# THE CHARACTERIZATION OF HIGHWAY RUNOFF WATER QUALITY

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von

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Graz, April 2005

## ERKLÄRUNG

Ich erkläre an Eides Statt, dass ich die vorliegende Arbeit selbstständig und ohne fremde Hilfe verfasst, andere als die angegebenen Quellen nicht benutzt und die den benutzten Quellen wörtlich und inhaltlich entnommenen Stellen als solche kenntlich gemacht habe.

Graz, April 2005 ..............................................

(Martina Winkler)

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## ABSTRACT

This diploma thesis gives an overview of the sources of highway runoff water, its nature, and its possible impacts.
One part of my thesis has been developed at the Laboratório Nacional de Engenharia Civil (Portugal).
As awareness for a responsible use of global water resources has increased in the last decades, it is essential to take an integral approach to pollution resulting from diffuse sources. In this context, a precise definition of highway runoff water characteristics in the scope of environmental impacts and for evaluating possible treatment measures is of particular importance.
Potential measures aimed at minimizing the environmental impact of run-off water are evaluated. Therefore different approaches emerged. One possible way is the use of mathematical models to predict pollutant loads. As demanded from the Laboratório Nacional de Engenharia Civil, an investigation on the applicability of different models developed to calculate water quality and quantity for this purpose has been carried out. Therefore, an introduction to water quality modeling and an overview of existing models is given. Two of these models, the Simple Method and regression equations developed by the U.S. Geological Survey, were tested with data from Portuguese roads. Regrettably, on the base of the available data, no general statement to the applicability of these equations can be given.



## KURZFASSUNG

Diese Diplomarbeit hat sich zum Ziel gesetzt, die Beschaffenheit von Straßenabflüssen, ihre Herkunft, ihre Belastung und ihre möglichen Umweltauswirkungen darzustellen.
Ein Teil der Arbeit ist am Laboratório Nacional de Engenharia Civil (Portugal) entstanden.

Da in den letzten Jahrzehnten der verantwortungsvolle Umgang mit globalen Wasserressourcen immer mehr in den Blickpunkt öffentlichen Interesses gerückt ist, ist es heutzutage unumgänglich eine ganzheitliche Betrachtung der aus diffusen Quellen stammenden Umweltverschmutzung in jene Thematik mit einzubeziehen. In diesem Zusammenhang sind eine genaue Bestimmung der Charakteristika und Umweltauswirkungen von Straßenabflüssen sowie mögliche Maßnahmen zur Minimierung der aus ihnen resultierenden Belastungen von besonderer Bedeutung. Hierzu wurden in der Vergangenheit unterschiedliche Ansätze entwickelt.

Eine mögliche Vorgehensweise ist die Verwendung mathematischer Modelle zur Abschätzung von Schadstofffrachten in Straßenabflüssen. Auf Wunsch des Laboratório Nacional de Engenharia Civil wurde eine Untersuchung über verschiedenartige, zu diesem Zweck verwendbare, Abflussmodelle durchgeführt.
Zwei Modelle, die Simple Method und Regressionsgleichungen der U.S. Geological Survey, wurden auf Basis portugiesischer Daten auf ihre Anwendbarkeit überprüft. Bedauerlicherweise reichte der vorhandene Datensatz nicht aus um eine konkrete Aussage bezüglich ihrer Verwendbarkeit zu treffen.

# Contents

# 1. Introduction

As in the last decades the awareness for a responsible use of global water resources increased, the protection of water bodies has become subject to new laws and guidelines. To meet them, the characterization of highway runoff and urban storm-water quality is of growing interest.

Highway runoff water is generated through the defined drainage of precipitation reaching the road surface. Drainage of runoff water from roads and roadbeds is necessary to protect the road, reduce the risk of aquaplaning, and protect the roadbeds from infiltrating and ascending water.
In the past, the runoff was passed to local infiltration or discharged untreated into rivers. This led to a number of environmental damages. Their rehabilitation partly turned out to be complicated and expensive. Nowadays, it is standard practice to infiltrate runoff water locally or centrally having, if necessary, pre-purification.

To deal with runoff water, its impact on the environment and the evaluation of appropriate treatment measures is a difficult task on which different approaches emerged.
Whereas in Europe a pragmatic approach (e.g., the definition of limit values or the requirement of official approvals) is taken, in the U.S.A decisions are often based on predictions.

The prediction of highway runoff water quality is complicated, as processes leading to runoff generation are mostly of stochastic nature and pollution sources generally are diffuse.
To evaluate the impact of pollutants on the aquatic environment and on water resources is even more complex, as the determination of long-term effects on the biota demands a selective analysis of the discharged persistent substances.

In respect of these facts, it is obvious to see which challenging task it is to define highway runoff water quality and to find accurate measures for treating runoff water in an ecological and economic compatible way.

# 2. Objectives

This diploma thesis gives an overview of the nature of highway runoff water, its sources, and its possible impacts.
It provides a definition of highway runoff water quality, which is indispensable in the scope of environmental impact studies and for evaluating possible treatment measures
One part of the work is to find and test models that have been used so far in the field of water quality modeling.
In this context, two simple runoff water quality prediction models, the Simple Method and the US Geological Survey regression equations, were tested on Portuguese road runoff.

# 3. Basic principles

## 3.1. Highway Runoff Water Quality

### 3.1.1. Sources and origins of pollutants

In practice it is not possible to identify details of the sources for road runoff that are both stationary and mobile (Hvitved-Jacobsen T., Vollertsen J., 2003).
An overview of the most important substances which can be found in highway runoff and their sources is given in Table 1.

**Table 1:** Sources of pollutant constituents

| Substance | Primary Sources |
|---|---|
| Particulates | Pavement wear, vehicles, atmosphere, maintenance, snow and ice, sediment disturbance |
| Nitrogen, phosphor | Atmosphere, fertilizers, sediments |
| Lead | Bearing wear, leaded fuel, tire wear, lubricating oil and –grease, atmospheric fallout |
| Zinc | Tire wear, motor oil, grease |
| Iron | Rust, steely highway structures, engine parts |
| Copper | Metal plating, bearing wear, engine parts, break pad wear, fungicides, insecticides |
| Cadmium | Tire wear, insecticides |
| Chromium | Metal plating, engine parts, break lining wear |
| Nickel | Diesel fuel, lubricating oil, metal plating, break lining wear, asphalt |
| Manganese | Engine parts, exhaust |
| Bromide | Deicing salts |
| Cyanide | Deicing salts, grease |
| Sodium, calcium | Deicing salts |
| Chloride, sulfate | Deicing salts, fuel |
| Petroleum | Spills, leaks, lubricants, antifreeze, hydraulic fluids, asphalt surface wear |
| PCB, pesticides | Spaying of highway roadsides, atmospheric deposition, |
| | PCB catalyst in synthetic tires |
| Pathogenic bacteria | Soil litter, bird dung, losses resulting from animal transports |
| Rubber | Tire wear |
| Asbest | Clutch and brake lining wear |
| PAH | Pavement wear, fuel |

Pollutant sources are distinguished into atmospheric and traffic related. Most of them are classified as diffuse sources.
A classification of pollutant sources, their origin, and the range of pollution rates is outlined in the chapters 3.1.1.1 and 3.1.1.2.

#### 3.1.1.1. Atmospheric pollution

Atmospheric pollution derives from the accumulation of exhaust gases, aerosols, germs and particles in the atmosphere. Its origins are natural and anthropogenic. Often the source of pollution is unknown, as pollutants can be transported over very long distances by the wind.
Pollutants are deposited through dry precipitation (dust fall) or through wet precipitation (rain out and wash out).
Talking from rain out, it means that aerosol particles start to operate as condensation nucleuses for pollutants, whereas wash out signifies the wash out of atmospheric particulate matter.

The process of accumulation and wash out is illustrated in Figure 1.

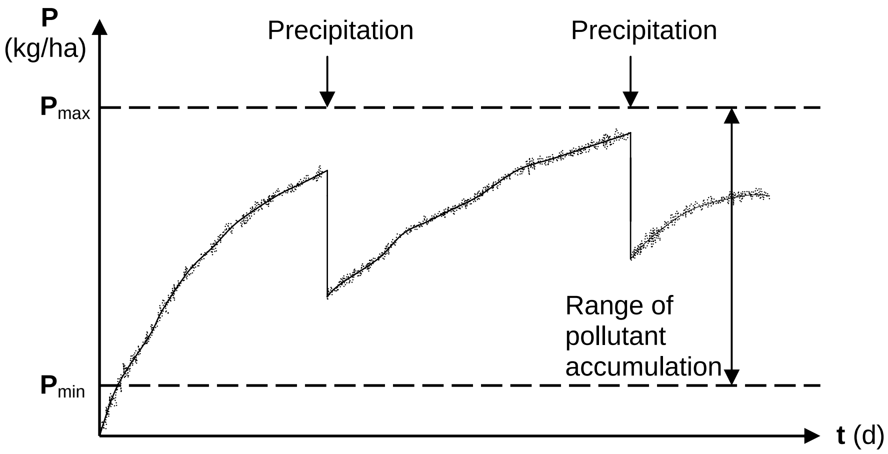


**Figure 1:** Accumulation and wash out of pollutants in the atmosphere (Sieker F., Grottker M., 1988; quoted by Fritzer H., 1992)

Basically, components of pollution are nitrogen, phosphorous, metals, and a variety of substances deriving from combustion emissions. On the average, dust deposit is composed of 25% organic substances, 40% water-soluble, and 35% inorganic substances. Major substances of content are: P, $NH_4$-N, $NO_3$-N, $SO_4$, Zn, Pb, and Cu (Fritzer H., 1992).

To give an idea of the range of pollutants in the atmosphere, some typical pollution rates are given Table 2 and Table 3.

**Table 2:** Typical atmospheric deposition rates in Denmark (Hvitved-Jacobsen T., Vollertsen J., 2003)

| Metal | Rural area | Suburban area | City | Dense populated area |
|---|---|---|---|---|
| | [mg/(m$^2$*a)] | [mg/(m$^2$*a)] | [mg/(m$^2$*a)] | [mg/(m$^2$*a)] |
| Zinc | 15 | 41 | 88 | 118 |
| Copper | 1.4 | 3.3 | 6.2 | 12.7 |
| Lead | 8 | 22 | 48 | 80 |

**Table 3:** Pollution rates on the total pollution load in German highway runoff resulting from precipitation and dust (Krauth Kh., 1982; quoted by Lange G., 1999)

| Parameter | A 81 Pleidelsheim | A 6 Obereisenheim |
|---|---|---|
| | [%] | [%] |
| Mineral oil | 11 | 15 |
| Carburetor fuel | 12 | 16 |
| Filterable substances | 17 | 28 |
| Fe | 14 | 17 |
| Pb | 22 | 27 |
| Cd | 27 | 29 |
| Cl | 1.7 | 0.3 |
| Cr | 40 | 22 |
| Cu | 29 | 24 |
| Zn | 31 | 31 |
| COD | 29 | 35 |
| P | 42 | 59 |
| $NH_4$-N | 73 | 83 |

The values stated in Table 2 and Table 3 were measured before the introduction of unleaded fuel.

### 3.1.1.2. Pollution caused by traffic

Traffic pollutes the road and its periphery. Responsible therefore is the regular operation and wear. Thereby the surface is charged with filth that later is partly removed through, e.g., rain, wind, and agitation through vehicles. The substances are subsequently deposited on the roadway.
Pollutants are found in different formations. They can be soluble, hydraulically or mechanically transportable or fixed to the surface.

Textures of some substances originating from traffic that contribute to the contamination of highways are given in Table 4.

**Table 4:** Textures of materials contributing to the contamination of highways (Brunner P. G., 1977; quoted by Fritzer H., 1992)

| Substance | Org.matter | $BOD_5$ | COD | Grease/oil | Pb | Zn | Cr | Cu | Ni |
|---|---|---|---|---|---|---|---|---|---|
| | [mg/g] | [mg/g] | [mg/g] | [mg/g] | [μg/g] | [mg/g] | [μg/g] | [μg/g] | [μg/g] |
| Gasoline | 999.5 | 154 | 682.1 | 38047 | 663 | 10 | 15 | 4 | 10 |
| Diesel | 999.6 | 80.2 | 399 | 385.3 | 12 | 12 | 15 | 8 | 8 |
| Motor oil | 999.6 | 143.8 | 220.8 | 989.2 | 9 | 1060 | 0 | 3 | 17 |
| Gear oil | 999.8 | 102.6 | 193.3 | 985.6 | 8 | 244 | 0 | 0 | 21 |
| Anti-freezer | 987.8 | 37.6 | 1102 | 143.8 | 6 | 14 | 0 | 76 | 16 |
| Brake fluid | 999.8 | 38224 | 2421 | 883 | 7 | 15 | 19 | 5 | 31 |
| Underbody coating | 998.7 | 89.8 | 309.5 | 958.1 | 116 | 108 | 0 | 0 | 476 |
| Lubricating grease | 973.9 | 143.3 | - | 753.1 | 0 | 164 | 0 | 0 | 0 |
| Gum | 986.3 | 38225 | 2097 | 191.6 | 1110 | 617 | 182 | 247 | 174 |
| Brake pads | 285.3 | 38246 | 416.5 | 38137 | 1050 | 124 | 2200 | 30600 | 7454 |

The most relevant traffic related pollution sources are (Fritzer H., 1992):

- The abrasion of road surfaces

  The surface abrades between 0.3 and 1 millimeter per year. Material is abraded in form of mineral dust resulting from concrete or bitumen.
  Bitumen abrasion can lead to the liberation of poly aromatic hydrocarbons. Abrasion also liberates a higher quantity of 3.4- Benzpyren than the entirety of abrasion from tires, loss of oil, and soot.

- The abrasion of tires

  Based on an average daily traffic of 1000 cars per day and kilometer, 0.12 kg of tires per km and day are abraded. Ninety percent of the abraded material is not readily biodegradable, this includes rubber and soot as well as sulfur and heavy metal oxides (Pb, Cr, Cu, Ni and Zn).
  The abrasion material contains a high fraction of carcinogenic substances.

- Drip loss

  Drip loss originates from fuel, motor or gear oil, lubricating grease, brake fluid and antifreeze. It contains a high level of $BOD_5$ and COD as well as heavy metals. Mostly, it is found punctually on car parks and toll places.

- Combustion emissions

  They consist of aerosol gases or soot particles and content hydrocarbons, nitrogen oxides, soot and tar.

- The abrasion of brake pads and clutch plates

  They content a high level of heavy metals, especially copper, nickel, chrome and lead.

## 3.1.2. The characteristics of highway runoff water

One of the main characteristics of highway runoff water is the high variability of concentrations and loads.
The formation process, precisely the accumulation of pollutants on the road surface and their loosening and removal from the surface has a big influence on variation.
Most influences, for example the recurrence of storm events, do have stochastic characteristics that can be expressed mathematically in terms of, e.g., a probability, a frequency or a return period (Hvitved-Jacobsen T., Vollertsen J., 2003).
Regarding the environmental impact of pollutants, it is important to specify their characteristics and behavior in regard of the environment.

### 3.1.2.1. The accumulation process

The knowledge of the surface pollutant load is essential for determining the pollutant load in runoff water, which is important for characterizing highway runoff water quality. In this context, the use of an applicable and accurate buildup function is fundamental.

There are two popular views on the pollutant accumulation process.
The first view is adopted in most water quality models and says that the surface pollutant load builds up from zero over the subsequent dry days.
The second view says that storm events only remove a small amount of pollutants and rebuildup occurs relatively fast, within several days. This results in a uniform surface pollutant load for most of the time.

Malmquist (1978) (quoted by Vaze, J., Chiew, F., 2000) through an experiment and Chiew, Duncan, and Smith (1997) (quoted by Vaze, J., Chiew, F., 2000) based on a modeling study, showed that storm events typically remove only a small part of the overall surface pollutant load. Furthermore, the results imply that the rainfall and runoff disintegrates and dissolves more surface pollutant than they can actually remove.

Vaze and Chiew (2000) stated that buildup over the dry days occurs relatively fast after rainfall, but slows down after several days as redistribution occurs. The surface pollutant load, through disintegration, also becomes finer over the dry days.

To express the accumulation process, there exist alternative equations.
In 1981, Novotny (quoted by Fritzer H., 1992) expected the pollution buildup rising linearly over the time. He neglected removal processes, taking place at the same time, leading to a transformation of the function. As a result of transformation the amount of surface pollution can not be determined that easily.

In 1988 Sieker and Grottker (quoted by Fritzer H., 1992) assumed an exponential curve, limited by a maximum value (P max) and a minimum value (P min), to describe the buildup process.

Figure 2 illustrates one possible accumulation curve, as seen by Sieker and Grottker (1988) (quoted by Fritzer H., 1992).

