency

for smaller particles. Since metals are associated with smaller particles, filtration may be required to meet potentially very low discharge limits. Organic media such as filtration media has a background contamination but increased removal and reduced  $C_{irr}$  can be reached with adapted materials for certain pollutants, increased contact time etc. [1]. Normally it is not possible to reach  $C_{irr}$ -values with only sedimentation, so to reach lower values one can use other or combine facilities in a “treatment train” [7], plant more vegetation, add a filter (Fig. 2) or improve the maintenance of the facility etc.

A stormwater management model is required to include site-specific parameters to design STFs to meet these objectives, e.g. StormTac Web [8]. Irreducible concentrations are here presented for phosphorus (P), copper (Cu), zinc (Zn) and suspended solids (SS). These 4 substances are selected since there are much available data and they are generally of priority in different countries, used in water quality criteria and as basis for designing STFs [2].  $C_{irr}$  is suggested to be estimated from outflow data from different types of STFs.

## 2. Method and Materials

### 2.1 Databases and Models for Application of $C_{irr}$

Runoff quality in the stormwater and recipient model StormTac Web [8] is estimated based on land use from e.g. the National Stormwater Quality Database (NSQD) [1] and the StormTac database [9]. StormTac Web is a stormwater and recipient model, a tool for action planning (such as watershed management plans within the water directive) and design. The quality pollutant calculation on part of the application employs updated land use specific concentration data [9], required to calculate yearly pollutant inflow concentrations and loads. Estimated reduction efficiencies and outflow concentrations are simulated based on site-specific parameters such as inflow concentration and  $C_{irr}$ . The simulations are performed for more than 100 land uses and 70 substances. The model requires little input data for performing long-term calculations of annual runoff fluxes and pollutant loads, which can be used for planning and design of stormwater treatment facilities [8]. The model inputs include: (1) precipitation (rain + snow), (2) the land-use data, including the corresponding runoff contributing area and the volumetric runoff coefficient, and (3) the StormTac database “standard concentrations” for each land use, which represent annual averages based mainly on long-term flow proportional sampling [8, 10].

The standard concentrations are updated

continuously. When new reliable data for a specific substance and land use are incorporated into the database, data for other comparable land uses are re-evaluated. The standard concentrations are also adjusted to consider different time trends. For the roads, the standard concentration is calculated as a function of annual daily traffic load (vehicles/day) [9].

The standard concentrations are also calibrated to data from case studies and adjusted after comparisons with data from similar land uses. Therefore, the standard concentrations are not equal to median value from the flow proportional sampling presented in the StormTac database. The standard concentrations for different pollutants and land uses are based on investigations where extensive flow or volume proportional sampling of runoff from catchments with one type of land use has been conducted. These measurements cover all seasons of the year, generating good estimates of the site mean concentrations and are conducted in a similar climate as where the model is applied.

For more than 15 different types of stormwater treatment facilities (STFs), such as swales, wet ponds and biofilters, the StormTac database contains treatment efficiencies (%) derived from flow-proportional input and output data from such facilities [9].

Furthermore, the database includes site-specific data of the STFs, e.g. the ratio of the footprint area of different facilities (e.g. biofilters and swales) to reduced watershed area (i.e. the watershed area multiplied by the runoff coefficient). Based on the data, regression equations are determined for calculating STF reduction efficiencies, which are updated continuously as more data are added to the database [10, 11].

Different regression equations are employed for different types of facilities. The regression equation for swales (Fig. 3) is based on the ratio of the swale area to the reduced drainage area, inflow concentrations, irreducible concentrations and bypass, see Eq. (1) [10, 11].



Fig. 3 A swale.

$$RE = [k_1 \ln(n_0) + k_2] \cdot f_{C_{in}} \cdot f_{C_{irr}} \cdot f_{bypass} \quad (1)$$

RE: reduction efficiency (%);

$k_1$ ,  $k_2$ : regression coefficients specific for each substance and facility;

$n_0$ : ratio of facility area to the reduced watershed area (%), where reduced watershed area is calculated by multiplying land use areas ( $A_i$ ) by the volumetric runoff coefficient ( $\phi_v < 1$ );

f: factor;

$C_{in}$ : inflow concentration ( $\mu\text{g/L}$ );

$C_{irr}$ : irreducible concentration ( $\mu\text{g/L}$ );

Bypass: If there is a bypass, the flow entering the facility is set as an input, representing a part of the total annual runoff volume which is also calculated in StormTac Web.

## 2.2 Irreducible Concentration

Ref. [3] suggested a preliminary estimate of  $C_{irr}$  of pollutants in general stormwater practice outflows as 150-200  $\mu\text{g/L}$  for P and 20,000-40,000  $\mu\text{g/L}$  for TSS. Outflow concentration data from different STFs have been compiled from the International BMP Database 2016 summary statistics [12] and the StormTac database [9]. Updated  $C_{irr}$ -values have been suggested from these data, compiled in Table 1.

