Estimation of pollutant loads transported by runoff by using a GIS model Case study: Luleå city centre

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Estimation de la charge polluante des eaux de ruissellement à l'aide d'un SIG : étude de cas au centre ville de Luleå (Suède)

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RÉSUMÉ

L'urbanisation des terres est synonyme d'imperméabilisation des surfaces et donc de diminution du taux d'infiltration des sols. Par conséquent, l'urbanisation engendre une augmentation du volume d'eau ruisselant sur ces surfaces. Les eaux pluviales urbaines transportent de grandes quantités de polluants provenant des activités en zones résidentielles, commerciales et industrielles. Le type de polluants et les concentrations en jeu dépendent grandement du type et de l'intensité des activités pratiquées sur les terres. En connaissant la taille des bassins versants et le type d'utilisation des terres, il est possible de prédire le volume de ruissellement.
Ensuite, au moyen de mesures de concentration des polluants et par généralisation sur le bassin versant, il est possible d'estimer les charges de ces polluants transportés par ruissellement vers les cours d'eau récepteurs. L'objectif principal de cette étude était d'analyser et de quantifier les charges annuelles de polluants transportées vers le milieu naturel. L'étude a été réalisée dans la ville de Luleå, au nord de la Suède. Un modèle SIG a été mis au point sur une surface de 230 hectares, répartie en 19 sous-bassins versants, à partir d'un modèle numérique d'altitude, d'une carte d'orthophotos, d'une carte du réseau d'eaux pluviales et d'une étude sur le terrain. Différents types d'utilisation des terres ont été identifiés au sein de chaque sous-bassin: routes, aires de stationnement, zones résidentielles et espaces verts. Les charges mensuelles et annuelles de polluants ont été estimées pour la totalité du bassin versant au moyen de ce modèle. Les polluants analysés dans cette étude sont les métaux lourds Pb, Zn, Cu et Cd, d'autres polluants tels que DCO, Tot-P, Tot-N, ainsi que les particules en suspension (TSS).

ABSTRACT

Urbanisation has produced an increase in impervious surfaces which is reducing the amount of stormwater infiltration and rapidly increasing the surface runoff. Urban stormwater carries a variety of pollutants from activities on residential, commercial, and industrial land. The concentration and types of contaminants depends greatly on the type and intensity of activities and land use. By knowing the catchment size and the type of land use, it was possible to predict stormwater runoff quantity. Subsequently, using generalised as well as measured pollutant concentrations, it was possible to estimate the pollutant loads transported by runoff to receiving water bodies. The main objective of this study was to investigate the annual pollutant loads transported to receiving water bodies. The study was performed in the Luleå, located in the north part of Sweden. A GIS model was created with a total area of 230 hectares divided into 19 sub-catchments by using a Digital Elevation Model, an Orthophoto map, a stormwater network map and a field study. Within each sub-catchment different kinds of land use were identified; roads, housing areas, parking areas, and green areas. As a result of this mapping, the pollution generated from the catchments was estimated as monthly and annual loads. Studied pollutants were heavy metals, Pb, Zn, Cu, and Cd and other pollutants included COD, Tot-P, Tot-N, and TSS.

KEYWORDS

Pollutant load, GIS, runoff

1 INTRODUCTION

When rainwater falls on a surface it is either evaporated, infiltrated or becomes surface runoff. In urban areas with a high percentage of impervious surfaces, the infiltration decreases drastically and most of the rainfall will become surface runoff (Villarrar, 2005).

In a natural environment, the runoff is purified during its flow through the ground before reaching surface waters or groundwater, while in urban areas, the surface runoff reaches the water body more rapidly. On the way to the recipient the water transports pollutants that have been accumulated on different surfaces (Stockholm Vatten, 2008).

Urban stormwater carries various kinds of pollutants as a result of different activities in residential, commercial and industrial land. During rainfall or snowmelt events, these pollutants are quickly washed off the surfaces. The concentrations and types of contaminants depend on the intensification of activities and type of land use. Westerlund (2007) stated that discharges in cold climate regions seem to particularly affect the environment severely due to the long winter period where the precipitation falls as snow and stays on the ground for several months and pollutants accumulate till the snowmelting period.