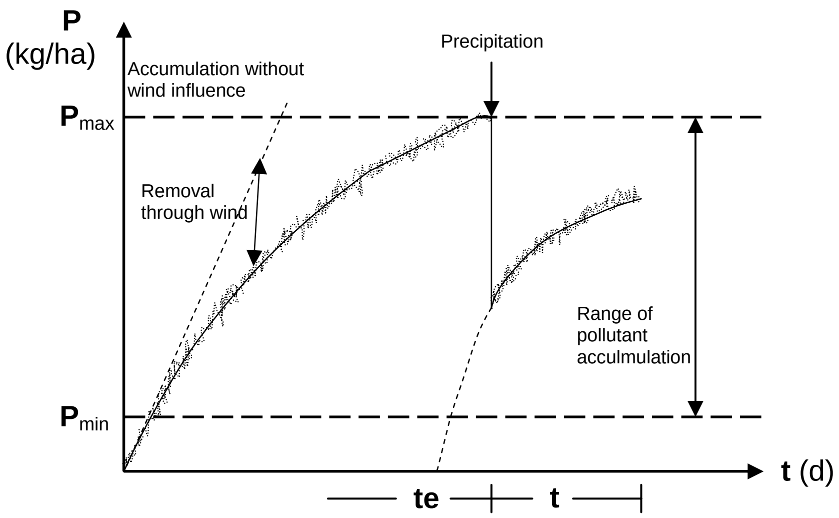


**Figure 2:** Accumulation of pollutants on the road
(Sieker F., Grottker M., 1988; according to Fritzer H., 1992)

Other studies, for example those performed by Sartor and Boyd (1972) (quoted by Ball J. E. et al., 1997) and Shaheen (1975) (quoted by Ball J. E. et al., 1997), found out that the available pollutant load on a road surface tends to reach an equilibrium between deposition and removal over a certain period of time. This equilibrium condition would be consistent with a build-up function that asymptotes to the equilibrium load. As a consequence, they suggest that the generic hyperbolic function should be used to estimate the available pollutant load on road surfaces.
For Ball et al. (1997) a temporal variation in the build-up of the pollutant constituents on the catchment surface is expressed through a power function, being the best generic form of build-up relationship.

The accumulation process is influenced by factors like the annual average daily traffic (AADT), the antecedent dry period, climatic conditions, road pavement and roughness, inclination, flow path and duration, the influence of street cleaning, etc.

### 3.1.2.2. Loosening and removal of pollutants

The process of loosening and removal of parts of the available surface pollutant load from the road surface is managed through the disintegration or solution of pollutants. It is dependent on the intensity and duration of the storm event.
During light rain events, mainly the free load becomes disintegrated, whereas intense events can also disintegrate the fixed load. Depending on the transport capacity of the runoff, part of the filth is removed from the surface as wash off. The remainder becomes a part of the fixed load as it attaches itself to the surface after drying (Vaze J., Chiew F., 2002).

Not every rainfall or wind event can be considered as cleansing event.

For Ball et al. (1997) only rainfall events with an average intensity greater than 7 mm/h and wind events with an average velocity greater than 21 km/h were found to be cleansing events. According to Hahn et al. (2000) an intensity of 0.5–1 mm per event is necessary to transport pollutants.

#### 3.1.2.3. Pollution transport

Under normal circumstances pollutants are not transported too far. They remain in the vicinity of roads.
Sartor and Boyd (1972) (quoted by Ball J. E. et al., 1997) found out that 95% of the constituent load is deposited within 1 m of the road immediately adjacent to the gutter. The city of Marburg investigated the pollution propagation near roads in 1992. It came to similar results, illustrated in Figure 3.

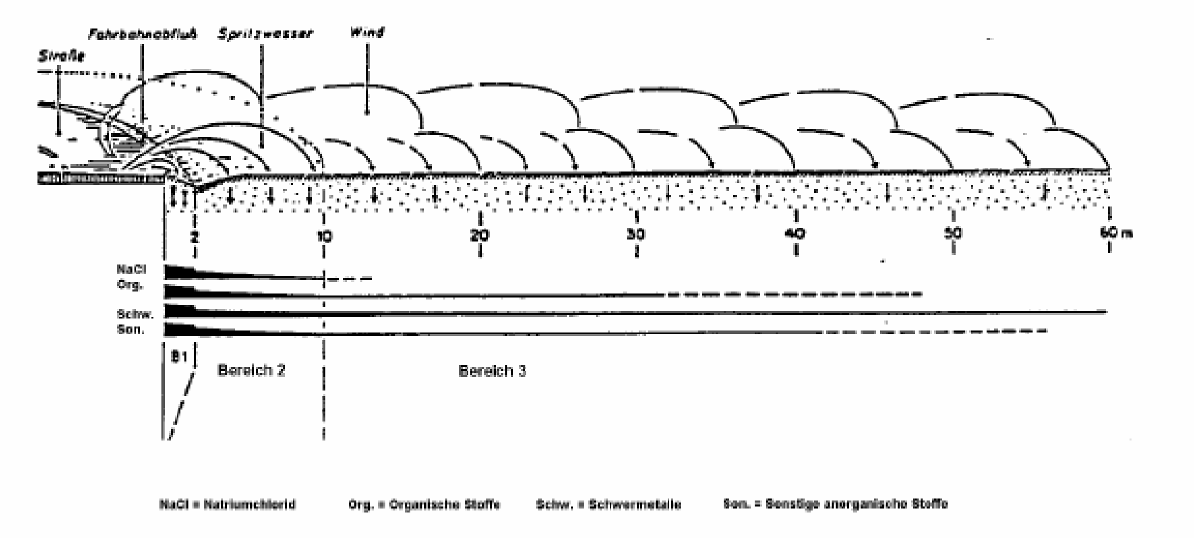


**Figure 3:** Soil pollution caused by highway runoff
(City of Marburg, 1992; according to Hahn et al., 2000)

From great importance for the processes of transport, dispensation, and deposition of pollutants is the fraction of fine particles, referred to as filterable substances. Pollutants tend to bind to them very easily.

An example for the importance of pollution transport for the characterization of runoff water is given by Krein and Schorer (2000) in an investigation on PAH's. They demonstrated how the selective transport, temporary storage of particles and a succession of mobilization and immobilization during each event lead to redistribution until PAH's enter a river.

Regarding water bodies, the processes of transport, distribution, and deposition of pollutants in already charged water bodies are related to the available surface concentration of particulates.
According to Hahn (1990) (quoted by Hahn M., 2000), investigations in this field should analyze the fraction of particulate matter in terms of the specific surface of particles and their affinity to pollutants. Therefore, the reference value must be

expressed in [m²/l], for the specific surface, which is specific for every grain fraction, in proportion to the water quantity and not to the solid load, expressed in [mg solids/l].

### 3.1.2.4. The range of pollution levels

As already mentioned, the variability of pollutant rates in highway runoff is very high. Therefore, it is difficult to declare determinate values.

Variability exists within each single event, between different events at a specific location and between sites. As an example, the standard deviation for pollutant concentrations that originate from a series of runoff events is typically of the same order of magnitude as the median value (Hvitved-Jacobsen T., Vollertsen J., 2003).

In addition to the variation caused by the character of pollution sources, the area from which the runoff derives is from high relevance.
The difference in pollutant concentrations is obvious when comparing non-urban to urban highways. Loads are higher in urban districts, where organic pollutants (wastage, animal excrements, roadside plants, etc.) tend to accumulate to a greater extend.
Studies conducted by Driscoll et al. (1990) express the difference. The observed values are stated in Table 5 and Table 6.

**Table 5:** Range of site median concentrations in rural highway runoff (Driscoll E. D. et al.; 1990 quoted by the FHWA, 1996)

| Rural Highways: Average daily traffic usually more than 30000 vehicles per day<br>Site Median Concentration ($C_{med}$) in mg/L<br>Percent of sites having a median EMC less than indicated concentration | | | | | |
|---|---|---|---|---|---|
| Pollutant | 10% of Sites | 20% of Sites | 50% of Sites | 80% of Sites | 90% of Sites |
| TSS | 12 | 19 | 41 | 90 | 135 |
| VSS | 6 | 7 | 12 | 19 | 25 |
| TOC | 4 | 5 | 8 | 13 | 17 |
| COD | 28 | 34 | 49 | 70 | 85 |
| NOC+3 | 0.23 | 0.29 | 0.46 | 0.72 | 0.91 |
| TKN | 0.34 | 0.47 | 0.87 | 1.59 | 2.19 |
| PO4-P | 0.06 | 0.08 | 0.16 | 0.33 | 0.48 |
| Zinc | 0.035 | 0.046 | 0.08 | 0.139 | 0.185 |
| Copper | 0.01 | 0.013 | 0.022 | 0.038 | 0.05 |
| Lead | 0.024 | 0.036 | 0.08 | 0.179 | 0.272 |

**Table 6:** Range of site median concentrations in urban highway runoff (Driscoll E. D. et al., 1990; quoted by the FHWA, 1996)

| Urban Highways: Average daily traffic usually more than 30000 vehicles per day<br>Site Median Concentration ($C_{med}$) in mg/L<br>Percent of sites having a median EMC less than indicated concentration | | | | | |
|---|---|---|---|---|---|
| Pollutant | 10% of Sites | 20% of Sites | 50% of Sites | 80% of Sites | 90% of Sites |
| TSS | 68 | 88 | 142 | 230 | 295 |
| VSS | 20 | 25 | 39 | 61 | 78 |
| TOC | 8 | 12 | 25 | 51 | 74 |
| COD | 57 | 72 | 114 | 179 | 227 |
| NOC+3 | 0.39 | 0.49 | 0.76 | 1.18 | 1.48 |
| TKN | 1.06 | 1.27 | 1.83 | 2.62 | 3.17 |
| PO4-P | 0.15 | 0.21 | 0.4 | 0.76 | 1.06 |
| Zinc | 0.025 | 0.032 | 0.054 | 0.091 | 0.119 |
| Copper | 0.102 | 0.163 | 0.4 | 0.98 | 1.562 |
| Lead | 0.192 | 0.31 | 0.329 | 0.469 | 0.564 |

To complete this chapter, average concentrations based on various bibliographic references are resumed in Table 7.

**Table 7:** Average concentrations in road runoff (AADT > 10000 vehicles/day) (BUWAL, 1996;Pfeifer, 1998; Heinzmann, 1993; Krauth et al. 1982; U.S. EPA, 1983; Dierkes, 1996; quoted by ÖWAV, 2002)

| TSS | COD | Total N | Total P | Cd | Cu | Pb | Zn | PAH |
|---|---|---|---|---|---|---|---|---|
| mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l |
| 200 | 100 | 2 | 0.5 | 0.0015 | 0.1 | 0.03 | 0.5 | 0.003 |

### 3.1.2.5. Characteristic of pollutants resulting from highway runoff in water bodies

Examining the effects highway runoff causes in water bodies, pollutants have to be treated from different viewpoints.

When focusing on acute pollution effects it is necessary to focus on extreme events statistics of a historical rainfall or runoff series.
Whereas for accumulative effects the total amount of a pollutant that is discharged during a number of events corresponding to the period considered is from relevance. Therefore the focus has to be set on the mean (median) pollutant concentration for a site (Hvitved-Jacobsen T., Vollertsen J., 2003).

Focusing on single events the “first flush” effect is from overwhelming importance. It means that in the beginning of a storm event higher pollutant concentrations are observed.
Generally, the highest pollution levels are found in the “first flush” of moderate storm events following extended dry periods. This runoff water consists of mostly unsolved substances, cumulative organic substances, and mineral oils (Fritzer H., 1992).
Barrett et al. (1995) stated that, in their investigation, a first flush effect was very evident during selected events but was small or negligible when all monitored storm events were considered.

Another argument that needs to be considered is that, so far, water pollution is widely treated emission oriented. According to the European Water Framework Directive, water quality also has to be observed immission-orientated. Regarding pollution from this viewpoint, pollutant load has to be split in different fractions.

Sartor and Boyd (1972) (quoted by Ball J. E. et al., 1997), and Shaheen (1975) (quoted by Ball J. E. et al., 1997) stated that the soluble fraction of constituent load in highway runoff is minimal in comparison to the particulate fraction.
The majority of constituents in road runoff are associated with particulate matter (Hewitt C. N., Rashed M. B., 1992; quoted by Perdikaki K., Manson C. F., 1999); it tends to accumulate in the sediments of receiving streams (Maltby L. et al., 1995; quoted by Perdikaki K., Manson C. F., 1999).

The particulate matter has to be split in fractions according to their potential risk.
According to Krein and Schorer (2000) the distribution of pollutants of different material and different particle size fractions is from overriding importance because of:

- different particle sizes are remobilized and transported under different hydraulic conditions
- the organic matter can be decomposed, whereby the associated pollutants become bioavailable
- selective feeding benthic organisms preferentially consume particles with higher organic concentration and smaller size

Generally, the particle size distribution of sediments from motorways (Ellis J. B., Revitt D. M., 1982; quoted by Ball et al., 1997) is log normal with the distribution dominated by the particle sizes of 500-2000 pm.
This dominance has also been noted in other studies by, for example, Sartor and Boyd (1972) (quoted by Ball J. E. et al., 1997) and Shaheen (1975) (quoted by Ball J. E. et al., 1997).
Ball et al. in 1997 stated that, similar to North American data, in Australia most of the constituent load is found sorbed to sediment particles of less than 70 pm in size.
According to Bradford (1977) (quoted by Ball J. E. et al., 1997) the fine-grained fraction of street dust accounts for approximately 6% of the total mass of solids and more than 60% of the trace metals.

Xanthopoulos (1990) (quoted by Hahn M. et al., 2002) split the particles in precipitation runoff in four fractions according to their hazardousness, as shown in Table 8.

**Table 8:** Classification of particles in precipitation runoff in four fractions dependent on their transportation characteristics and pollutant charge (Xanthopoulos C., 1990; quoted by Hahn M. et al., 2002)

| Fraction | Transportation characteristics, pollutant charge |
|---|---|
| > 600 µm | Bed load, uncharged |
| 60-600 µm | Moderately charged, deposable substances |
| 6-60 µm | Heavy charged, deposable substances |
| < 6 µm | Heavy charged, non-deposable substances |

The pollutants concentrated in sediments are bound, but some of the constituents of sediments can solubilize under certain physicochemical conditions. They may or may not be finally incorporated into the organism (Amyot M. et al., 1996; quoted by Perdikaki K., Manson C. F., 1999), adding to the toxicity of the overlying water (Dallinger R., Kautzky H., 1985; Shea, 1988; quoted by Perdikaki K., Manson C. F., 1999).

Perdikaki and Manson (1999) stated that there exists only a weak and mostly nonsignificant relationship between sediment and species metal concentrations. They suggest that metals in ingested sediments, do not contribute significant amounts of metals to the whole body burden of the species. The non-significant correlations between metals in the sediments and the biotic indices indicate that community structure is not influenced by sediment metal concentrations at their sites.

Hvitved-Jacobsen and Vollertsen (2003) provide a traditional grouping of pollutants relevant for road runoff and often applied when dealing with the corresponding effects:

- Biodegradable organic matter
- Nutrients
- Heavy Metals (Cu, Pb, Zn, Cd, Ni, Cr)
- Organic micropollutants (Pesticides, aromatic hydrocarbons, phenols, halogenated aliphatic and aromatic organics, PCB's, PAH's, softeners, anionic detergents, ethers, dioxins and furans)
- Solids (suspended solids)
- Pathogenic microorganisms

The highest risk to the aquatic environment is caused by persistent substances through the accumulation in sediments and creatures. They can be divided into heavy metals and organic micropollutants and are going to be described below.

*Heavy metals*

Heavy metals are found in different formations in water bodies: as free ions, as dissolved (mobilized) inorganic or organic complexes, as insoluble (immobilized) complexes or as absorbed suspended particles (Fent, K., 1998; quoted by Holz A., 2004).

Therefore, total pollutant load or concentration has to be split in the ecotoxic relevant mobile (dissolved) fraction, the fraction with an ability to be mobilized, and the non-reactive immobile heavy metal fraction.
The toxicity of particle bound heavy metals depends on the particle size distribution; the distribution of particle associated heavy metals in runoff water shows an inverse relationship between concentration and medium particle size (Krein A., Schorer M., 2000). It is also influenced by factors like the pH-value and the fraction of already absorbed pollutants.
Daub and Stiebel (quoted by Hahn M. et al, 2000) investigated highway runoff in 1990. Pollutant distributions for two simultaneous taken samples are illustrated in Figure 4, Figure 5, Figure 6 and Figure 7.