The reduction efficiency (RE) (%) of a stormwater treatment facility can be expressed as a function of pollutant inflow and outflow loads or concentrations. Furthermore, RE depends on site-specific parameters.

Higher inflow concentration and more vegetation can result in higher RE, and  $C_{irr}$  can stop further treatment [13]. To consider  $C_{irr}$  in the design processes we present simply the general functions of RE as a function of inflow concentration  $C_{in}$  and outflow concentration  $C_{out}$ , Eq. (2), from which  $C_{out}$  is calculated in Eq. (3). The condition of  $C_{irr}$  in Eq. (4) is used to calculate the maximum achievable RE,  $RE_a$  in Eq. (5) [14]:

$$RE = 100 (C_{in} - C_{out})/C_{in} \quad (2)$$

$$C_{out} = C_{in} - C_{in} RE/100 \quad (3)$$

$$C_{irr} \leq C_{out} \quad (4)$$

$$RE_a = 100 (C_{in} - C_{irr})/C_{in} \quad (5)$$

100: unit conversion factor;

RE: reduction efficiency (%);

$C_{in}$ : inflow concentration ( $\mu\text{g/L}$ );

$C_{out}$ : outflow concentration ( $\mu\text{g/L}$ );

$RE_a$ : maximum achievable reduction efficiency (%).

To evaluate data, the “BMP-weighted” and “storm-weighted” approaches can be used [12]. The BMP-weighted approach represents each BMP with one value representing the central tendency and variability of each individual BMP study. The storm-weighted approach combines all the storm events for the BMPs in each category and analyses the overall storm-based data set. When implementing the concept of  $C_{irr}$  the hypothesis is that the BMP-weighted should be used, since it considers periods with releases of pollutants from the facility

materials or sediments to the water phase; else too small  $C_{out}$ -values would be used, not considering the effects of longer time periods.

The BMP-weighted effluent concentrations from the BMP database ([www.bmpdatabase.org](http://www.bmpdatabase.org)) in Access format have been compiled by StormTac Corporation by weighting each event effluent concentration by the event flow, and then calculating minimum concentrations per facility type. These minimum data have been compiled in Ref. [9] and used as suggested irreducible concentrations in Table 1. The database includes several more BMP types and much more substances [9].

To further show how  $C_{irr}$  can have great impacts on the choice of type and size of treatment facilities, StormTac Web was used in an example case study designing stormwater treatment for a 20 ha residential area with surrounded forest, using a swale (Fig. 3) combined with a biofilter (Fig. 4) for treatment.

### 3. Results and Discussions

#### 3.1 Results

In Table 1, minimum outflow concentrations from the International BMP Database and the StormTac database are compiled for different facility types. The



Fig. 4 A biofilter.

Table 1 Minimum total outflow concentration ( $\mu\text{g/L}$ ), excluding outliers. Compiled data from StormTac database include calculated BMP-weighted data from the BMP database and are suggested irreducible concentration ( $C_{irr}$ ) for each facility.

Facility type	Database	P ( $\mu\text{g/L}$ )	Cu ( $\mu\text{g/L}$ )	Zn ( $\mu\text{g/L}$ )	TSS ( $\mu\text{g/L}$ )
Swale	StormTac database, BMP-weighted ( $C_{irr}$ )	82	1.5	14	5,700
	<i>BMP database, storm-weighted</i>	50	1.0	4	1,500
Filter strip	StormTac database, BMP-weighted ( $C_{irr}$ )	61	3.3	17	5,700
	<i>BMP database, storm-weighted</i>	25	1.5	2.0	1,500
Wet pond	StormTac database, BMP-weighted ( $C_{irr}$ )	20	1.1	2.5	2,900
	<i>BMP database, storm-weighted</i>	5.0	0.70	2.0	300
Wetland	StormTac database, BMP-weighted ( $C_{irr}$ )	20	1.1	2.5	2,900
	<i>BMP database, storm-weighted</i>	8.0	0.40	2.5	300
Biofilter	StormTac database, BMP-weighted ( $C_{irr}$ )	21	3.7	3.9	3,000
	<i>BMP database, storm-weighted</i>	6.0	0.80	0.70	400
Underground retention filter basin	StormTac database, BMP-weighted ( $C_{irr}$ )	30	2.0	2.0	5,000

compiled data from the BMP database are storm-weighted. That approach was selected for the referred report because it provides a much larger data set for analysis [12]. The BMP data show that it occasionally, without taking into account the long-time effects, can give very low outflow concentrations. The StormTac database also includes BMP-weighted data. They represent long-term performance data from each case study whereby they are suggested as irreducible concentrations,  $C_{irr}$ .