According to Westerlund (2007) the snowmelt induced runoff is often increased because of saturated or frozen soils during the spring melt. Also, flows caused by rain on snow events can create significant flooding due to the frozen conditions and the rain has the ability to rapidly melt the snowpack, adding to the flow. According to Westerlund (2007) in cold climate many pollutants were similar to those found for other climatic conditions. However some of the pollutants were present in higher amount due to heating of building and cold starts of engines which demand higher energy and fuel usage.

A common practice in most areas is to drain away the precipitation as quickly as possible to the nearest water body. Conversely, sustainability is a demand and there is a general desire to enhance indicators for quality of life. The EU Water Framework Directive (WFD) was established in year 2000, and the objective was to reach good ecological status within European river basins, thus according to Scholes et al. (2007) stormwater management will become a key focus and WFD will support legislation that promotes integrated approaches to water management such as use of Best Management Practices (BMP) or Water Sensitive Urban Design (WSUD).

The objective of this study was to estimate the annual pollutant loads (Pb, Zn, Cu, Cd, Tot-N, Tot-P, COD and TSS) transported by runoff from the Luleå city centre to receiving water bodies.

2 AREA DESCRIPTION

The area selected in this study was the city centre of Luleå which was located in the north part of Sweden at a latitude of 65° 35'N and a longitude of 22° 09'E. Luleå has a population of approximately 72 000 inhabitants. The annual precipitation in the area was about 500 mm, while 40 to 50% of this amount occurs as snow and stays on the ground for 5-6 months, thus there was no runoff during November to March. The snowmelt usually starts in March-April and continues to May. The monthly average temperature and precipitation was shown in Table 1. The average annual air temperature was 1.5°C and the lowest temperature occurs in January with an average of -12.2 °C (SMHI, 2001).

Table 1 Monthly average temperature and precipitation in Luleå (SMHI, 2001)

	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Temp(C)	-12.2	-10.7	-6	0.1	6	13	16	14	8.3	3	-4	-9
Precipitation(mm)	32	24	29	30	33	35	55	62	56	51	48	35

Figure 1 The study area in Luleå city centre defined with the white colour

3 METHODOLOGY

3.1 Urban runoff quantity

To decide the quantity of runoff from Luleå city centre, a simple steady state rational formula was used. Rain intensities and runoff coefficients were derived from Table 1 and 2 respectively. To decide on runoff coefficients, the study area was classified into following main areas: roads (high and low traffic loads), parking areas, buildings and roofs, and green areas. Table 2 shows runoff coefficients for different surfaces in urban areas in UK. The runoff coefficient for different areas has a range that is also applicable for Swedish conditions (Svenskt Vatten, 2003).

Table 2 Typical values of runoff coefficient in urban areas (David Butler & John Davis, 2004)

Area description	Runoff coefficient	Area description	Runoff coefficient
City centre	0.70-0.95	Parks and gardens	0.05-0.30
Suburban businesses	0.50-0.70	Asphalt and concrete paving	0.70-0.95
Industrial	0.50-0.90	Roofs	0.75-0.95
Residential	0.30-0.70	Lawns	0.05-0.35

After producing the sewer system layout in the model, the catchment was divided into sub-catchments draining towards each pipe or group of pipes in the system. To find the areas of the sub-catchments and in each sub-catchment find the roads, parking places, houses, and green areas, ArcGIS 9.2 was used. These four categories of land uses within each sub-catchment were needed as they have varying percentages of impervious surfaces and later on they were needed to define the runoff quality since runoff over different land uses generates various pollutant concentrations.

Basically three kinds of data was used and merged in order to define the areas of the sub-catchments:

- **Orthophoto map:** Orthophoto was an aerial photograph that was geometrically corrected.
- **Digital Elevation Map:** a map that represents continuous elevation values over a topographic surface by array of Z-value which was referenced to a common datum (ESRI, 2007).
- **Stormwater network map:** a map that visualises the place of stormwater collection pipes and it contains pipes elevation data.