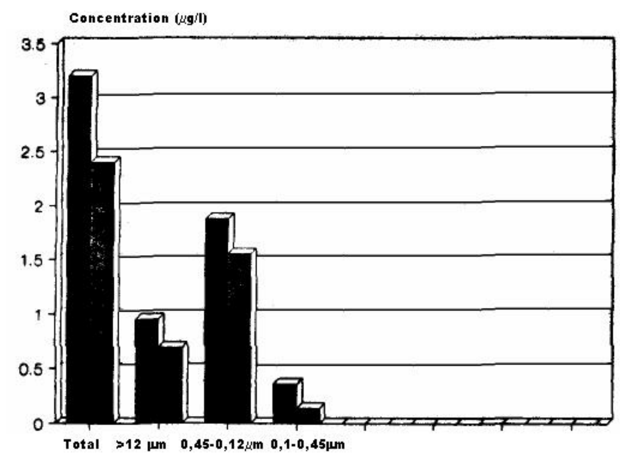


**Figure 4:** Distribution of different fractions of lead in precipitation runoff (Daub J., Striebel T., 1990; according to Hahn M. et al, 2000)

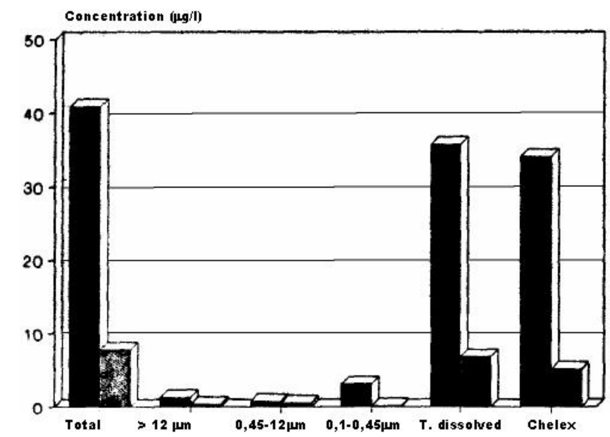


**Figure 5:** Distribution of different fractions of nickel in precipitation runoff (Daub J., Striebel T., 1990; according to Hahn M. et al, 2000)

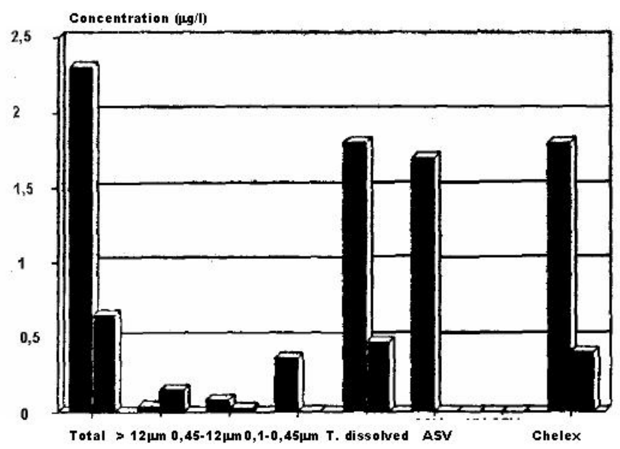


**Figure 6:** Distribution of different fractions of cadmium in precipitation runoff (Daub J., Striebel T., 1990; according to Hahn M. et al, 2000)

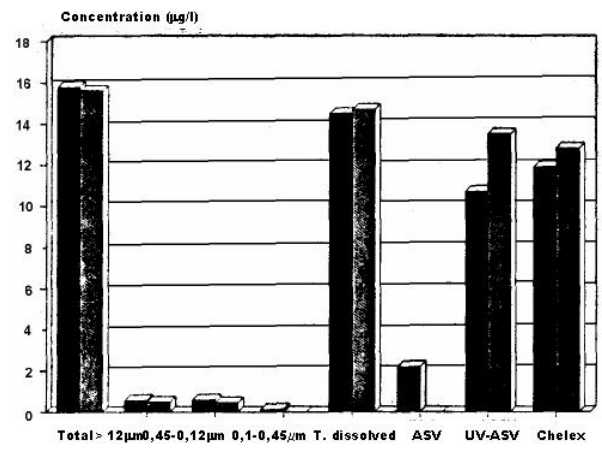


**Figure 7:** Distribution of different fractions of copper in precipitation runoff (Daub J., Striebel T., 1990; according to Hahn M. et al, 2000)

The dissolved fraction of lead remained below the detection limit (1 µg/l). It is obvious that lead is fixed to suspended loads. Mainly, the grain fraction between 0.45 and 12 µm has been charged with pollutants.
For nickel the dissolved fraction was the most relevant one.

A high fraction of the dissolved cadmium fraction was convertible, but not necessarily ASV-unstable. ASV means Anodic Stripping Voltametry and is an electrochemist method that measures poorly bound and free metals in a dilution.
The total concentration of copper is low and nearby completely dissolved and convertible. The high fraction of UV-ASV-unstable particles is an indication for a strong organic complexation.

*Organic micropollutants*

Also, organic oligo-elements have to be split in a dissolved and a non-dissolved fraction. Within this group special attention has to be given to polycyclic aromatic hydrocarbons.

Polycyclic aromatic hydrocarbons in general are hydrophobic. The three most relevant according to Daub and Striebel (1990) (quoted by Hahn M. et al., 2000) are:

- Phenanthrene: water solubility: 1.29 mg/l
- Fluoranthen: water solubility: 0.26 mg/l
- Benz(a)pyren: water solubility: 0.0038 mg/l

Krein and Schorer (2000) distinguished five groups of PAH's which correspond to the molecular size and to the affinity of different grain-size in road runoff. They found out that acenaphtylene and acenaphtene behave rather independent due to their high fugacity. Small three-ring molecules such as fuorene, phenanthrene and anthracene are enriched in the fine sand fraction. A distinct bimodal distribution was found for four- and five-ring molecules. Six-ring molecules have their concentration maximum in the fine and finer middle silt fraction.

Some hydrograph concentration curves of polycyclic aromatic hydrocarbons in highway runoff during a certain rainfall according to Daub and Striebel (1990) (quoted by Hahn M. et al., 2000) are illustrated in Figure 8.
Daub and Striebel (1990) (quoted by Hahn M. et al., 2000) differ between the dissolved fraction and the fraction absorbed by suspended solids. The decrease in concentration of PAH's absorbed by suspended solids over the time is similar for all three PAH's. The following augmentation in concentration is dissimilar, as fluoranthen and benz(a)pyren are to a lesser extend soluble than phenantren. According to Hahn (1990) (quoted by Hahn M. et al., 2000) phentantren, in the beginning of a storm event, is transported to a greater part in its dissolved phase than fluoranthen and benz(a)pyren.

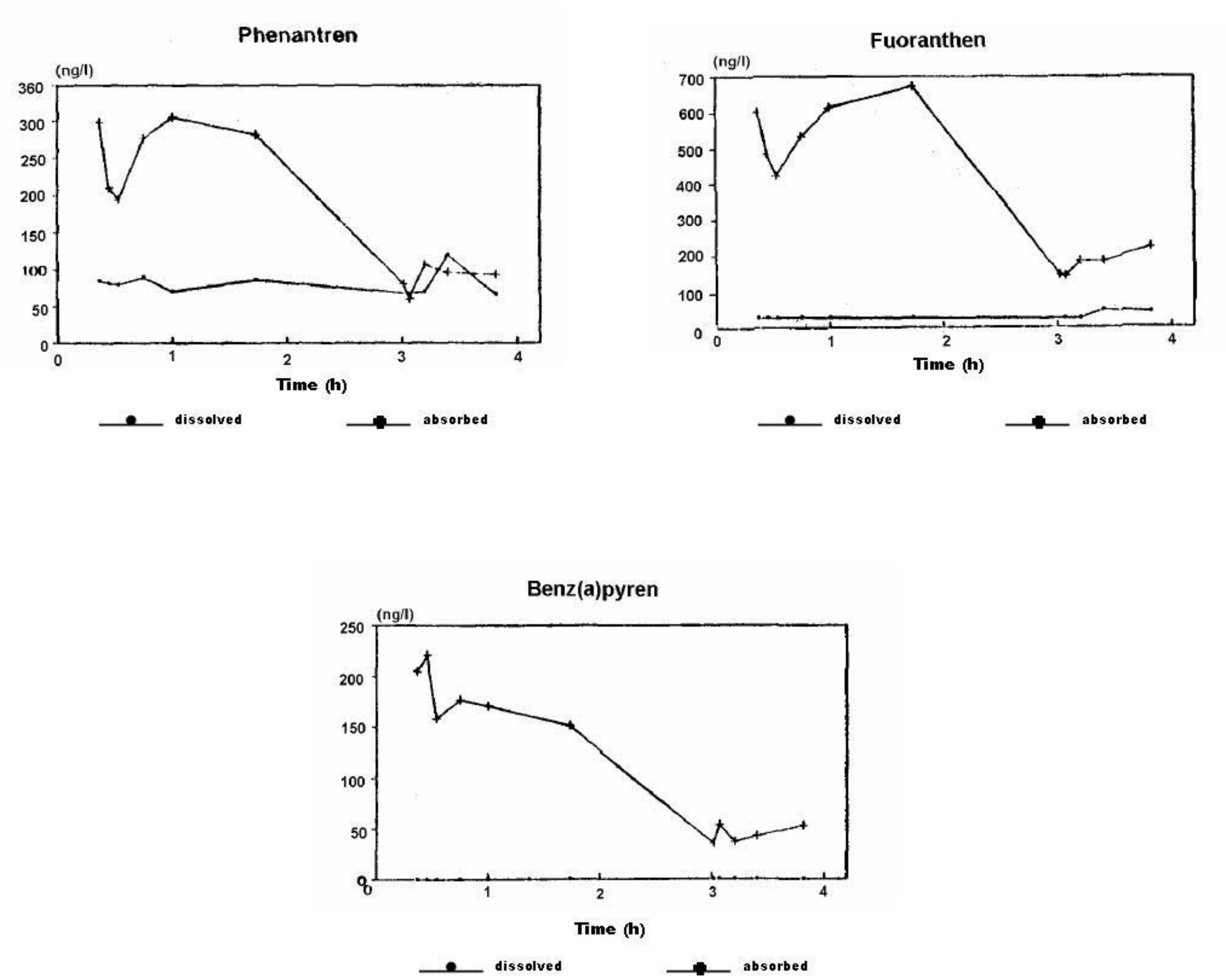


**Figure 8:** Hydrograph of organic micropollutant concentrations in road runoff (Daub J., Striebel T., 1990; according to Hahn M. et al, 2000)

The behavior of PAH's depends on the physical and chemical molecule characteristics, as they control solubility and volatility.
Generally, sealed areas such as streets and residential sites are rapidly exhausted and successively again re-enriched.

#### 3.1.2.6. Characteristics of pollutants resulting from highway runoff in natural soils

For understanding the processes taking place in soils, a definition of soils is from overwhelming importance.
Soils beneath the road surface are lifeless, as they consist of mechanically heavy burdened and compressed gravel.
Also, roadside soils are modified soils undergoing removal, landfill and sealing processes. Generally, they are made of coarse-grained, carbonate enriched or alkalescent substances (e.g., limestone, construction waste or slag) covered by a humus upper layer. These soils are compressed and therefore contain a low

percentage of oxygen. They do have a bad infiltration behavior in comparison to natural soils.
An accurate definition of natural soil types is too complex to be treated in this diploma thesis. It is provided by, e.g., Hahn et al. (2000).

Highway runoff enters a soil by infiltration. There it is incorporated, leached and transferred. It is dispersed in different ways, dependent on soil matrix characteristics.

Pollutants propagate in soils in three different ways:

- Transportation with the leachate
- Discrete movement in a second liquid phase
- Diffuse dispersion in the gas phase

In the majority of cases, pollutants enter the soil with the leachate.

A discrete movement in a second liquid phase requires a big quantity of a liquid fluid (e.g., oil) entering the soil. In this way, pollutants can quickly reach the ground water.

Diffuse dispersion is relevant for substances having a high vapor pressure, e.g., some organic substances.

To which extend dispersion mechanisms influence substance movement in soils depends on the leachate flow and the characteristics of the soils and substances.

Processes that affect substances in soils are the mechanical retention, called filtration, the absorption and chemical precipitation, called buffering, and conversion or decomposition, called transformation, as well as dilution.
In unsaturated soil zones mainly filtration, sorption, complexation and microbial decomposition take place. In the ground water zone, dilution processes are of prime importance.

The impact of these processes is variable and dependent on different factors. Soil factors from relevance are the pH-value (dependent on the acidity, acidification and the buffer system), the redox potential, and the type of water (ground. - and backwater, absorption. - and capillary water)

The most important processes are specified below (Hahn M. et al., 2000):

- Filtering

  Filtering means the retention of unsolved substances in the soil. Its effectiveness depends on the soil porosity and the soil water flow. Coarse-disperse substances (d>100 nm) remain either on the soil surface or enter the pore space, which is more frequently. Particles, passing coarse pores, are transported into the soil until they are captured by narrow pores. Thereby the pore space gets more and more clogged, in opposite direction to the leachate flow.
  To keep the pore space active as long as possible, a void volume between 10 and 40 percent of pores having 1 to 100 μm is favorable.

- Colmation

  Colmation is defined as the effect of filtered substances acting as a secondary filter and is influenced by physical and chemical bonding forces.

- Sorption

  Sorption signifies the reaction of dissolved substances with the surface of particles from the unsolved phase. It is divided into absorption (movement from the dilution to the unsolved phase) and desorption (movement from the unsolved phase to the dilution) (Grotehusmann D., 1995; quoted by Hahn M. et al., 2000). Sorption is most important for immobilization processes of heavy metals and organic pollutants. The sorbents are clay minerals, sesquioxides ( = Fe-, Al-, and Mn- oxides), and organic substances.
  Different soils do have different sorption capacities, which are outlined in Table 9.

**Table 9:** Absorption capacity of different soil types
(Geiger W., Dreiseitl H., 1995; quoted by Hahn M. et al., 2000))

| Soil type | Absorption capacity |
|---|---|
| Coarse sand, gravel | very low |
| Fine sand | low |
| Sandy silts, clayey and silty sands, upland moor turf, lowland moor turf | medium |
| Clayey silts, medium and heavy clayey sands | high |
| Tones | very high |

- Chemical precipitation

  Chemical precipitation only affects heavy metals. If the supply of one heavy metal exceeds a certain limit of solubility, chemical precipitation occurs. The concentration of a certain metal in the soil dilution stays constant after reaching the limit.

- Decomposition processes

  Organic pollutants, besides of being absorbed, undergo complex biological and chemical decomposition processes (Geiger W., Dreiseitl H., 1995; quoted by Hahn M. et al., 2000).
  These processes are influenced by the availability of the pollutant for the organisms, the quantity of decomposing microorganisms, and the activity of organisms in the soil.

- Complexation

  Soluble organic substances, having a low molecular weight, are able to build stable complexes with metals. These complexes are mobile and biological available, whereas higher polymerized, compact humic substances are absorbents for metals and reduce their mobility and bioavailability (Alloway B. J., Ayres B. C., 1996; quoted by Hahn M. et al., 2000).

The behavior of selected substances in soils is explained below (Hahn M. et al., 2000):

- Polychlorinated biphenyl

  It is abiotic to 50% and decomposes very slowly. The decomposition is dependent on the sorption and the chlorination rate.

- Polycyclic aromatic hydrocarbons

  Polycyclic aromatic hydrocarbons tend to accumulate in the soil, as they are very hydrophobic. Preferably, they are bound through sorption to organic substances (Alloway B. J., Ayres B. C., 1996; quoted by Hahn M. et al., 2000). Exceptionally, they are able to enter the ground water zone when solved by solvents
  (e.g., tensides, mineral oil, or humic substances).

- Lightly volatile halogenated hydrocarbons

  Lightly volatile halogenated hydrocarbons are very mobile in soils and groundwater. They can disperse in ground water in a range of two kilometers before settling in the aquifer. For reduction of these substances, dilution is the basic mechanism (Xanthopoulus C., Hahn H. H., 1994; quoted by Hahn M. et al., 2000).

- Aromatic hydrocarbons

  Benzene, toluene, phenols, styrene, and xylene tend to enter a moderate bond to humus or tone minerals. The mobility potential of aromatic hydrocarbons is highly variable. Chlorinated phenols move slowly and are more easily binding than benzene, xylene and toluene. Nitrobenzene and toluene are moderately to highly mobile. M- and p-xylene, as well as styrene, are less mobile.

- Petrochemical products, fuel, oils and lubricants

  Hydrophobic oils enter hydrophobic bonds with soil components. A high fraction of oil components bind to humus, the remainder can reach the ground water zone and thereon build an oil film.
  The settling of oils depends on their specific weight, their viscosity, and their permeability.
  Complete decomposition requires a period of 40 to 50 years, depending on local characteristics.

- Heavy metals

  For evaluating the effect of heavy metals, the background pollution level of the metal is from high influence.
  Heavy metals are able to enter very different compounds in soils. Some possible compounds are listed in Table 10.

**Table 10:** Occurrence of heavy metals in soils
(Rufus et al., 1994; quoted by Hahn M. et al., 2000))

| Compact | Frontier, conventional 0.45 µm | Dissolved |
|---|---|---|
| • Metals bound to the silicate lattice of primary minerals<br>• Hardly soluble metal salts and oxides (e.g., sulfides, carbonates, phosphates, silicates, cyanides, and oxides)<br>• Metals absorbed to surfaces (non-specific and specific absorbed) | | • Anorganic complexes (aquocomplexes, oxo complexes, chlorine complexes)<br>• Organic complexes (simple complexes, chelates) |

Potential behaviors of selected heavy metals (Hahn M. et al., 2000):

- Cadmium

  Cadmium is very mobile, especially in soils of low pH-values. It can be bound minerally or organically. If soils contain a high fraction of chloride, cadmium-chloro-complexes are built. That reduces the ability of soils for binding cadmium. Under certain conditions, cadmium can drop out as sulfide or carbonate (Grotehusmann D., 1995; quoted by Hahn M. et al., 2000).

- Lead

  Lead is very immobile and little soluble for pH-values higher than 5. Also, an elevated fraction of organic substances leads to a lower solubility. Lead is highly bound through specific absorption, especially to sesquioxides. Under strongly reduced conditions, its mobility rises.
  80 % of the entering lead stays in the upper 20 centimeters of the soil. Even after a period of 10 Years, 99% of the lead is found in the upper 50 centimeters.

- Nickel

  Nickel is rather mobile. Mostly, it is bound to sesquioxides and tone minerals or integrated in mineral components. A low pH-value, as well as the formation of soluble organic complexes, is able to mobilize nickel (Scheffer F., Schachtschabel P., 1998; quoted by Hahn M. et al., 2000).