### 3.2 Example Case Study

The hypothetical example case study consists before exploitation of 15 ha forests and 5 ha residential area. There is a sensitive creek downstream the area of exploitation. The planned exploitation is to add 5 ha residential area in the forest area so there will be 10 ha forest and 10 ha residential area after exploitation. The municipality has set a criterion not to increase the pollutant load on the creek after exploitation, especially regarding phosphorus (P). StormTac Web was used for calculating pollutants and required treatment.

The total P concentration and load before exploitation were calculated to 70  $\mu\text{g/L}$  and 2.2 kg/year respectively. After exploitation these increased to 110  $\mu\text{g/L}$  and 3.9 kg/year. As a first step a large swale was simulated for P reduction. A 3,600  $\text{m}^2$  swale resulted in 82  $\mu\text{g/L}$  and 3.0 kg/year, see the upper picture in Fig. 5, i.e. not enough treatment in this case. A larger swale would probably not reduce this load any further since the outflow concentration from the swale has reached the corresponding irreducible concentration of 82  $\mu\text{g/L}$ , see Table 1.

The simulation has stopped further treatment due to e.g. leakage from the sediments, decomposition of plants and re-suspension during periods of high flow. The calculated reduction efficiency was stopped at 23%. The relatively low reduction can also be explained by low inflow P concentration.

To get further reduced P load we simulated a biofilter (Fig. 4) downstream the swale. This type of facility has the potential to reduce  $C_{out}$  to around 21  $\mu\text{g/L}$  (Table 1), if simulated site-specific conditions so permit. A biofilter with a treatment area of 750  $\text{m}^2$  was simulated in series with the swale which resulted in  $C_{out} = 45 \mu\text{g/L}$ , P load = 1.6 kg/year, i.e. < 2.2 kg/year and sufficient treatment with an overall RE = 58%, see the lower picture in Fig. 5.

### 3.3 Discussion

The data in Table 1 are compiled from outflow concentrations in the StormTac database, where there are data for many more substances and facility types. The aim is that  $C_{irr}$  shall represent minimum values of sites with a certain facility type. The original data consist of mean outflow concentrations during annual periods from each site.  $C_{irr}$  should not be based on short term minimum concentrations since there could be e.g. release processes during events of high flow or decomposition processes from plants, if not harvested. The database will be complemented continuously, resulting in revised  $C_{irr}$ -values. In StormTac Web, the reduction efficiency is adjusted so that no less concentration than  $C_{irr}$  is obtained at the outlet [13]. However, it is possible to unlock this restriction if it is believed possible to achieve lower levels by adapting the choice of plants, adding filters or the like.

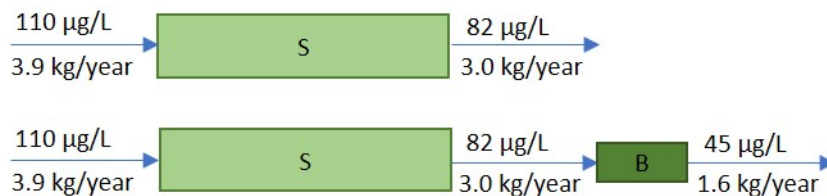


Fig. 5 The upper picture shows a swale (S) and the lower a swale combined with a biofilter (B).

If it is required to lower the calculated outflow concentration of a certain substance for a certain designed facility, then it is possible to complement the facility with more plants or to add a downstream filter facility adapted for better reduction of that substance. This can be simulated with models that include this parameter and shows the importance of not designing and estimating reduction efficiency without considering site specific conditions.

In many cases, a treatment train incorporating different processes that target different pollutant characteristics can be needed to achieve strict discharge limits. It can be composed of sedimentation (e.g. in wet ponds) followed by filtration unit processes (e.g. in biofilters) [7]. If it is required to lower the calculated outflow concentration of a certain substance, then it is possible to complement the facility with more plants or to add an outlet filter with materials adapted for better reduction of specific substances.

#### 4. Conclusions

Stormwater treatment facilities need to be designed based not on general percent removals, but instead based on site-specific conditions for different treatment components, considering irreducible concentrations ( $C_{irr}$ ). The compiled results indicate that there is no general irreducible barrier and that much lower  $C_{irr}$  than preliminary suggested by Ref. [3] may be achieved. Irreducible concentration is a relative concept as opposed to using the concept as an absolute delimiter. It is possible to get concentrations as low as desired, but it is often not practical to design facilities to achieve extremely low concentrations since that would require e.g. treatment trains and/or chemical addition [15]. Earlier research [16] and the compiled minimum effluent data in Table 1 indicate large variations between different BMP types. There is a  $C_{irr}$  that normally can be achieved for a certain type of facility, which can affect the choice and dimension of the chosen type of facility.