Orthophoto map and DEM (Digital Elevation Map) of the Luleå city centre was ordered through the databases at the digital map library. The orthophoto was in the RT90_25_gon_V coordinate system and the datum of D_RT_1990.

DEM cell size was 50*50m which means the resolution for elevation map was 50 meters. The DEM data from the database had ASCII format and by using ASCII to raster conversion tools in Arc Toolbox the raster file achieved.

A map of the stormwater system was needed because the runoff does not always follow the topography but was instead transported in the man-made collection system with slightly different slope. The Luleå municipality provided this data in a shapefile format for the stormwater system. As well, a field study helps to decide on some of the borders and areas, due to the insufficient resolution of the DEM.

The hydrological tools in ArcGIS Spatial Analyst allowed us to determine the flow direction, identify sinks, and fill the sinks. With the sink function, any sinks in the original DEM were identified. The problem with the sinks was that any water which flow into the sink can not flow out, thus to ensure proper drainage mapping, these sink point can be filled with the Fill tool. Therefore in the hydrological tools sink and fill was applied on the original DEM.

Having the DEM, ArcGIS can derive the flow direction map which identifies the down-slope direction for each cell. The Basin tool uses the results of the Flow direction tool to identify the drainage basins, made up of the connected cells that drain to a common location (ESRI, 2007).

By having the basin, orthophoto map, stormwater system and the field study, a decision was made to define the areas of the sub-catchments. Figure 2 shows pre-processing and post-processing of data for sub-catchments delineation.

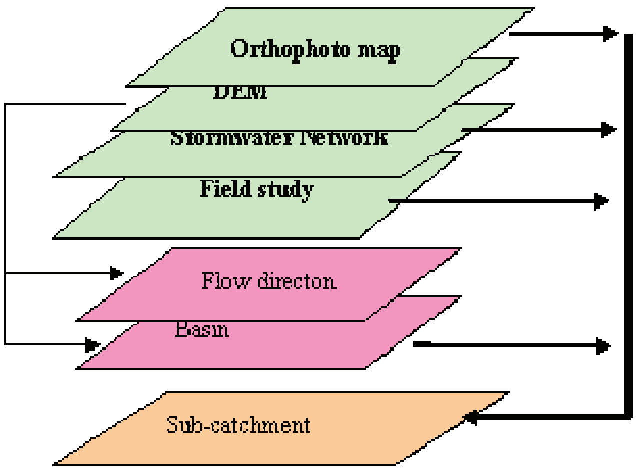

Figure 2 Data processing for sub-catchment delineation.

The new shapefile of the sub-catchments was created in ArcCatalog and they were digitized in ArcMap. In this project, 19 sub-catchment areas were identified. Subsequently, in each area three different shapefiles were created and separately digitized. These categories were housing area, roads -divided to high and low traffic- and parking area and the assumption was that the rest were the green area.

The area for all shapefiles was calculated by calculate geometry tool. All the areas were converted to an Excel file for 19 sub-catchments and 5 categories; high and low traffic roads, parking areas, housing areas and green area. Then data for the minimum and maximum runoff coefficient and monthly rain intensity (monthly millimetres precipitation) from the literature review was put in the same file. The range for Q was calculated for the different sub-catchment areas through multiplying the area by the runoff coefficient range (see Table 2) and by the rain intensity (see Table 1). Runoff quantity was available as a range since runoff coefficient had a range.

3.2 Urban runoff quality

To calculate the pollutant loads transported to receiving water bodies, pollutant concentration values for different surfaces were extracted from other studies (see, Table 3). Subsequently, it was possible to find the pollutant loads generated by each surface within the sub-catchments.

Within each sub-catchment different kinds of land use were identified as they produce varying loads of pollutants. Roads, parking areas, houses and green areas were the chosen types of land use. Roads and parking areas were impervious surfaces that produce runoff with high pollutant concentrations. Road pollution was considered positively correlated with traffic loads, therefore roads have been divided in two categories, a) high traffic roads with more than 15000 vehicles/24hours and, b) low traffic roads with less than 15000 vehicles/24hours. Table 3 shows literature values for the different pollutant concentrations generated from the different categories; low and high traffic roads, housing area, parking area and green area.