- Chrome

  Chrome is widely immobile. Mostly, it is bound to sesquioxides and tone minerals. In soils, only little organic bound chrome exists. Chrome becomes soluble and convertible in very acidic soil zones.

- Copper

  Copper, for pH-values lower than 6, mostly binds to humic substances. In the neutral area it binds to sesquioxides, whereto it is fixed very well. In comparison to the other metals, copper is heavily bound to soluble organic complexes. For pH-values higher than 6 this fraction rises up to 99%. Under reduced conditions, copper can drop out as sulfide (Grotehusmann D., 1995; quoted by Hahn M. et al., 2000).

- Zink

  Zink is relatively mobile and bound to organic and mineral soil components. For pH-values higher than 7 it is bound mostly to sesquioxides. Beneath, it is bound to humic substances. For pH-values lower than 5, zink is bound mostly to tone minerals (Grotehusmann D., 1995; quoted by Hahn M. et al., 2000).

## 3.2. The Impact of Highway Runoff Water in Water Resources

### 3.2.1. The treatment of highway runoff

The impact of highway runoff in water resources is mostly dependent on its pre-treatment. Highway runoff can be caught in gutters or pipes and directly discharged into rivers, led into a retention or infiltration pond, or run over a slope.

If collected and discharged directly into a river the pollutants can negatively affect water bodies.
Runoff water passing wet basins, under regular conditions, does not pose an environmental risk.
In dry basins an emptying of the basin subsequent to a storm event can lead to the washout of pollutants and therefore its innocuousness can not be guaranteed.
Infiltration basins and swales are able to purify polluted water to a better part.

A highway storm water runoff study conducted by McNamee, Porter, and Seeley, Inc. (1998) came to the conclusion that in several cases, passing grass swales, the concentration of metals in rainfall exceeded the concentration in runoff. Overall, the dissolved-to-total recoverable ratios were higher in the rainfall samples than in the highway runoff samples. Therefore, runoff water passing grass swales regularly does not pose a risk to water bodies.

### 3.2.2. The risk of highway runoff for receiving waters

Under normal conditions, total concentrations of pollutants in undiluted highway runoff do not exceed wastewater pollutant limits or formal in-stream criteria for protection of aquatic life.
Regarding in-stream dilution, it is possible that the in-stream concentrations will be well below levels of concern in receiving waters.
Investigations on the impact of road runoff on receiving streams (Perdikaki K., Manson C. F., 1999; Barrett M. E. et al., 1995) came to the conclusion that pollutant concentrations do not differ significantly between upstream and downstream sites of rivers for many heavy metals.
Nevertheless, in combination with pollution resulting from other sources highway runoff water can contribute to the accumulative pollution of receiving waters.

As the majority of constituents in road run-off are associated with particulate material (Hewitt C. N., Rashed M. B., 1992; quoted by Perdikaki K., Manson C. F., 1999), they tend to accumulate in the sediments of receiving streams (Maltby L. et al., 1995; quoted by Perdikaki K., Manson C. F., 1999) and therefore do pose little risk to creatures.
Although, constituents of sediments can solubilize under certain physicochemical conditions adding to the toxicity of the overlying water (Dallinger R., Kautzky H., 1985, Shea, 1988; quoted by Perdikaki K., Manson C. F., 1999).

Concerning ground water, investigations on infiltration ponds (Golwer A., Schneider W., 1983; quoted by Grotehusmann, D., 1999) and grass swales (McNamee, Porter, and Seeley, Inc., 1998) testified that highway runoff is largely purified through infiltration and therefore states little risk. The effectiveness of the infiltration is mostly dependent on the absorption characteristics of pollutants to soil particles (Hvitved-Jacobsen T., Vollertsen J., 2003).

### 3.2.3. Possible effects on the biota resulting from highway runoff

A general overview of the integrated effects of both, pollutants and flow, of road runoff is given in Table 11 (Hvitved-Jacobsen T., Vollertsen J., 2003).

**Table 11:** Different effects of road runoff in aquatic and soil systems (Hvitved-Jacobsen T., Vollertsen J., 2003)

| Overall Effect | Subdivision and Comments |
|---|---|
| Physical habitat changes | 1) Flooding<br>2) Erosion caused by overland flow and peak flows in channels and rivers<br>3) Sediment deposition in receiving waters |
| Dissolved oxygen depletion | Effects on biological communities |
| Eutrophication | Effects of both nutrients (N and P) and organic matter as substrates for excessive biological growth and activity |
| Toxic pollutant impacts | Effects of heavy metals and organic micropollutants |
| Public health risk | 1) Direct impacts by pathogenic microorganisms and viruses<br>2) Indirect impacts via contaminated food |
| Aesthetic deterioration and public perception | Can be caused by discharge of gross solids and sediments |

One of the possible negative impacts of highway runoff water on water bodies is a high level of turbidity. It is caused by the first flush of water entering a river with basically low mean water level after a heavy rainfall. It can affect grill-breathing animals like fishes.

Readily biodegradable substances in highway runoff water entering a water body during a storm event will be eliminated quickly. Therefore, highway runoff is only able to cause a negative impact on water bodies having basically a low mean water level.

Gusinde, et al. (1979) (quoted by Fritzer H., 1992) stated that runoff water from new-built concrete highway surfaces has an elevated pH-value, which can result in negative effects through eutrophication.

The entry of suspended solids can reduce light transmission, which limits in-stream photosynthesis and diminishes aquatic food supply and habitat. Suspended solids may also coat and abrade aquatic organisms, reduce surface water quality and suitability for various usages, and lead to diminished capacities of reservoirs or other conveyance systems via deposition (Goldman et al., 1986; quoted by Barrett M. E. et al., 1995).

Furthermore, an elevated level of insoluble substances can cause negative impacts on aliment animals for fishes as well as on fish eggs and larvae trough clogging of the pores between the substrate of the riverbed.

Persistent substances, especially cadmium, copper, lead and zinc pose a higher risk to water bodies. They decrease the ability of self-purification of receiving waters.
Scheffer and Schachtschabel (2002) (quoted by Hahn M., 2004) stated that, for instance, copper and zinc, contrary to cadmium and lead, are indispensable for the growth of plants, but can develop toxic effects in already little-elevated concentrations. Cadmium and lead can cause relevant ecotoxic and humantoxic effects through accumulation.

The environmental behavior of persistent substances is highly dependent on their solubility and absorbability.

An important factor is the background pollution, which needs to be remembered in a collective evaluation for every heavy metal. An already elevated concentration of absorbed heavy metals leads to a higher concentration of dissolved heavy metals, which signifies a higher fraction of active ecotoxic heavy metals in the water body.

The highest influence on the solubility of heavy metals has the pH-value; a lower pH-value elevates the fraction of dissolved substances.

A summary of pH-values that mobilize different heavy metals, according to Blume and Brümmer (1991) (quoted by Holz A., 2004) is given in Table 12.

**Table 12:** Ph-values that mobilize different heavy metals
(Blume H. P., Brümmer G., 1991; quoted by Holz A., 2004)

| Heavy Metal | Cd | Zn | Ni | Cu | As | Cr | Pb | Hg |
|---|---|---|---|---|---|---|---|---|
| pH-value | 6.5 | 6-6.5 | 5.5 | 4.5 | 4-4.5 | 4-4.5 | 4 | 4 |

The toxic impact of heavy metals on the environment also depends on their mobility, their concentration, as well as on their dimension and exposure time. This is illustrated in Figure 9.

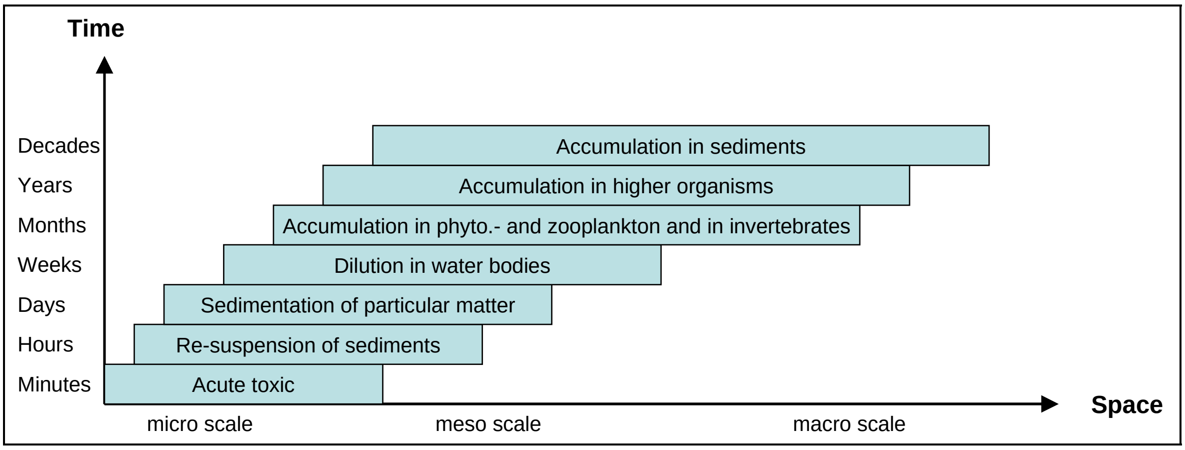


**Figure 9:** Relation between temporal and spatial effects of heavy metals in rivers (Lijkelma L., 1998; according to Holz, A. 2004)

A summary of ecotoxic heavy metals, their impact on creatures, and exotoxic limit values is given by Behra et al., (1993) (quoted by Hahn M. et al., 2000):

- Cadmium

  Shows a poor tendency to bind itself to organic or inorganic complexing agents. Acute toxic for fishes. Fortification of its toxic impact in combination with copper and zinc. For concentrations higher than 0.17 μg/l, psychological diseases and mortality of fishes and crustacean have been observed.
  Non-effective-level: 0.01-0.5 μg/l

- Copper

  Shows a high tendency to bind itself to organic complexing agents. Already in low concentrations highly toxic for almost each water organism. Fortification of its toxic impact in combination with zinc and cadmium. Concentrations of 1 μg/l activate effects on the photosynthesis of algae, 2 μg/l causes physiological and immunological disorder on fishes. The lethal concentration for 50% of the population of water fleas lies at 4-6 μg/l, for the population of aquatic worms at 6 μg/l.
  Non-effective-level: 0.05 μg/l

- Nickel

  Shows a tendency to bind itself to organic complexing agents, but has a poor tendency to bind itself to inorganic complexing agents. Lethal effects on crustacean and fish larvae can be observed for concentrations higher than 5 μg/l. Concentrations higher than 10 μg/l activate photosynthesis effects on algae.
  Non-effective-level: 0.5-10 μg/l

- Lead

  Shows a poor tendency to bind itself to organic or inorganic complexing agents, but it tends to bind to surface particles. Covering the ground, it can have negative effects on there living populations. For concentrations higher than

7 µg/l distortion of the vertebral column and muscle athropies on fishes have been diagnosed. Concentrations of 30 µg/l cause histopathalogic, haemolytic, and neurotoxologic effects on fishes as well as perturbance of algae growth. 130 µg/l is the lethal dosis for invertebrates. Methyl forms, generated through bacteriological processes, do have a greater impact on higher organisms.
Non-effective-level: 3-10 µg/l

- Zink

  Shows a poor tendency to bind itself to organic or inorganic complexing agents as well as to surface particles. Therefore it is mostly found dissolved. It represses reproduction and is lethal for crustacean above a concentration of 30 µg/l and on fishes above a concentration of 60 µg/l. Aquatic worms die above a concentration of 100 µg/l. Zink is from poor humantoxic importance. Non-effective-level: 0.5-2 µg/l

The non-effective-levels, for which effects on organisms are not expected, are only valid for the dissolved fractions of these heavy metals. Therefore total concentrations or loads are not applicable on the evaluation of pollutant impacts on creatures.
Also, the interaction between metals and their alloy or combination as well as the effects of other bio accumulating substances need to be observed.

### 3.2.4. Bioaccumulation

The highest danger of persistent substances lies in their bioaccumulation in organisms. Metal bioaccumulation depends not only on sediment metal concentrations but also on different abiotic and biotic factors (Van Hattum B. et al., 1991) (quoted by Perdikaki K., Manson C. F., 1999).

It is quite difficult to define ecotoxical limits. The existing values are mostly obtained through animal experiments and are multiplied by a factor 100 when applied on humans.

Bioaccumulation in creatures is the more dangerous the higher the place of a creature in the food chain is. This effect is called biomagnification.
Seals, for example, are one of the most endangered species as a big part of their body is made of a fatty substance, where PCB’s and DDT accumulate. Seals are on the end of the maritime food chain. The high level of pollutants in the Mediterranean and Baltic Sea already led to a radical diminution of the seal population. Seals suffer from a diminution of reproduction, stillbirths, and a weakening of their immune system.

## 3.3. Legal Basics

Predominately, the member states of the European Union are bound to EU-laws. The discharge of runoff water into a water body (including ground water) signifies a use of this body which needs to be recorded, according to EU-, federal, and state laws. The discharge of certain substances into water bodies is prohibited or requires an approval. Exceptions can be made, if impacts to the water body remain insignificant.

In Germany, ground water protection, as well as the protection of soils, is regulated by the federal soil protection law. The law prohibits a direct discharge of runoff water, if, despite to a positive impact on the ground water, soils become negatively affected.
According to the German federal law, the use of a water body needs to be approved, but exceptions are tolerated. The infiltration of runoff water, which is recommended by German state laws and most guidelines, signifies such a use.
The ATV-Arbeitsgruppe 1.4.1 (1995) argued that every infiltration would need an approval, according to the German water resources act. Moreover, it states that a laminar infiltration (plain- or swale infiltration) is a natural process and therefore would build an exception to this approval. Each infiltration of collected runoff water under help of certain facilities meets the conditions of a discharge into the water body and therefore needs to be approved. In water protection areas, such facilities could even become subject to meet additional requirements.

In Austria, according to the Wasserrechtsgesetz, the need for an approval is limited to ground water use. The use of bodies of flowing water is tolerated, as long as water quality, river or lake bank conditions, a certain law or public interest is not violated. Soil- and groundwater protection is issue of state laws.

A more detailed explanation of some relevant directives, laws, and guidelines is given in chapter 3.3.1, chapter 3.3.2, and chapter 3.3.3.

### 3.3.1. European law

#### 3.3.1.1. Treaty establishing the European community

Therein, general objectives concerning the environment are given in article
130 r para. 1.

These are:

- Preservation and protection of the environment as well as the improvement of its quality
- Protection of human health
- Circumspect and reasonable use of natural resources

According to article 130 r para. 2, European environmental policy bases on the principles of precaution and prevention. It says that, if possible, environmental damage has to be reduced at its origins according to the polluter pays principle.
The responsibility for the implementation of necessary measures and financing, according to article 130 r para. 4, carry the member states.

#### 3.3.1.2. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy

The principal objective of the European water framework directive was to establish a unitary regulation frame for all water bodies. Its main target is to avoid a long-term deterioration of fresh water quantity and quality to guarantee melioration and the sustainable rationing of fresh water resources (Perfler R., 2004).

An important innovation in water policy is the introduction of article 10, which calls for the appliance of the combined approach for the discharges into surface waters. It says that the member states shall ensure the establishment and (or) implementation of:

(a) the emission controls based on best available techniques, or
(b) the relevant emission limit values, or
(c) in the case of diffuse impacts the controls including, as appropriate, best environmental practices

Where a quality objective or quality standard, whether established pursuant to this Directive, in the Directives listed in Annex IX, or pursuant to any other Community legislation, requires stricter conditions than those which would result from the application of paragraph 2, more stringent emission controls shall be set accordingly.

To achieve the targets and limit values, article 11 provides a program of measures which includes:

- measures to promote an efficient and sustainable water use
- a prohibition of direct discharges of pollutants into groundwater subject to certain provisions
- measures to eliminate pollution of surface waters by those substances specified in the list of priority substances agreed pursuant to Article 16(2) and to progressively reduce pollution by other substances
- for point source discharges liable to cause pollution, a requirement for prior regulation, such as a prohibition on the entry of pollutants into water, or for prior authorization, or registration based on general binding rules, laying down emission controls for the pollutants concerned, including controls in accordance

with Articles 10 and 16. These controls shall be periodically reviewed and, where necessary, updated

- for diffuse sources liable to cause pollution, measures to prevent or control the input of pollutants. Controls may take the form of a requirement for prior regulation, such as a prohibition on the entry of pollutants into water, prior authorization or registration based on general binding rules where such a requirement is not otherwise provided for under Community legislation. These controls shall be periodically reviewed and, where necessary, updated

In article 16, strategies against pollution of waters, it says that the European parliament and the council shall adopt specific measures against pollution of water by individual pollutants or groups of pollutants presenting a significant risk to or via the aquatic environment, including such risks to waters used for the abstraction of drinking water.
Its ultimate aim is to achieve concentrations in the marine environment approaching background values for naturally occurring substances and close to zero for man-made synthetic substances.
Therefore, a list of 33 priority substances, including the priority hazardous substances, from point and diffuse discharges was defined.

Hazardous substances are defined as substances or groups of substances that are toxic, persistent and liable to bio-accumulate, and other
substances or groups of substances which give rise to an equivalent level of concern.
In Annex IX emission limit values and environmental quality standards are appointed for these 18 hazardous substances.