Based on presented results,  $C_{irr}$  for phosphorus (P) varies from 20-82  $\mu\text{g/L}$  depending on facility. For copper (Cu)  $C_{irr}$  varies between 1.1-3.7  $\mu\text{g/L}$ . For zinc (Zn),  $C_{irr}$  varies between 2.0-17  $\mu\text{g/L}$  and for total suspended solids (TSS) between 2,900-5,700  $\mu\text{g/L}$  depending on facility. The outflow concentrations and the estimated irreducible concentrations for different STFs were generally lower for wet ponds, wetlands, biofilters and underground retention basin filters than for swales and filter strips. This outflow concentration and load data can be simulated with e.g. StormTac Web or the like, beginning with calculating inflow quality from land use data. Also, other site-specific parameters are to be considered in the design.

The design parameter “irreducible concentration” ( $C_{irr}$ ) is recommended to be considered when designing stormwater treatment facilities. The parameter can be used to investigate the need for combined serial facilities or complemented design elements. Such elements can be required to decrease  $C_{irr}$  and thereby reach project specific limit outflow concentrations and loads.

The presented values of  $C_{irr}$  are uncertain and this uncertainty is now being investigated and quantified regarding both inflow and outflow concentrations and loads, before and after treatment.

#### References

- [1] Clark, S. E., and Pitt, R. 2012. “Targeting Treatment Technologies to Address Specific Stormwater Pollutants and Numeric Discharge Limits.” *Water Research* 46: 6715-30.
- [2] Larm, T., and Hallberg, M. 2008. “Design Methods for Stormwater Treatment-Site Specific Parameters.” In *Proceedings of the 11th International Conference on Urban Drainage, ICUD*, Edinburgh, Scotland, UK, 2008.
- [3] Schueler, T. R., and Holland, H. K. 2000. “Irreducible Pollutant Concentrations Discharged from Stormwater Practices: The Practice of Watershed Protection.” *Watershed Protection Techniques* 2 (2): 369-72. Center for Watershed Protection. <http://www.cwp.org>.
- [4] Center for Watershed Protection. 2007. *National Pollutant Removal Database. Appendix C: Updated BMP Removal Efficiencies from the National Pollutant*

- Removal Database & Acceptable BMP Table for Virginia.* Center for watershed Protection, Ellicott City, Maryland, USA.
- [5] Randall, W. C., Ellis, K., Grizzard, J. T., and Knocke, W. R. 1982. “Urban Runoff Pollutant Removal by Sedimentation, Stormwater Detention Facilities.” In *Proceeding from Conference on Stormwater Facilities, ASCE*.
- [6] Urbonas, B. R., and Stahre, P. 1993. *Stormwater Best Management Practices Including Detention*. USA.
- [7] Pitt, R. 2010. *Evaluation of Biofiltration Media for Engineered Natural Treatment Systems*. Report from University of Alabama to Geosyntec Consultants, CA.
- [8] Larm, T. 2000. “Watershed-Based Design of Stormwater Treatment Facilities: Model Development and Applications.” PhD thesis, Royal Institute of Technology, Stockholm, Sweden.
- [9] Larm, T. 2019. “StormTac Database.” <http://www.stormtac.com>.
- [10] Snezana, G., Larm, T., Österlund, H., Marsalek, J., Wahlsten, A., and Viklander M. 2019. “Measurement and Conceptual Modelling of Retention of Metals (Cu, Pb, Zn) in Soils of Three Grass Swales.” *Journal of Hydrology* 574: 1053-61.
- [11] Larm, T., and Alm, H. 2016. “Design Criteria for Local Stormwater Facilities to Meet Pollution and Flow Requirements.” In *Proceedings of NOVATECH 2016*.
- [12] Geosyntec Consultants, Inc., and Wright Water Engineers, Inc. 2017. *International Stormwater BMP Database 2016 Summary Statistics*.
- [13] Larm, T., and Alm, H. 2014. “Revised Design Criteria for Stormwater Facilities to Meet Pollution Reduction and Flow Control Requirements, Also Considering Predicted Climate Effects.” *Water Practice and Technology* 9 (1): 9-19.
- [14] Minton, G. R. 1998. “Stormwater Treatment Northwest.” Vol. 4, August.
- [15] Geosyntec Consultants, Inc., and Wright Water Engineers, Inc. 2009. *Urban Stormwater BMP Performance Monitoring*.
- [16] ASCE. 2000. *Data Evaluation Report, Task 3.4*. National Stormwater Best Management Practices Database Project.