Table 3 Average and min-max values for pollutant concentrations (mg/l) in road runoff for roads (two different traffic loads), housing area, parking area and green areas. Adopted from Lindgren (2001), Larm, (1994) and Nordeidet et al., (2004).

		Pb Average Min-max	**Zn** Average Min-max	**Cu** Average Min-max	**Cd** Average Min-max	**Tot-N** Average Min-max	**Tot-P** Average Min-max	**COD** Average Min-max	**TSS** Average Min-max
Roads	Low traffic	0.02	0.1	0.035	0.0005	1.2	0.15	40	75
	≤15000	0.01-0.05	0.05-0.275	0.02-0.07	0.0003-0.0009	0.6-1.8	0.1-0.25	20-80	40-150
	High traffic	0.025	0.155	0.045	0.0005	1.5	0.2	60	100
	15000-30000	0.015-0.06	0.075-0.350	0.025-0.09	0.0003-0.0009	0.8-2.1	0.1-0.35	30-120	50-200
Housing area	General	0.15	0.2	0.033	-	1.9	0.3	80	100
		-	-	-	-	-	-	-	-
	Roofs	-	-	-	-	-		-	20
		0.01-0.1	0.05-1	0.01-1	0.001-0.004	-	-	10-22	-
Parking area		-	-	-	-	-	-	-	-
		0.03-0.3	0.1-0.4	0.03-0.1	0.002-0.004	-	-	100-200	20-150
Green area		0.01	0.03	0.01	-	2.0	0.4	40	40
		-	-	-	-	-	-	-	-

To do a sensitivity analysis for the model, flow was kept constant and the pollutant concentration range, (except for general housing area and green area where only average values were available) was used. Next, the pollutant concentration was kept constant, meaning that the average concentrations were used and the flow range as a result of the runoff coefficient range was used. For the category housing area, the general values were used for all pollutants apart from Cd, since literature values did not exist. Instead, the concentrations for Cd were retrieved from the roof category.

For the categories green area and housing area, only average concentrations were available instead of the range for pollutant concentration and consequently the outcome was calculated by multiplying the constant average flow (Q) by the average pollutant concentration. Accordingly there were no ranges of pollutant loads available for the categories green area and housing area. Finally, these constant pollution values from green area and housing area were summed up with the range (minimum and maximum) of pollution from other surfaces. It was decided to continue the calculations based on the range of flow and constant pollutant concentration. The two calculations were performed assuming no difference between the pollution concentrations in snowmelt and rainfall runoff. The two approaches are illustrated in Figure 3.

However, a cold climate makes the calculations more complex and therefore to be specific and accurate, the year was divided into a rain period and a snow period. Using the same pollutant concentrations for both rain and snow periods when calculating loads seems slightly unrealistic as there are differences according to other studies (Westerlund, 2007 and Viklander 1997). For this reason the model was checked for 8 different conditions which were shown in Figure 3.

According to the temperature data for Luleå it was assumed that for five months of the year, November to March, the precipitation occurs as snow and during the other seven months, April to October, it occurs as rain. To check the sensitivity of the model to length of the snow periods, the case with two months of snow consisting of January and February was also calculated. Three scenarios were set up to study the effects of different snow handling strategies in Luleå city centre based on these two conditions for snow and rain period (see Figure 3). The first assumption was that the snow transported from the Luleå city centre due to snow handling operations was ignored; in other conditions 50% and 100% of the snow was removed from roads and parking areas and transported out of the catchment area.