These substances are outlined in Table 13.

**Table 13:** List of priority substances in the field of water policy (Directive 2000/60/EC, 2000)

| | | | |
|---|---|---|---|
| (1) | Alachlor | (21) | Mercury and ist compounds |
| (2) | Anthracene | (22) | Naphtalene |
| (3) | Atrazine | (23) | Nickel and ist compounds |
| (4) | Benzene | (24) | Nonylphenols<br>(4-(para)-nonylphenol) |
| (5) | Brominated diphenylethers | | |
| (6) | Cadmium and ist compounds | (25) | Octylphenol<br>(para-tert-octylphenol) |
| (7) | C10-13-Chloroalkanes | | |
| (8) | Chlorfenvinphos | (26) | Pentachlorobenzene |
| (9) | Chlorpyrifos | (27) | Pentachlorophenol |
| (10) | 1,2-Dichloroethane | (28) | Polyaromatic hydrocharbons<br>(Benzo(a)pyrene)<br>(Benzo(b)fluoranthene)<br>(Benzo(g,h,i)perylene)<br>(Benzo(k)fluoranthene)<br>(Indeno(1,2,3-cd)pyrene) |
| (11) | Dichloromethane | | |
| (12) | Di(2-ethylhexyl)phthalate(DEHP) | | |
| (13) | Diuron | | |
| (14) | Endosulfan<br>(alpha-endosulfan) | | |
| (15) | Fluoranthene | (29) | Simazine |
| (16) | Hexachlorobenzene | (30) | Tributyltin compounds<br>(Tributytin-cation) |
| (17) | Hexachlorobutadiene | | |
| (18) | Hexachlorocyclohexane<br>(gamma-isomer, Lindane) | (31) | Trichlorobenzenes<br>(1,2,4-Trichlorobenzene) |
| (19) | Isoproturon | (32) | Trichloromethane (Chloroform) |
| (20) | Lead and ist compounds | (33) | Trifluralin |

## 3.3.2. Austrian law

### 3.3.2.1. Wasserrechtsgesetz (1959)

The matter of the Austrian Wasserrechtsgesetz is to protect water bodies from contamination and misuse. It was introduced in 1959.

Regarding runoff water the law says that non- or little polluted runoff water from residential areas shall be treated, if possible, in a natural way.

If anthropogenic polluted runoff water, like runoff water from heavily frequented roads, is assumed to change the character of the receiving water it shall be treated according to the best available technology.

The use of ground water needs an approval by the public authority. The use of other water bodies is tolerated, as long as water quality, river or lake bank conditions, a certain law or public interest is not violated.

Related to the Wasserrechtsgesetz are specific emission regulations for each industrial branch. These regulations set limit values for the discharge of, e.g., sewage water into bodies of flowing water and into public sewerage.
Regarding runoff water collected in special sewers, which also concerns collected road runoff water, a specific emission regulation is planed. Until its introduction, the Allgemeine Begrenzung von Abwasseremissionen in Fließgewässer und öffentliche Kanalisation (AAEV, 1996) (general emission regulation) has to be applied to collected road runoff water. For non-collected runoff water the AAEV (1996) is valid.

Therein, limit values for certain emissions are given.

For example, temperature is limited with 30 degrees and the pH-value with 6.5-8.5.

Limit values for certain substances are outlined in Table 14.

**Table 14:** Allgemeine Begrenzung von Abwasseremissionen in Fließgewässer und öffentliche Kanalisation (AAEV) (BMLF, 1996)

| Constituent | Limit [mg/l] | Constituent | Limit [mg/l] |
|---|---|---|---|
| TSS | 30 | Cu | 0.5 |
| Al | 2 | Ni | 0.5 |
| As | 0.1 | Hg | 0.01 |
| Ba | 5 | Ag | 0.1 |
| Pb | 0.5 | Zn | 2 |
| Cd | 0.1 | Sn | 2 |
| Cr | 0.5 | $Cl_2$ | 0.4 |
| Co | 1 | N | 10 |
| Fe | 2 | - | - |

Parallel to emission regulations, immission regulations for bodies of flowing water are required. For rivers having a $Q_{95\%}$ >400 l/s a draft concept already exists (Kainz H. et al., 2002). It is outlined in Table 15.

**Table 15:** Allgemeine Immissionsverordnung, draft concept, (AlmVF) (BMLF, 1995)

| Constituent | Type A | Type B |
|---|---|---|
| | [mg/l] | [mg/l] |
| $BOD_5$ | 2 | 3.5 |
| COD | - | - |
| DOC | 3 | 5.5 |
| NH4-N | 0.3 | 0.5 |
| NO3-N | 6 | 6 |
| P. total | 0.07 | 0.15 |

Type A stands for rivers in mountainous regions, type B for rivers in lowland regions.

## 3.3.3. Austrian, German, and Swiss Guidelines for the treatment of road runoff

### 3.3.3.1. OEWAV Regelblatt 35 (draft concept, 2002)

The OEWAV creates guidelines and technical rules for Austrian planers.

Its guideline suggests that runoff water originating from highways, defined as roads having an AADT higher than 15000 vehicles per day, should be collected separately and, if possible, be preliminary purified before discharged into rivers.
The minimum requirements for purification are a mechanical treatment and filtration. If the relation of the impermeable surface area of the road ($A_S$) to the average river discharge is higher than 0.1, it is required to proof the necessity of further runoff water treatment.

A common treatment measure would be to infiltrate the water in a basin. This method generally requires a mechanical pre-treatment. The soil of the infiltration basin ($A_i$: $A_S$ > 15) has to have at least a $k_f$-value (transmissibility coefficient) of $10^{-5}$ m/s.

### 3.3.3.2. ATV-DVWK-A 138 (2002)

The ATV-DVWK carries out the same consultative function in Germany as the OEWAV in Austria.
Its work sheet ATV-DVWK A 138 for design, construction and operation of infiltration facilities suggests classifying the use of treatment measures according to the AADT.
Concerning highways (roads with an AADT>15000) it defines three classes of treatment depending on the relation of impermeable surface area ($A_S$) to the infiltration area ($A_i$).

If:$A_S$:$A_i \leq 5$ runoff water is infiltrated on a plane area.
If $A_S$:$A_i \leq 15$ it is infiltrated locally or ran into basins after a pre-treatment.
If $A_S$:$A_i > 15$ tray or basin infiltration facilities have to be built, but also in this case the runoff has to be pre-treated.

### 3.3.3.3. Wegleitung Grundwasserschutz (2003)

The guideline to groundwater protection released by the Swiss federal office for environment, forests and landscape is the newest guideline and has been released in 2003.

The guideline mentions traffic as origin of pollution for areas near roads.
As main factors of pollution it lists components of fuel, dust, shower water, road salt and the risk of leakage from accidents in which fuel or harmful goods emit.
It gives an overview of the different areas and protection zones and the limits and sanctions of use. They as stated in Table 16.
Furthermore, special limits and sanctions for transportation use are stated in Table 17.

**Table 16:** Summary of the most important measures and restrictions of use in special areas (BUWAL, 2003)

| Zones, areas | Most important measures and restrictions of use |
|---|---|
| Other areas (o.D) | • due diligence<br>• authorization duty for the exploitation of material<br>• prohibition of material deposition<br>• preservation duty for ground water sources |
| **Particulary vulnerable areas** | |
| Waterbody protection area (Wa) | • local authorization for the construction of buildings and facilities required<br>• construction ban for buildings and facilities stating a risk to water bodies<br>• special regulations for the extraction of gravel, sand, and other material |
| Inflow area (Ia) | local authorities restrict certain actions and the use of certain substances, e.g.:<br>• the use of mobile and persistent pesticides<br>• constriction for the disposal of sludge or liquid manure<br>• ban for the use of certain plants for land cultivation, etc. |
| **Groundwater protection zones** | |
| Zone S3 | • extraction ban for gravel, sand, and other material<br>• prohibition of constructing beneath the level of ground water |
| Zone S2 | additional to the measures proposed in S3:<br>• building ban (exceptions possible)<br>• excavation ban<br>• prohibition of actions influencing the quality or quantity of drinking water<br>• prohibition of the use of mobile and persistent pesticides<br>• prohibition of the disposal of sludge or liquid manure |
| Zone S1 | additional to the measures proposed in S3 and S2:<br>• strict building ban and prohibition of land use |
| Areas of groundwater protection | • building ban<br>• extraction ban for gravel, sand and other material |

**Table 17:** Summary of the most important measures and restrictions of use in special areas specifically for transportation use (BUWAL, 2003)

| | o.D | Wa | Ia1 | Areal | S3 | S2 | S1 |
|---|---|---|---|---|---|---|---|
| Roads without restrictions for tank lorries: | | | | | | | |
| • on road embankments or in terrain level | | +b | + | | | | |
| • in underground crossings or terrain slittings | ++ | b | b | -2-2 | +4b4 | - | - |
| Roads restricted for tank lorries: | | | | | | | |
| • on road embankments or in terrain level | | | + | | | | |
| • in underground crossings or terrain slittings | ++ | +b | b | -2-2 | +4b4 | - | - |
| In tunnels | Special table for subterrain constructions | | | | | | |
| Roads on agricultural used land and forest roads | + | + | + | -[2] | + | -[30] | -[31] |
| Petrol stations | + | b | b | - | - | - | - |
| Major parking lots | + | + | + | -2 | b4 | - | - |

+ permitted from the viewpoint of groundwater protection (no authorization necessary)

+n permitted, under constrictions, from the viewpoint of groundwater protection (no authorization necessary)

+b basically admissible; authorization according article 32 GSchV

b admissible under certain conditions; authorization according article 32 GSchV

-b not admissible; exceptions can be made by responsible authorities after proving the case

-n not admissible; exceptions can be made by responsible authorities under consideration of additional requirements

\- not permitted

A definition of groundwater protection zones is given in Figure 10.

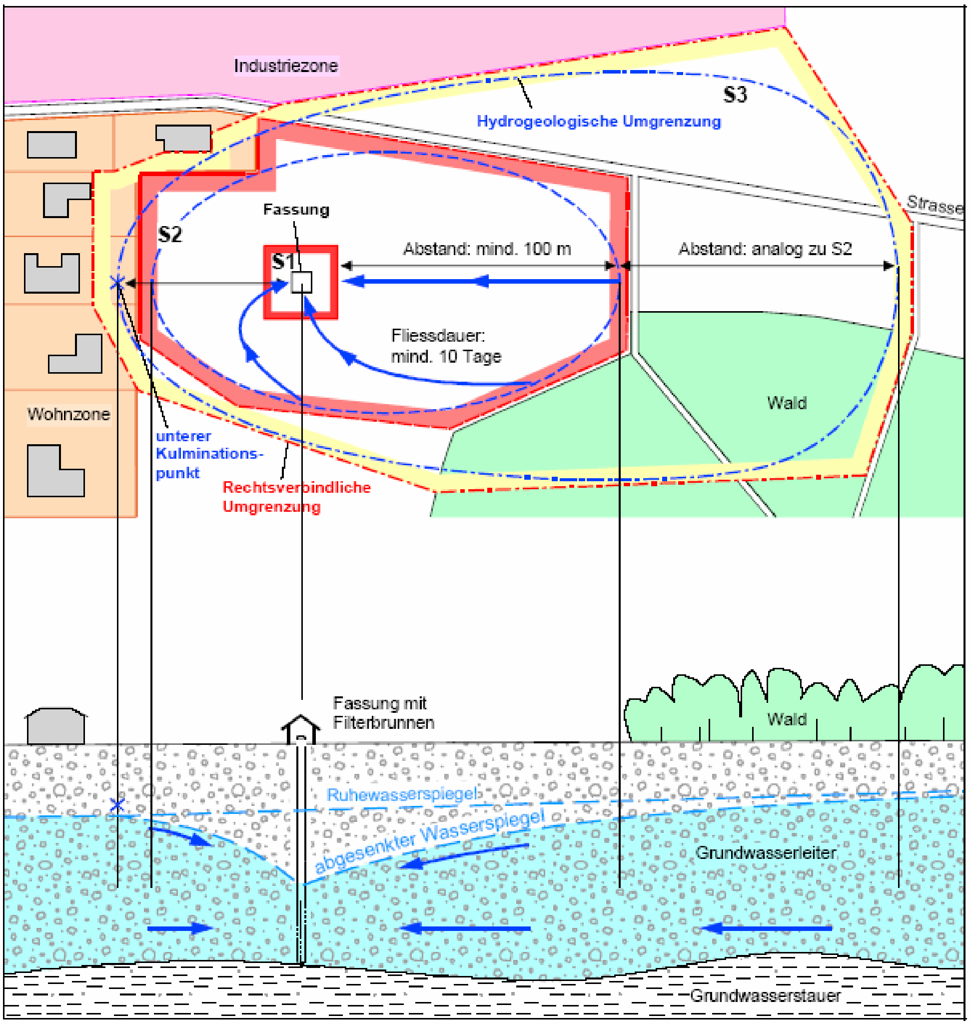


**Figure 10:** Groundwater protection zones (BUWAL, 2003)

# 4. Highway Runoff Water Quality Modeling

## 4.1. An Introduction to Water Quality Modeling

What is needed in general to manage problems related to runoff water is to define the problems that are to be solved, to know the origin of the pollutants, and the effectiveness of runoff management practices that can control the problem of pollutants at their sources and at their outfalls (Tasker G. D., Granato G. E., 2000).

The accurate characterization of highway runoff therefore is important, beneath of being a decision criteria, e.g., to comply storm water permit requirements, to address legal requirements, to aid in developing new treatment systems, to develop runoff load models and to fulfill data gaps for statistical analysis.

Generally, the use of measured data is preferable to the use of simulated data, as models are not satisfactory substitutes for good field sampling programs. They are more useful in extending and extrapolating measured data.
Computer models are able to perform some types of analysis, like frequency analysis, which could rarely be performed otherwise since periods of water quality measurements are seldom very long.

The use of models to simulate the processes influencing the quantity and quality of stormwater results from a decrease in economic resources to test alternative management strategies for urban drainage systems. The economic concerns regarding urban runoff have to be considered also for highway runoff.

Methodologies and models, mostly developed for the use on urban watersheds, have already been applied to a greater or lesser extend on estimating the quality and quantity of highway runoff.
One of the determining factors for the limited success of these models, until now, was the high variability of runoff water quality data (Smullen J. T. et al., 1996; quoted by May D., Sivakumar M., 2004).

Monitoring studies on numerous highways in the EU and the USA showed that the range of pollutant concentrations in highway runoff is very widespread and that therefore using models for this purpose leads to a number of problems.

The unreliability of models is based on the complexity of the actual physical processes that convert rainfall into runoff. As such, these processes cannot be replicated mathematically with exact certainty.

Another detected problem is that the model output is highly dependent on reliable input data.

Input data for water quality models, to a better part, have stochastic nature, which makes it hard to define. Even if this data is very simple, it can become a great challenge to obtain the required data for the given task.

Data may be obtained from existing studies. If not, it can require extensive field monitoring to gain them. For some conceptualizations, e.g., buildup and wash off, it even will not always be possible to measure fundamental input parameters. Therefore such parameters will only be obtained through model calibration.

A basic principle for almost any model is that its predictive ability will be poor without suitable site-specific data for calibration (Shelley P. E., Gaboury D. R, 1986; quoted by Tasker G. D., Granato G. E., 2000) and its credibility insufficient without a proper validation.

Another important part of any modeling process is dealing with uncertainty. The analyst needs to know the severity of the statistical uncertainty of the methods used to predict water quality (Tasker G. D., Granato G. E., 2000).

Ideally, models which fully replicate the processes and the spatial and temporal variability of these processes should be used. In practice, however, this does not happen because many processes are so complicated and interrelated that a full description may be impossibly complex and even when a process can be described concisely and completely, the volume of calculations involved may be prohibitive.
The data available to define the control parameter values for operation of a particular model are limited (Ball J.E., 1992).
Through the use of simplifying assumptions, there are several mathematical models and equations that can simulate generation processes and predict resultant runoff volumes and rates with acceptable accuracy.
Simplifying assumptions are made to idealize the real situation. Alternative idealizations result in the emphasis of different processes and require different magnitudes of computational effort. Consequently, instead of one model of reality, alternative models with differing degrees of complexity and computational effort may be developed (Ball J.E., 1992).

One conceptual subdivision of a catchment model is the one presented by Ball (1992) who proposed the following four components:

- Generation - that component of the model primarily concerned with the estimation of the available quantity of water and pollutant constituents.

- Collection - that component of the model primarily concerned with the accurate prediction of the quantity and quality of flow at the entry point to the transport component of the model. Generally this is the hydrologic component of the model.

- Transport - that component of the model where the water and pollutant constituents are routed along the channels of the catchment drainage system. This, typically, is referred to as the hydraulic component of the model.

- Disposal - that component of the model where the runoff and pollutant constituents are discharged into receiving waters.

To find the correct models for obtaining the needed information is a difficult task.

The most important question for a decision maker is which model provides the required management information providing the best blend of accuracy and speed (Tasker G. D., Granato G. E., 2000).

Therefore modeling principles and an introduction to modeling are written by several authors, for example James and Burges (1982), Kibler (1982), Huber (1985, 1986) and are summarized in a more recent manual of practice (Water Pollution Control Federation, 1989) (quoted by Donigian A. S. et al., 1991).

Some of the most important are:

- Have a clear statement of project objectives. Verify the need for quality modeling. (Perhaps the objectives can be satisfied without quality modeling).
- Use the simplest model that will satisfy the project objectives. Often a screening model, e.g., regression or statistical, can determine whether more complex simulation models are needed.
- To the extent possible, utilize a quality prediction method consistent with available data.
- Only predict the quality parameters of interest and only over a suitable time scale. That is, storm event loads and event mean concentrations will usually be the most detailed prediction necessary, and seasonal or annual loads will sometimes be all that is required. Do not attempt to simulate intra-storm variations in quality unless it is necessary.
- Perform a sensitivity analysis on the selected model and familiarize yourself with the model characteristics.
- Calibrate and verify the model results. Use one set of data for calibration and another independent set for verification. If no such data exist for the application site, perhaps they exist for a similar catchment nearby.

Within the responsibility of the analyst lies to document efforts and to:

- examine the representativeness of data used to construct models,
- assess uncertainties in models, and
- evaluate the potential predictive ability for sites not included in the construction of the model (Tasker G. D., Granato G. E., 2000).

Storm water pollutant models vary widely in their cost, effort and accuracy depending on the complexity of the model used, its data requirements, drainage area resolution and need for model calibration and verification; they range from the simple to complex, encompassing “back of the envelope” methods to full-blown, multi-year computerized models (Harremöes P., 1988).

The resources needed to support a modeling effort increase in direct proportion to the complexity of the model chosen for analysis (Tasker G. D., Granato G. E., 2000).

In the following chapter an overview of some available models is given.

## 4.2. An Overview of Available Models

The search for applicable models resulted in the finding of a great number of runoff water quantity and (or) quality prediction models. Some of these models can be used on highway runoff water and will be introduced in this chapter.

Preliminary it can be said that

- Both, models used for water quality prediction and water quantity prediction, are not able to produce viable results without undergoing the processes of calibration and verification.
- Simple prediction models generally perform better over a long averaging time than on a single storm event whereas more complex models can even produce intra-storm variations.

### 4.2.1. Simple empirical models

Simple models are based on the knowledge of accurate mean pollutant concentrations, which can be presumed out of local studies and (or) literature.
Moreover demographic and hydrologic factors need to be considered.

There exist different types of simple empirical models, e.g.:

- The multiplication of the mean pollutant coefficient with a typical average runoff volume based on the arithmetic mean over a specified time period to obtain pollutant loads for this period, e.g., annual or seasonal.

- The definition of unit loads. This method provides mass values for each pollutant per area and per time.

- The treatment of a pollutant as a fraction (potency factor) of total suspended solids. For example, Lager et al. (1977), Manning et al. (1977) and Zison (1980) (quoted by Donigian A. S. et al., 1991) provide summaries of such values.

Simple models provide an order-of-magnitude estimate of values and do not indicate correlation among variables.

The variation of predicted values can only be obtained trough a variation in input data or, e.g., a Monte Carlo simulation.
The accuracy of a Monte Carlo simulation is limited by the number of parameters in use.

Empirical models, for example, are: The USEPA Screening Procedures (Mills and others, 1985), the Simple Method (Schueler, 1987) (quoted by Donigian A. S. et al., 1991) and the VSA- Guideline (2002). The last two are presented in more detail.

- *Simple Method*

The Simple Method has been developed by Schueler (1987) for the Metropolitan Council of Governments to estimate pollutant loadings in urban watersheds.
It is based on data generated during a Nationwide Urban Runoff Program (NURP) study in the Washington, D.C. area and the NURP data analysis during the 1970's and 1980's which covered measurements of rainfall, runoff and water quality at over 100 sites in over 30 cities.

The method uses a loading function approach which estimates storm water pollutant loads as the product of mean pollutant concentrations and runoff depth over specified periods of time.
Its application is limited to small watersheds (<2,5km²) and when quick and reasonable storm water pollutant load estimates are required.

Equations:

Calculation of the runoff coefficient:

$$R_v = 0.05 + 0.009(I)$$

Calculation of the runoff depth [acre –feet/time interval]:

$$R = \left[(P) \bullet (P_j) \bullet (R_v)/12 \bullet A\right]$$

Calculating of annual pollutant loads [pounds/acres per time interval]:

$$L = \left[(R) \bullet (C) \bullet (2.72)\right]/A$$

or

$$L = \left[(P) \bullet (P_j) \bullet (R_v)/12\right] \bullet (C) \bullet (2.72)$$

In which:

$R_v$ = Mean runoff coefficient, expressing the fraction of rainfall converted into runoff [-]
$I$ = Percent of site imperviousness [%]
$R$ = Runoff [acre-feet/time interval]
$P$ = Rainfall depth over desired time interval [inches/time interval]
$P_j$ = Fraction of rainfall events that produce runoff [-]
$A$ = Area of the site [acres]
$L$ = Urban runoff load [pounds/acres per time interval]
$C$ = Flow-weighted mean concentration of the pollutant in urban runoff load [mg/l]

The mean runoff coefficient $R_v$ depends on the percent of site imperviousness I.
It has been classified by Schueler as only weakly correlated with storm-related variables such as precipitation volume, intensity, and duration.

Schueler (1987) (quoted by Mandel R. et al., 1997) suggested a value of 0.9 for the fraction of rainfall events that produce runoff ($P_j$), based on a comparison of the rainfall reported at the National Airport and the reported runoff at NURP sites in metropolitan Washington. A double mass curve analysis showed that 10% of the annual precipitation volume produced no runoff.

The use of the recommended value of 0.9 as an estimate of the volume of storms that produce runoff may be less well supported, however, since this was derived from data from the Washington metropolitan area only.
As the factor has a high influence on the calculation, it should be defined with higher accuracy if used to make predictions on annual loads (Mandel R. et al., 1997).

Schueler (1987) (quoted by Mandel R. et al., 1997) noted, that 50% of the storm events produced less than 0.5 cm of precipitation. He assumed that precipitation from these storms may not satisfy interception, depression storage, and infiltration.

- *VSA-Guideline: Disposal of rainwater*

The guideline proposes to multiply specific pollutant fractions of street dust by the dust load to obtain pollutant loads.
Parameter contents are given in Table 18.

**Table 18:** Contents of different parameters in street dust (VSA, 2002)

| Parameter | Street dust |
|---|---|
| | [mg/kg] |
| Fe | 17000 |
| Pb | 500 |
| Cd | 3.5 |
| Cr | 70 |
| Cu | 200 |
| Zn | 1000 |
| Ni | 60 |
| Polycyclic aromatic hydrocarbons | 200 |
| Absorbable halogen compounds | 200 |
| Hydrocarbons | 200 |

### 4.2.2. Spreadsheets

Spreadsheets are used to comfortably apply simple empirical models.
Pollutant loads are obtained by multiplying a constant concentration by the runoff volume. Usually, runoff volumes are calculated by introducing a runoff coefficient multiplied by a rainfall depth. The runoff coefficient can vary according to the land use.
Also for this method the estimation of constant concentrations is the determining.

The big advantage of the spreadsheet use is that a mixture of land uses (with varying concentrations) can easily be simulated, and an overall load and flow-weighted concentration can be obtained from the study area (Walker J. F. et al., 1989; quoted by Donigian A. S. et al., 1991).

Spreadsheets also provide graphic tools for result output which makes results vivid and easier to understand.
As already mentioned, very simple prediction methods generally perform better over a long averaging time and poorly at the level of a single storm event (Donigian A. S. et al., 1990; quoted by Donigian A. S. et al., 1991). Therefore, the spreadsheet approach is best suited to estimate values over a long averaging time, such as annual or seasonal loads.

### 4.2.3. Statistical models

Statistical models can be classified as either parametric (methods in which a specified data distribution is necessary to support design assumptions) or nonparametric (methods that do not depend on a specified data distribution to establish their meaning).
Table 19 gives an overview of different parametric and nonparametric techniques.

**Table 19:** Basic statistical techniques for parametric and nonparametric data analysis (adapted from Tasker G. D., Granato G. E., 2000)

| Technique | Measure | Basis | Definition | Comments |
|---|---|---|---|---|
| Arithmetic mean (Average) | Location | P | The sum of all data divided by the sample size. | Can be affected by the presence of and (or) changes in the magnitude of one or more outlying observations. Representativeness depends upon the assumption that the data are normal (or at least unimodal and symmetric). |
| Median | Location | N | The middle value when data are ordered from lowest to highest. | When there is an even number of data points the median is the average of the two central observations. The median is also referred as the 50th percentile. |
| Mode | Location | N | The data value that occurs with the highest frequency. | A data set may have more than one modal value. |
| Geometric mean | Location | P | The mean of the logarithms of data that is transformed back into original units. | Representativeness depends upon the assumption that the data are normal (or at least unimodal and symmetric) in log space. |
| Trimmed (or weighted) mean | Location | P | The mean censored data divided by the sample size after censoring. | Trimmed means (or weighted) means are computed once values judged as outliers have been eliminated (or weighted with a value of zero). It is typical to trim a given percentage from the bottom and top of the data in an attempt to apply systematic methods. |
| Range | Spread | N | The difference between the largest and the smallest measurements in a set. | Although nonparametric, the range is affected by the presence of and (or) changes in the magnitude of one or more outlying observations. |
| Variance | Spread | P | The sum of squared deviation of all measurements divided by one less than the total number of data points. | The variance can be unduly affected by the value of one or more outlying observations. |
| Standard deviation | Spread | P | The positive square root of the variance. | The standard deviation can be unduly affected by the value of one or more outlying observations. |
| Coefficient of variation | Spread | P | The ratio of the standard deviation over the mean. | A measure of spread normalized to the magnitude of the mean. |
| Interquarile range | Spread | N | The difference between the 75th and the 25th percentile values (by number of the measurements) when data are ordered from lowest to highest. | Typically used as a measure of central spread because the 25th, 50th (median), and 75th percentiles split the data into four equal-sized quarters(by number of measurements). Other percentile ranges may be used as well. |
| Median absolute deviation (MAD) | Spread | N | The median of absolute values of the difference between each data point and the data median. | The MAD, because it is the median of population of absolute differences, is resistant to the effect of outliers. |
| Coefficient of skewnesss | Skewness | P | The third central moment divided by the variance cubed. | A positive value indicates that the population is right-skewed, and a negative value indicates left skew. |
| Quartile skew coefficient | Skewness | N | The difference between the range of each quartile (25th to 50th and 50th to 75th) divided by the IQR. | A positive value indicates that the population is right-skewed, and a negative value indicates left skew. Other percentile ranges may be used as well. |

The concept of parametric statistical methods is to determine the properties of an underlying probability distribution based on the data acquired through the monitoring of a given number of events. The structure of a given population (the probability distribution) will determine which method of analysis to use.
According to Driscoll (1986) (quoted by Donigian A. S. et al., 1991) a lognormal distribution assumption is good, but (Donigian A. S. et al., 1991) when the model is combined afterwards with weak hydrologic assumptions, e.g., prediction of runoff using a runoff coefficient, no confidence can be given to results.

For the evaluation of the applicability of statistical methods, a general understanding of the characteristics of water-resources data is necessary.
Applying a model, the classification of variables of interest, a familiarity with the population structure and basic methods of analysis, and (if necessary) selection and proper use of population transformation techniques are needed (Tasker G. D., Granato G. E., 2000).

The use of inappropriate methods of data transformation would inevitably lead to the violation of the statistical assumptions underlying the methods chosen for analysis.
Often, populations of data on stormwater-runoff quantity and quality are best modeled as logarithmic transformations (Tasker G. D., Granato G. E., 2000).

Models, that use readily available rainfall statistics and water quality data, are able to estimate a frequency distribution of concentrations, loads, and potential for receiving water. That is useful for assessing levels of exceedance of water quality standards, such as risk and return periods.

Needless to say that those methods require large amounts of water-quality, land-use, and highway-related data for parameter estimation (Tasker G. D., Granato G. E., 2000).
For example, Thomson and others (1996) (quoted by Tasker G. D., Granato G. E., 2000) determined that samples from at least 15 to 20 storms from each study site are required to provide reasonable estimates in statistical analysis of pollutant concentrations.

Tasker and Granato (2000) stated that statistical techniques are commonly best suited to highway-runoff modeling needs at any scale (local, regional, or national).

Some statistical models are:

*Environmental Protection Agency (EPA) Statistical Method*

The EPA Statistical Method uses a lognormal frequency distribution assumption to estimate the distribution of event mean concentrations.
When coupled to an assumed distribution of runoff volumes (also lognormal), the distribution of runoff loads may be derived. When coupled again to the distribution of stream flow, an approximate (lognormal) probability distribution of in-stream concentrations can be derived.

*FHWA statistical pollutant loading and impact model approach:*

The FHWA statistical pollutant loading and impact model approach (Driscoll et al., 1989) has been developed from a screening tool in the EPA NURP studies (EPA statistical method).
The model uses lognormal distributed storm event statistics and the probability distribution of stream flow volume at a given site to estimate potential dilution in receiving waters. It is heavily dependent on distributional assumptions.
Input data required is the mean and the coefficient of variation of storm event depth, duration, intensity and the time between two storm events, area, runoff coefficient for the hydrologic component, event mean concentration, and coefficient of variation for the pollutant.
Driscoll uses tables with average event mean pollutant concentrations divided in nonurban (AADT <30000) and urban (AADT >30000) roads.

The model has not been designed for interpretation of study site data in terms of potential relations between constituents and site characteristics.

### 4.2.4. Buildup and washoff models

Buildup and washoff models have been created in 1969 by the American Public Works Association. The model bases on the estimation of a linear buildup of dust and dirt and of associated pollutants on urban street surfaces.
In1972, Sartor and Boyd investigated buildup mechanisms on the surface and washoff of pollutants during rainfall events. Buildup and washoff are part of some simulation models like the original SWMM model, the most flexible of the models, (Metcalf and Eddy Inc., 1971), the STORM, USGS and the HSPF models (Huber, 1985) (quoted by Donigian A. S. et al., 1991).

Although physically based, models that include buildup and washoff mechanisms employ conceptual algorithms because the true physics is related to principles of sediment transport and erosion that are poorly understood in this framework (Donigian A. S. et al., 1990; quoted by Donigian A. S. et al., 1991).

An advantage of these models is that it is easier to simulate potential control measures, such as street cleaning and surface infiltration, with them than with most other models.

The definition “Buildup” stands for the processes that are taking place between storms including deposition, wind erosion, street cleaning, etc. Different processes lead to an accumulation of solids and other pollutants on the surface which are partly removed through wash off during storm events.

For buildup, normalized loadings, e.g., mass/day-area or mass/day per curb-length, or just mass/day, are required, along with an assumed functional form for buildup vs. time, e.g., linear, exponential, Michaelis-Menton, etc. For washoff, the relationship of washoff (mass/time) vs. runoff rate must be assumed. Usually this happens in form of a power equation (Donigian A. S. et al., 1990; quoted by Donigian A. S. et al., 1991).

In the last years buildup processes on road surfaces have been investigated more precisely. Ball et al. (1997), for example, developed simple regression relationships for estimating the constituent load as a function of the time necessary for pollutant accumulation on a road in close proximity to the University of New South Wales, Australia.
They found out that power functions are most appropriate to describe the buildup-process of pollutant constituents. The hyperbolic relationship was the most significant for the build-up of sediment on the road surface.

Equations:

Power function:

$y=ax^b$

Hyperbolic function:

$$y = \frac{x}{a + bx}$$

In which:

x = antecedent dry period [days]
y = constituent load [mg]

The different regression coefficients are stated in Table 20.

**Table 20:** Regression coefficients for different build-up functions (Ball J. E. et al., 1997)

| Constituent | Constant | Power coefficient | Hyperbolic coefficient |
|---|---|---|---|
| Sediment | a | 3.77 | 0.21 |
| | b | 0.57 | 0.07 |
| Zinc | a | 1.04 | 0.63 |
| | b | 0.49 | 0.36 |
| Lead | a | 1.92 | 0.39 |
| | b | 0.58 | 0.15 |
| Iron | a | 49.56 | 0.017 |
| | b | 0.59 | 0.0047 |
| Copper | a | 0.45 | 1.82 |
| | b | 0.62 | 0.51 |
| Chromium | a | 0.057 | 20.48 |
| | b | 0.57 | 3.25 |

Calibrated buildup and washoff models normally are good and flexible predictors, especially for intra-storm variations.
To predict, e.g., annual loads it is necessary to predict a normal event multiplying it by the number of significant storm events per year.

### 4.2.5. Continuous curve number models

Continuous Curve Number Models were not designed to calculate runoff water quality. They are only mentioned for completion and should not be used for highway water quality modeling.

Since conceptually, a curve number is a measure of the infiltration capacity of the soil, the use of these models for impervious surfaces is open to question. Therefore, there is little theoretical justification for using the Curve Number Procedure on urban land (Mandel R. et. al., 1997) or highways.

The continuous curve number models were originally developed by the U.S. National Resource Conservation Service to calculate runoff for events with a particular return period on the basis of watershed characteristics such as land use and soil type. Land uses are assigned curve numbers based on the soil type, the condition of the soil and the vegetation covering it. Curve numbers are used to predict runoff volume generated from a given precipitation volume.
In the terminology of watershed modeling, a curve number is treated as a distributed parameter. Alternatively, a curve number for the entire watershed could be calculated as the weighted average, by area, of the curve numbers of distinct areas. Then, the curve number is treated as a lumped parameter of the watershed, and runoff is calculated for the entire watershed using the lumped curve number.
With a growing interest for the simulation of water quality, curve number models were adapted to continuous simulation. They are able to calculate runoff on a daily basis using daily precipitation for input.