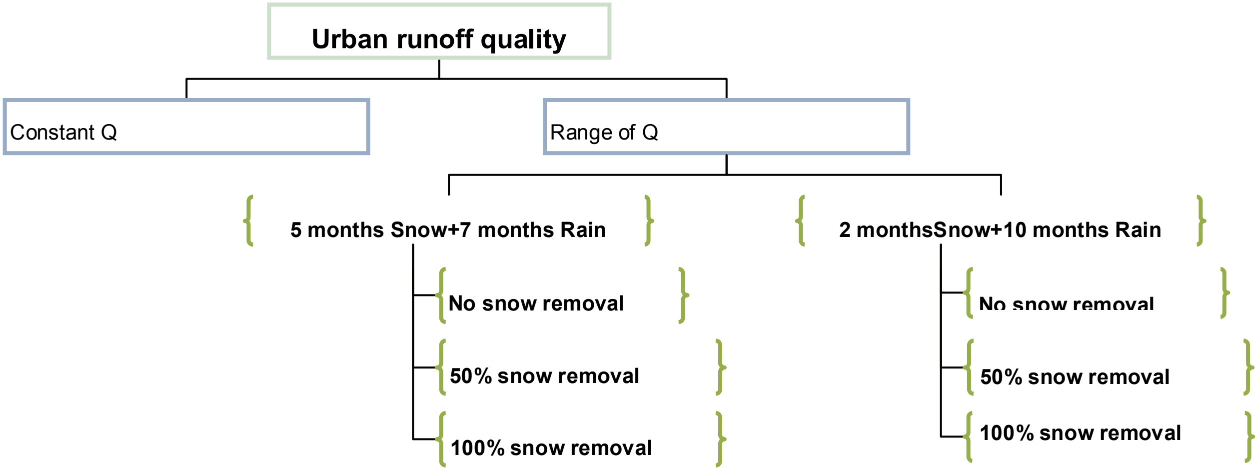

Figure 3 Schematic diagrams for different scenarios to check the sensitivity in the model

Measurements carried out by Westerlund (2007) on snowmelt and rainfall induced runoff from a road with a traffic load of 7400 vehicles per day in Luleå demonstrates that heavy metal concentrations were about 2.8 times higher and TSS was 7 times higher in snowmelt induced runoff as compared to rainfall induced runoff. Pollutant concentrations for rain values from Westerlund (2007) were similar to the average literature values in Table 3. The concentrations for Tot-P was extracted from Viklander (1997) where measurements showed that Tot-P was 3.5 times higher in snow as compared to rain. It was assumed that Tot-N and COD showed the same variation between snow and rain as Tot-P.

Considering the same tendency for high traffic roads and parking areas, the heavy metal concentrations was assumed to be 2.8 times higher during the snowmelt as compared to the general values and Tot-N, Tot-P and COD 3.5 times higher, while TSS was assumed to be 7 times higher compared to the general values. Literature studies showed a higher pollution load at roads and parking areas and consequently snow pollutant concentrations for roofs and green areas were assumed to be half the increase as the concentrations for roads and parking area. As a result of these assumptions, the new concentrations were used to determine the annual pollutant loads more accurate.

4 RESULT AND DISCUSSION

4.1 Urban runoff quantity

The GIS model with 19 different sub-catchments contributes with runoff to four water bodies (see Figure 4). The runoff from sub-catchments 2, 3 and 4 flows into water body A, sub-catchments 5 to 13 flow into water body B, sub-catchments 14 to 19 flow into water body C and sub-catchment 1 flows to water body D.

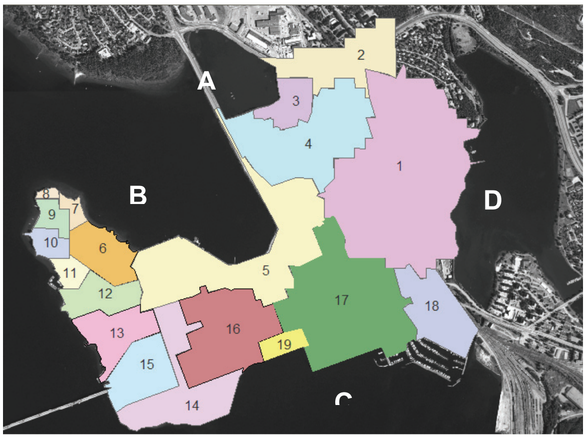

Figure 4 19 sub-catchment and 4 water bodies have been identified

Sub-catchment 1 was the largest one with an area of 51 ha. Sub-catchments 7, 8, 9 and 10 consist only of the category green area or the other categories were either negligible or impossible to distinguish with this resolution. Roads with high traffic are only located in sub-catchments 4, 5 and 14, 15, 16.

Stormwater flow was calculated for every sub-catchment in the case of five months of snow and seven months of rain. The study area of 230 ha generates 460 000 to 730 000 m^3 annual runoff from the surface.

The housing area generates 26-33% of the flow while low traffic roads generate 26-30%. Parking areas with a generation of 24-28% was the category which generates the third highest flow. The category green area, due to its ability to infiltrate more water, has a low flow generation. Also, high traffic roads generate a low flow as a result of the small area compared to the other categories in the study area.

4.2 Urban runoff quality

The results of the calculations based on the assumptions for different pollution generation from rainfall and snow melt induced runoff can be seen in Table 4. The highest pollutant loads were generated from the scenario with five months of snow and seven months of rain and no snow removal. The lowest pollutant loads were generated was the time that 100% of snow removal occurred in the same condition. A linear reduction of loads occurred by increasing the amount of snow removal, but the slope of the line for five months of snow and seven months of rain was steeper and that was due to higher amount of snow period and as a result higher volume of snow to remove. The case of 50% snow removal from 5 months of snow shows quite the same pollutant loads as 2 months of snow and no snow removal.

Snow removal assists to compensate the amount of pollutant loads reaching the water bodies around the urban area and also to increase convenience for people during snow periods. Whereas snow removal was a kind of pollution relocation, therefore it was required to have a special plan for snow which will be transported to out skirts and try to install equipment in those areas to treat snow melts before let it pour to water bodies.

Table 4 Annual estimated pollutant load calculated based on different assumptions (kg/year)

	Pb Min-Max	Zn Min-Max	Cu Min-Max	Cd Min-Max	Tot-N Min-Max	Tot-P Min-Max	COD Min-Max	TSS Min-Max
Constant Q	33-81	62-112	15-35	0.82-1.23	619-836	106-134	36300-62700	31256-71365
Range of Q	47-64	79-109	19-27	0.72-0.96	528-928	80-151	38900-56400	39000-56300
5 Snow+7 Rain (different concentration but no snow removal)	65-85	120-160	30-40	1.02-1.36	760-1290	110-210	64200-91800	99600-141400
5 Snow+7 Rain (50%snow removal)	55-70	95-130	20-30	0.8-1.1	650-1150	100-190	48900-70900	72400-104400
5 Snow+7 Rain (100% snow removal)	40-55	65-90	15-20	0.6-0.8	550-1010	85-170	33500-50000	45200-67500
2 Snow+10 Rain (no snow removal)	55-75	95-130	25-30	0.84-1.11	620-1070	90-170	48100-69300	60000-85800
2 Snow+10 Rain (50% snow removal)	50-70	85-120	20-30	0.77-1.02	580-1020	90-170	43000-62400	50900-73500
2 Snow+10 Rain (100% snow removal)	45-60	80-100	20-25	0.71-0.93	550-980	85-160	37900-55400	41800-61200

5 CONCLUSIONS

There are various ways of calculating the pollutant loads based on differences in pollutant concentrations during snowmelt and rainfall runoff, length of snow period and diverse snow handling strategies.

The conclusion of this study for the worst case scenario of five months of snow and seven months of rain and no snow removal, approximately 65-85 kg of Pb, 120-164 kg of Zn, 30-40 kg of Cu, 1-1.4 kg of Cd, 760-1300 kg of Tot-N, 110-210 kg of Tot-P, 64200-91800 kg of COD and finally 99600-141400 kg of TSS was transported to four water bodies around the Luleå city centre.

This study was a first step to roughly estimate the pollutant loads transported by runoff to near water bodies from Luleå city centre.

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