The basis of the Curve Number Procedure is a hypothesized relation between runoff and infiltration.

Basis of the Curve Number Procedure:

$$\frac{F}{S} = \frac{Q}{P - I_a}$$

In which:

F = Actual retention of precipitation during a storm

S = Maximum potential retention

Q = Runoff

P = Precipitation

$I_a$ = Initial rainfall abstraction, which represents the precipitation intercepted by vegetation or other surfaces, and depression storage

Continuous Curve Number Models are, for example, the Generalized Watershed Loading Functions (GWLF) and the Environmental Policy Integrated Climate (EPIC, formerly the Erosion Productivity Impact Calculator).

### 4.2.6. Simulation models

Most simulation models use model parameters that provide a direct physical definition in an attempt to give a detailed description of the physical system.

The use of simulation models requires a high degree of institutional expertise and experience as well as a substantial modeling effort for each site of interest.

Although parameter estimation is not as data dependent as for statistical water-quality assessment models, detailed site-specific information and data to calibrate the models on current conditions is required to guarantee validity of results.

The complexity of simulation models and the large range of reasonable input parameters inherent in the model calibration process can lead to differences in professional judgment, which can negatively affect acceptance of simulation-model results (Tasker G. D., Granato G. E., 2000).

Frequently used simulation models are: SWMM (Huber and Dickinson, 1988), STORM (U.S. Army Corps of Engineers, 1977), HSPF (Bicknell et al., 1993), FHWA urban highway storm drainage model (Dever et al., 1993), MOUSE (1985) (quoted by Donigian A. S., 1990).

Models explained precisely are:

*The Hydrologic Simulation Program- Fortran (HSPF)*

Hydrological Simulation Program-FORTRAN (HSPF) is a comprehensive package for simulating watershed hydrology and water quality for conventional and toxic organic pollutants. It can represent hydrologic and water quality processes in runoff, subsurface flow, and in stream reaches and allows the integrated simulation of land and soil contaminant runoff processes with instream hydraulic and sediment-chemical interactions.

The model is the culmination of hydrologic routines that originated with the Stanford Watershed Model in 1966 and eventually incorporates many nonpoint source modeling efforts of the EPA Athens laboratory (Johansen N. B. et al., 1984; quoted by Donigian A. S. et al., 1991).

It is a continuous simulation model that operates on a user-defined time step.
Therefore continuous input data to drive the simulation is required. Input data has, at least, to content of continuous rainfall records. Additional records of evapotranspiration, temperature, and solar intensity are desirable. Default values are provided where reasonable values are not available.

The program is a distributed parameter model, which means that runoff from pervious and impervious land is simulated separately. Land use parameters can be chosen from impervious land, forestland, urban pervious land, pasture and cropland. For impervious land, all precipitation is converted into runoff, except for precipitation

stored in retention capacity and detention storage which are user-specified inputs to the model.
The program allows the bypassing of whole sections of the program where data is not available.
The result of the simulation is a time history of the runoff flow rate, sediment load, and nutrient and pesticide concentrations, along with a time history of water quantity and quality at any point in a watershed.

*The Source Loading and Management Model (WinSLAMM)*

WinSLAMM was developed in the mid 1970's, primarily as a data reduction tool for the use in early street cleaning and pollutant source identification projects sponsored by the EPA's Storm and Combined Sewer Pollution Control Program (Pitt R., 1979; Pitt R., Bozeman M., 1982). It was developed for a better understanding of the relationships between sources of urban runoff pollutants and runoff quality. The program is able to predict the concentrations and loadings of different pollutants from a large number of potential source areas calculating mass balances for particulate and dissolved pollutants and runoff flow volumes for different development characteristics and rainfall. It includes a variety of source area and outfall control practices like infiltration practices, wet detention ponds, etc.

WinSLAMM is strongly based on actual field observations, and does not rely on pure theoretical processes. The program is intended as a planning tool, to better understand sources of urban runoff pollutants and their control.

Many currently available urban runoff models have their roots in drainage design where very large and rare rains are from highest interest. In contrast, storm water quality problems are mostly associated with common and relatively small rains. The assumptions and simplifications that are legitimately used with drainage design models are not appropriate for water quality models. WinSLAMM was made for the storms of most interest in storm water quality analyses.
Additional information contained in WinSLAMM was obtained during the EPA's Nationwide Urban Runoff Program (NURP) (EPA 1983).
The program can describe a drainage area in sufficient detail for water quality investigations without requiring a great number of information. It applies stochastic analysis procedures to represent the uncertainty in model input parameters in order to better predict the actual range of outfall conditions (especially pollutant concentrations). WinSLAMM is the only found simulation model that includes freeway land use as land use parameter which can be defined through ten source areas including paved land and shoulder areas, large turf areas, undeveloped area, other pervious area, other directly connected impervious area, and other partially connected impervious area.

For input rainfall depths, durations, inter-event time periods from actual or stochastically generated rain data, runoff coefficient data, particle size distribution of sediments, particulate solids concentration, particulate residue loading, pollutant probability distribution data, and street delivery data need to be known.

Results are given optional for one rain event or for outfall summaries. Data is provided for runoff volume, particulate concentration, particulate loading, pollutant concentration, and the percent contribution from each source area for runoff, particulate loading, and pollutant loading.

*The Modeling of Urban Sewers (MOUSE)*

The program was developed by the Danish Hydraulic Institute, in cooperation with various other laboratories and private software firms.
Included in the package are modules for generation of runoff from rainfall, sewer routing (the S11S model, comparable to the SWMM Extra Block), and a simple quality routine that uses the constant concentration approach (Jacobsen P. et al., 1984; Johansen N. B. et al., 1984; quoted by Donigian A. S. et al., 1991).
MOUSE is a link-node based model that performs hydrology, hydraulic, water quality, and sediment transport analysis of storm water and wastewater drainage systems, including sewage treatment plants and water quality control devices.
It has a special module for the modeling of surface water. The primary role of the Surface Runoff Quality (SRQ) Module is to provide a physically-based description of the relevant processes associated with sediments and pollutants due to surface runoff, and then provide surface runoff sediment and pollutant data for the other pipe sewer network sediment transport and water quality modules. The following processes can be accounted for:

- Build-up and wash-off of sediment particles on the catchment.
- Surface transport of pollutants attached to the sediment particles.
- Build-up and wash-out of dissolved pollutants in potholes and stilling basins.

### 4.2.7. Regression models

The origin of regression models lies in sediment discharge rating curves developed as a function of the flow rate in natural river channels.

Regression analysis relates loads and event mean concentrations to catchment, demographic and hydrologic characteristics as well as to highway-design features and traffic volumes.
In other words, it estimates the average response of a system as it relates to variation of one or more known variables.
A variable that is described in terms of other variables in a regression model is called the response variable (or the dependent variable, or the predicted variable). Variables used to describe the response variable are called predictors (or explanatory variables, carriers, or independent variables) (Tasker G. D., Granato G. E., 2000).

Regression equations, in contrast to, e.g., statistical models, only predict the mean and cannot calculate the frequency distribution of a predicted variable (Tasker G. D., Granato G. E., 2000).

An overview of different regression methods is given in Table 21.

**Table 21:** General guide to regression methods (adapted from Tasker G. D., Granato G. E., 2000)

| Method | Response classification | Predictor classification | General purpose and assumptions |
|---|---|---|---|
| Ordinary least-squares regression | Continuous | Usually continuous but nominal can be used in addition | Describes the relation between response and predictors. Errors are independent and identically distributed with no outliers. Normality of errors is required for hypothesis testing. |
| Nonparametric regression | Continuous | Usually continuous but nominal can be used in addition | Describes the relation between response and predictors. Error distribution unspecified. Functional form may or may not be specified. Useful when errors are not approximately normally distributed. |
| Robust regression | Continuous | Usually continuous but nominal can be used in addition | Describes the relation between response and predictors. Useful for detecting outliers and highly influential observations. Fits main portion of data, giving outliers little or no weight. |
| Generalized least-square regression | Continuous | Usually continuous but nominal can be used in addition | Describes the relation between response and predictors. Errors can be correlated and variances of errors may be different. Useful when observations of response variable are not independent or not measured with equal accuracy. |
| Tobit regression | Part continuous Part nominal | Usually continuous but nominal can be used in addition | Describes the relation between response and predictors. Useful when response variable is censored below a detection limit. |
| Logistic regression | Nominal | Usually continuous but nominal can be used in addition | Predictors probability of response being in one category or another. |
| Contingency tables | Nominal | Nominal or ordinal groups | Describes the relation between nominal response and nominal or ordinal predictors. |
| Ridge regression | Continuous | Usually continuous but nominal can be used in addition | Describes the relation between response and predictors. Useful when predictors exhibit high multicollinearity. Regression coefficients are biased. |
| SPARROW | Continuous | Continuous | Nonlinear regression method to predict water quality for a stream reach based on spatially referenced predictors. The predictors are a function of point and nonpoint sources and their location relative to the stream reach. |
| Artificial neural networks | Continuous or nominal | Continuous or nominal | Flexible nonlinear nonparametric model for prediction. Any underlying model or functional relations may be impossible to extract. Data-in/predictions out black box. |

Highway- and urban-runoff studies have generally been limited to ordinary least squares (OLS) and generalized least squares (GLS) regression techniques. There are, however, a number of linear and nonlinear regression methods that may be appropriate for interpretation of local, regional, and national highway-runoff and urban-stormwater data when the classification of variables and the structure of the data violate the design assumptions of the OLS and (or) GLS methods.
Another possibility is to use transformation methods to increase the linearity of relations between variables. Transformations are also used to reduce or eliminate problems of nonconstant variance (Tasker G. D., Granato G. E., 2000).

The OLS model, however, requires several restrictive assumptions about the parameters and errors in the model, which are often not valid for hydrologic data. To fully implement OLS regression, one must demonstrate that the response variable is linearly related to predictors, that the data used to fit the model is representative of the population of interest, that the variance of the residuals is constant, that the residuals are independent, and that the residuals are normally distributed (Helsel D.R., Hirsch R. M., 1992; quoted by Tasker G. D., Granato G. E., 2000).

In using OLS regression, one assumes that observed values of the response variable are independent, resulting in independent residuals. In cases where this assumption is not approximately true, estimated generalized least-squares regression (GLS) can be used if the dependence of the residuals can be estimated from the data.

There are a number of difficulties in applying regression equations:

- They are notoriously difficult to apply beyond the original data set from which the relationships were derived (Driscoll E. D. et al., 1990; quoted by Donigian A. S. et al., 1990). Therefore they are subject to very large potential errors when extrapolated to different conditions.

- Obtained event mean concentrations are poorly or not correlated with runoff flow or volume (Huber W. C., 1980; EPA, 1983, Driscoll E. D. et al., 1989; quoted by Donigian A. S. et al., 1991).

- The validity of regression models is affected by curvature, outliers, and high leverage points. Outliers, observations (or a subset of observations) that appear to be inconsistent with the remainder of that set of data, are fairly common in hydrologic data (Hirsch R. M. et al., 1993; quoted by Tasker G. D., Granato G. E., 2000). Outliers should be checked for possible gross errors in measurement or mistakes in recording the observations. Rejecting them out of hand is not a prudent practice.

- The measurement of predictors used to estimate the regression coefficients using significantly different methods with different measurement errors.
  For example, consider a regional regression study covering several states in which each state uses a different method to estimate average annual daily traffic flow,*T*. In these cases, it is necessary to adjust the regression model for errors in the predictors (Tasker G. D., Granato G. E., 2000).

Information about the suitability of a model can be provided by regression statistics. Therefore the correlation coefficient should be known to determine whether the resulting equation explains much of the variance in the data (Tasker G. D., Granato G. E., 2000).

Generally, regression analysis should include visual analysis of scatter plots, and examination of the regression equation, evaluation of the method design assumptions, and regression diagnostics (Tasker G. D., Granato G. E., 2000).

Representative models are: FHWA (Kobinger et al.,1981; Driscoll et al., 1990), State departments of transportation in Washington (Chui et al., 1982), California (Kerri et al., 1985), Texas (Irish et al., 1998), Ontario Ministry of Transportation (Thompson et al., 1996; 1997), USGS regression method (Tasker and Driver, 1998) (quoted by Donigian A. S. et al., 1990).

Some of them are represented below:

*Multiple Linear Regression equation used by the California Department of Transportation (Caltrans):*

Equation for the estimation of the event mean total copper concentration:

$$\mu g / L = e^{2.944-(0.233\bullet X_1)+(0.127\bullet X_2)-(0.247\bullet X_3)+(0.077\bullet X_4)+(5.66\bullet X_5)}$$

In which:

X1= event rainfall [cm]
X2= antecedent dry period [days]
X3= cumulative precipitation [cm]
X4= drainage area [ha]
X5= AADTx$10^6$ [vehicles/day]

*U.S. Geological Survey Regression Equations for Estimating Pollutant Load*

Driver and Tasker in 1990 developed thirty-four multiple regression models (mostly log-linear) of storm runoff constituent loads and storm runoff volumes and thirty-one models of storm runoff event mean concentrations, identified as the “USGS method“. They used ordinary and generalized least-squares regression methods to generate the equations.

The equations were developed for determining pollutant-loading rates based on regression analyses of data from sites throughout the USA, the Nationwide Urban Runoff Program (NURP) study in the Washington, D.C., area and the national NURP data analysis during the 1970’s and 1980’s.
The two most significant explanatory variables were total storm rainfall and total contributing drainage area. Impervious area, land use, and mean annual climatic characteristics were also significant explanatory variables in some of the models.

A big advantage to most other methods is that the equations do not require preliminary estimates of event mean concentrations.
Unfortunately, for the aspect of highway runoff prediction, these models do not include transportation related parameters.
However, Young and others, in 1996, identified these equations as applicable for estimating highway-runoff quantity and quality.

Equation for Estimating Storm Runoff Loads and Storm Runoff Volumes:

$$Lp = \left[ \beta_0{}' \bullet X_1{}^{\beta_1} \bullet X_2{}^{\beta_2} \bullet .....X_n{}^{\beta_n} \bullet BCF \right]$$

In which:

$L_p$ = Estimated storm runoff load or volume [kg or m³]

$X_1$ = Total contributing area [m²]

$X_2$ = Impervious area [%]

$X_3$ = Total storm rainfall [mm]

$X_4$ = Storm duration [min]

$X_5$ = Maximum 24-h precipitation intensity that has a 2 years recurrence interval [mm/h]

$X_6$ = Mean annual rainfall [mm]

$X_7$ = Mean minimum January temperature [C°]

$X_8$ = Industrial land use [%]

$X_9$ = Commercial land use [%]

$X_{10}$ = Residential land use [%]

$X_{11}$ = non urban land use [%]

$\beta_0{}'$ = Regression constant

$\beta_1$ = Regression coefficient for the total contributing area

$\beta_2$ = Regression coefficient for the impervious area

$\beta_3$ = Regression coefficient for the total storm rainfall

$\beta_4$ = Regression coefficient for the storm duration

$\beta_5$ = Regression coefficient for the maximum 24-h precipitation intensity, 2y

$\beta_6$ = Regression coefficient for the mean annual rainfall

$\beta_7$ = Regression coefficient for the Mean minimum January temperature

$\beta_8$ = Regression coefficient for the percentage of industrial land use

$\beta_9$ = Regression coefficient for the percentage of commercial land use

$\beta_{10}$ = Regression coefficient for the percentage of residential land use

$\beta_{11}$ = Regression coefficient for the percentage of non urban land use

BCF = Bias correction factor

The BCF is a multiplicative term included in regression models which are formulated in the logarithmic space and then transformed into original units; it is designed to prevent underestimation of concentrations or loads as an artifact of transformation.
Several methods may be used to estimate a BCF. A nonparametric method developed by Duan (1983) generally provides reasonable estimates for a BCF that is not affected by the structure of the data (Driver N. E. Tasker G. D., 1990, Helsel D. R., Hirsch R. M., 1992; quoted by Tasker G. D., Granato G. E., 2000).
Driver and Tasker (1990) used the Duan method to estimate BCF for storm-runoff loads, volumes, and selected constituent concentrations from NURP data and calculated BCF's that ranged from about 1.1 to 2.8 for their runoff models (Tasker G. D., Gratano G. E., 2000).

*Equation for Determining Mean Seasonal or Annual Loads*:

There exist several equations provided by the U.S. Geological Survey for calculating mean seasonal and annual loads. The annual or seasonal load is determined by first calculating the mean load for a storm. For the equation mentioned below, a storm event is defined as event in which the total rainfall reaches at least 1.3 mm and two storms are separated by at least six hours.
For obtaining the mean annual load, the mean event load has to be multiplied with the mean number of storms per year.
The analysis is limited to drainage areas between 0.017 km² and 1.37 km².
It is necessary to use another method for drainage areas much beyond these limits.

Equation:

$$L_m = \left[ 10^{\left[\beta_0 + \beta_1 \bullet \sqrt{\left(\frac{A}{2.59}\right)} + \beta_2 \bullet A_1 + \frac{\beta_3 \bullet H_{MAR}}{25.6} + \beta_4 \bullet \left(T_J \bullet \left(\frac{9}{5}\right) + 32\right) + \beta_5 \bullet X_2\right]} \bullet BCF \right] \bullet 0.45636$$

In which:

$L_m$ = Estimated mean load for a storm [kg]
$A$ = Drainage area [km²]
$A_I$ = Impervious area [km²]
$H_{MAR}$ = Mean annual rainfall [mm]
$T_J$ = Mean minimum January temperature [C°]
X2 = Indicator coefficient which is 1 if industrial land use plus commercial land use is greater than 75 percent
BCF = Bias correction factor

$\beta_0$ = Regression constant
$\beta_1$ = Coefficient for drainage area
$\beta_2$ = Coefficient for impervious area
$\beta_3$ = Coefficient for mean annual rainfall
$\beta_4$ = Coefficient for mean minimum January temperature
$\beta_5$ = Coefficient for X2

### 4.2.8. Artificial neural networks

The simplest description of a neural network is that it is an artificial, a computational, copy of a brain (Iyengar S. S., Kashyap R. L., 1991; quoted by Mc Manus I., 2002). Neural networks work by attempting to mimic the way in which human (and animal) brains operate (Zurada J. M., 1992; Iyengar S. S., Kashyap R. L., 1991; Mehrotra K. et al., 1997; quoted by Mc Manus I., 2002).

From a mathematical point of view ANN is a complex non-linear function with many parameters that are adjusted (calibrated, or trained) in such a way that the ANN output becomes similar to the measured output on a known data set (STOWA, 2000)

A neural network is comprised of a set of basic interconnected blocks called nodes. The interconnections between nodes are called weights and each weight possesses certain strength. The strength of the weight determines the importance of the linkage.
Nodes receive input from other nodes or external sources, sum this input, apply an activation function and output the result. In this way the input signals propagate through the neural network with some of the nodes acting as outputs from the network (Iyengar S. S. and Kashyap R. L., 1991; quoted by Mc Manus I., 2002).

There are a wide range of activation functions that can and have been used for neural networks and which can be divided into two main groups: discrete and continuous.
Discrete activation functions (eg. step function) are often used in classification problems where the neural network is acting to classify the input signals as a specific item.
Continuous activation functions are used where the output needs to be 'soft'. For example, in controlling an aircraft one obviously wants the control surface deflections to be able to take a wide range of values rather than only two possible values (Mc Manus I., 2002).

The way in which the input signals propagate throughout the network is determined by the structure of the neural network.
There are a wide range of structures from neural networks ranging from networks where every node is connected to every other node to highly structured networks where nodes are only connected to specific nodes.
The most common neural network structure used is the Feedforward Neural Network (FNN). In a FNN the neural network is as is standard partitioned into input, hidden and output layers (Zurada J. M., 1992; quoted by Mc Manus I., 2002).This means that data flows from the input layer to the first hidden layer, then to the second hidden layer etc. No data flows from, for example, the second hidden layer to the input layer.
Typically in this structure data only ever flows to the very next layer in the neural network. This structure although very limited is very powerful and FNN have been used in the full spectrum of neural network applications from classification problems to control problems (Mc Manus I., 2002; quoted by Mc Manus I., 2002).

The learning or training process for a neural network works by modifying the strengths of the interconnections between nodes. The process requires input data

and an indication of the validity of the output data generated by the neural network (Mc Manus I., 2002).
There are a wide range of training methods available with the training method typically linked to a specific neural network structure. Every training algorithm, although different, works on the same basic principle. This principle is that the error between the current output and the desired output is used to modify the weights within the neural network (Zurada J. M., 1992, Mehrotra K. et al., 1997; quoted by Mc Manus I., 2002).

A major pitfall is present in the training of neural networks that becomes apparent if a neural network is trained too much using the same sets of data. This situation is known as overtraining and results in the neural network memorising the right output set for each input (Mehrotra K. et al., 1997; quoted by Mc Manus I., 2002).
The solution to the problem of overtraining is to use two sets of data (Mehrotra K. et al., 1997; quoted by Mc Manus I., 2002). One set is used for training while the other set is used for validation purposes.

After each training cycle the error between the neural network output and the desired output is calculated using the validation set. Training is continued while this error continues to decrease (Mc Manus I., 2002).

Unsupervised neural networks often incorporate self-organizing features, enabling them to find unknown regularities, meaningful categorization and patterns in the presented input data (STOWA, 2000).

Neural networks are highly flexible and, as such, are capable of performing a very wide range of tasks. They have been applied to tasks including image restoration, pattern recognition, optimization and control. Essentially there are no limitations on what a neural network is capable of performing due to its ability to learn
(Mc Manus I., 2002).
Most logical relationship can be generalized and approximated by ANN’s with reasonable accuracy if a set of input output data with high variability is available (STOWA, 2000).

The success of the application of artificial neural networks depends mainly on the amount of available relevant data and on the experience of a modeler, leaving a lot to the "art of modeling".
Some types of neural networks are given in Table 22.

**Table 22:** Neural network applications and types (Zurada J. M., 1992**;** quoted by Mc Manus I., 2002)

| Applicaton | Neural Network |
|---|---|
| Classification, feature detection | Single/multilayer perception network, continuous or discrete activation function, typically feedforward structure |
| Pattern recognition | Multilayer perception network, continuous or discrete activation function, feedforward structure |
| Expert system | Multilayer perception network, continuous or discrete activation function, feedforward structure |
| Optimization | Single/multilayer perception network, continuous or discrete activation function, typically feedforward structure |
| Image reconstruction | All types of neural networks and activation functions, although feedback methods are commonly used |
| Control applications | Multilayer feedforward and feedbackward neural networks, typically continuous activation functions |

## 4.3. The Austrian Approach

For defining treatment measures for polluted runoff water, the Austrian Bundesministerium für Verkehr, Innovation und Technologie (BMVIT) designed the RVS 3.03 (guidelines and regulations for road construction) to protect roadside water bodies. Accordingly, highway runoff water should be returned in the water cycle without causing any harm.
The RVS 3.03 defines three normal cases: roads on dams with roadside infiltration, roads in trenches with roadside swales, or roads with gutters passing the water to a retention basin subsequently passing it to receiving water or to infiltration.
The way of treating runoff water according to the RVS 3.03 is shown in Figure 11.

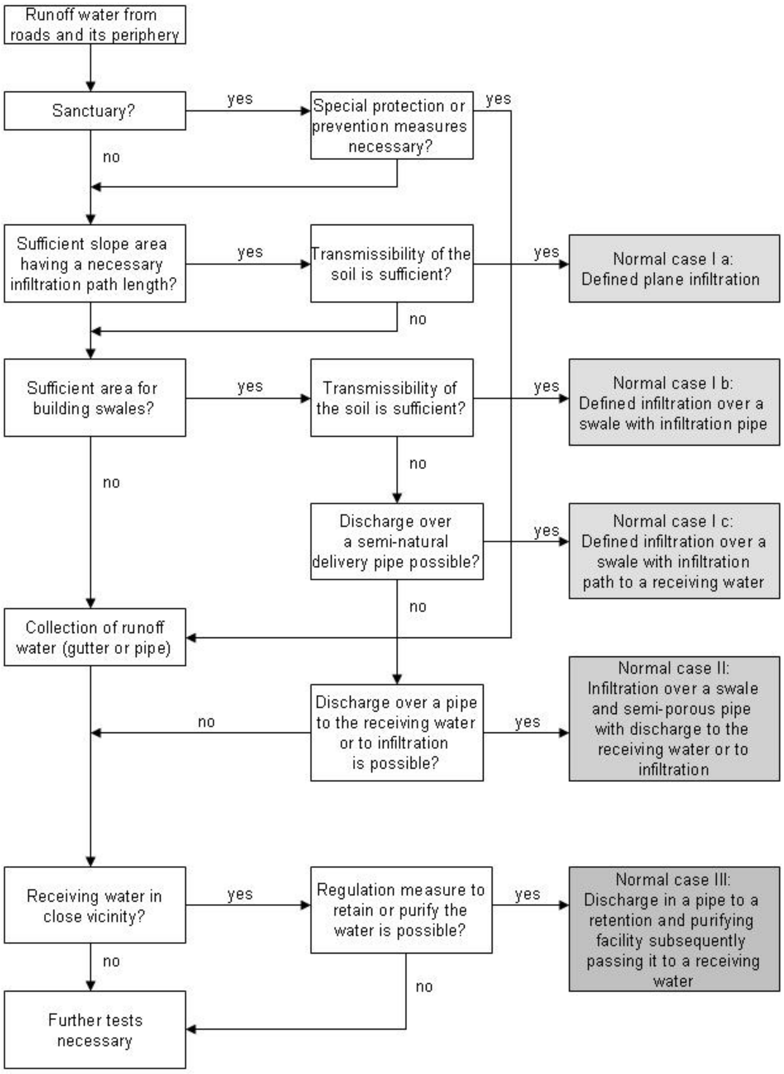


**Figure 11:** Normal cases for runoff water treatment (BMVIT, 2002)

To help planners implementing the RVS 3.03 a computer program has been developed. It is presented below.

*Program "Wasser"*

In Austria, actions causing negative impacts on the aquatic environment need a legal approval. If runoff water discharged in the aquatic environment causes a "more then negligible" alteration of water quality, the water has to be treated according to the best available technology and the conservation of the ecological operability.

Therefore, according to the RVS 3.03, the computer program "Wasser" has to be applied.
The program was developed to provide an objective and comprehensible decision frame for planers, surveyors and representatives of the public authority, but does not substitute the evaluation of the public authority.
It is a tool for planning preventive measures for water bodies and allows an order of priorities for these measures. The aim has been laid on a competent correlation between presently valid parameters and defined normal cases.

For using the program the planer should has to be familiar with the:

- Operating system "Windows"
- RVS 3.03
- Austrian laws, guidelines and standards

For input data, general and special parameters of the highway and its periphery have to be known by section.
One out of three normal cases has to be chosen: roads on dams with roadside infiltration, roads in trenches with roadside swales, or roads with gutters passing the water to a retention basins subsequently passing it to a receiving water or to infiltration.

For each normal case certain parameters are required. These parameters are related to:

- Traffic
- Construction
- Maintenance
- Meteorology
- Use
- Preload
- Soil
- Groundwater
- Drainage
- Receiving watercourse
- Roadside

Through parameter variation the user is able to optimize results. The output of the program is a clear definition of measures which have to be taken to avoid negative impacts on the environment.
The program is going to be updated when necessary.

## 4.4. Important Investigations in the Field of Runoff Modeling

### 4.4.1. An evaluation of the use of runoff models to predict average annual runoff from urban areas (Mandel, Caraco and Schwartz, 1997)

Ross Mandel, Debbie Caraco, and Stuart S. Schwartz evaluated of using runoff models to predict average annual runoff from urban areas in 1997.
They were commissioned to update the estimates of chemical contaminant loads in urban runoff in the Chespeake Bay Basin for the revision of the Chespeake Bay Toxics Loading and Release Inventory. The average annual chemical contaminant loads in urban runoff in the Chesapeake Bay Basin for the inventory where primarily observed by Olsenholler in 1991. She used a loading function approach, in which the chemical contaminant load was calculated as the product of the average annual runoff volume and an event mean concentration for each chemical contaminant. The event mean concentrations were derived from data collected for the National Urban Runoff Program, 1978-1982. Average annual runoff was estimated using the Simple Method.

Mandel, Caraco and Schwartz tested several runoff models to determine which model would fit best for estimating average annual chemical contaminant loads for urban areas. Tested models where the Simple Method, the Chesapeake Bay Program Watershed Model based on the Hydrologic Simulation Program-Fortran (HSPF), the Curve Number Method as implemented in the National Engineering Handbook, the Curve Number Method as implemented in Urban Hydrology for Small Watersheds.

The best way to evaluate runoff models would have been to compare their predictions against empirical data. In the original conception of this project, the runoff models were to be evaluated by comparing the annual runoff predicted by the models for a gaged, urbanized watershed with the annual runoff calculated from the gage record by base flow separation. It proved impossible to make such a simple comparison, because there existed no gaged watershed in the Chesapeake Bay Basin which was completely urbanized and had available all of the land use and soil data necessary to run the models.
Nevertheless, using the land use, soil, and stream flow data available for these three watersheds, the runoff models were compared in the following manner:
First, a computer program was developed to estimate average annual runoff from stream gage records using standard base flow separation techniques.
Then, the predicted runoff from the gaged watersheds was calculated using the EPIC and GWLF models with both distributed and lumped urban curve numbers, and the predictions were compared to the runoff estimates from base flow separation.
Finally, the Simple Method, the Watershed Model, and the curve number models were used to calculate average annual runoff from the strictly urban areas of the three watersheds.
The performances of the models were then evaluated according to three criteria: (1) an indirect comparison with runoff estimate derived from base flow separation,

(2) theoretical soundness of the modeling approach, and (3) availability of input data and ease of implementation.

The results of this evaluation were:

When all models were used to calculate average annual runoff only from urban areas, it was found that all of the models that calculated runoff from pervious and impervious areas separately (the distributed curve number models, the Simple Method, and the HSPF Watershed Model) had similar predictions, in contrast to the lumped curve number models. The estimate of runoff from the base flow separation could not be used to discriminate between the distributed curve number models, the Simple Method, and the Watershed Model.
The use of curve numbers for impervious surfaces is not recommended, since conceptually, a curve number is a measure of the infiltration capacity of the soil. Therefore, the Curve Number Procedure should not be used on urban land.
Average annual runoff from urban pervious and impervious land already was calculated using the HSPF Watershed Model. Therefore, the authors recommend using this information to calculate the average annual runoff from urban land. The runoff could also be easily calculated from Watershed Model output using the Simple Method.
As the Chesapeake Bay Program already uses the HSPF Watershed Model for calculating nutrition loads in the Chesapeake Bay Basin, it would be a natural extension of the use of this model to use its output to calculate chemical contaminant loads in runoff from urban areas. In fact, it appeared to them, that some explanation would be necessary if the model was not used to calculate average annual runoff for the estimation of chemical contaminant loads.
The authors recommended the following steps for the use of a model on the Chesapeake Bay Basin:

- Use HSPF Watershed Model estimates of annual runoff for urban pervious and impervious areas to calculate the estimates of average annual runoff from urban areas necessary for estimating chemical contaminant loads in urban runoff.
- Improve the representation of urban land uses and impervious areas in the GIS land use layers supporting the Watershed Model.
- Use the runoff estimates from the Simple Method to help guide any recalibration of the runoff from urban areas in the Watershed Model.

### 4.4.2. Techniques for predicting total phosphorus in urban stormwater runoff at unmonitored catchments (May and Sivakumar, 2004)

The paper investigated the applicability of using artificial neural network (ANN) and multilinear regression models to predict urban storm water quality at unmonitored catchments. Models were constructed using logarithmically transformed environmental data. Violations of the assumption of data independence lead to the inclusion of insignificant variables when a straightforward stepwise regression was applied.
The data used in this study consisted of water quality, climatic and geographic

data collected by the US Environmental Protection Agency and US Geological Service in the 1970's and 1980's.

May and Sivakumar analyzed total phosphorus as dependent variable measured as load or concentration. The independent variables used in the analyses that had values for every storm event were percentage of residential land use, percentage of non urban land use, percentage of commercial land use, percentage of industrial land use, impervious area, drainage area, total event rainfall, and mean annual rainfall. Not included in the study was the maximum 24-hour precipitation intensity that has a 2-year recurrence interval.

The main objective of the study was to model storm events at typical urban watersheds. Therefore catchments with drainage areas larger than 3000 hectares, proportions of agricultural land use greater than 50%, proportions of industrial land use greater than 50%, population densities greater than 130 people per hectare or with detention basins upstream of the sampling point were removed.
A base ten logarithmic transformation was then applied to the dependent variables and independent variables. A constant was added to variables that had zero values in order to scale the data into a suitable domain prior to logarithmic transformation.
Logarithmic transformation of the data ensured that large, potentially outlying values did not bias the optimization of calibration coefficients. The other advantage of the logarithmic transformation was that it enabled the construction of nonlinear, non-additive models using a simple multilinear regression procedure.

Regression models were initially constructed using data from 754 storm events. Both the standard error of estimate and average absolute percentage error were then used to compare predictions from a series of regression models, ranging from a simple one variable model to more complicated multivariable models.
The dependent variable producing the minimum error was analyzed in more detail. Since multiple storm events were monitored at almost all of the catchments in the data set, the majority of independent variables did not satisfy the assumption of data independence. All analyzed independent variables, besides total storm rainfall, had constant values for a given catchment.
Variables leading to an increase in either of the error measures were typically considered to be insignificant and removed from the model.

A second regression analysis was undertaken on a regional subset of the data. Catchments with mean annual rainfalls between 500 and 1000 millimeters were separated from the total data set, in accordance with the study by Driver and Tasker (1990). The variables found to be significant in the study by Driver and Tasker were analysed along with the variables found significant in the cross-validated, regression analysis of the larger data set. The variables were entered into the regression model in order of their anticipated significance. Cross validation using 10% of the data for validation was used to verify the significance of the independent variables. Variables not reducing the validation set errors were typically considered to be insignificant and removed from the model.

ANN models were constructed using the dependent and independent variables found significant in the regression analysis. The "pruning method"
based upon the sensitivity analysis of constructed ANN models was perceived

to be an excessively time consuming way to select ANN input variables.
Feed forward, back propagation neural networks were optimized using the normalized cumulative delta rule-learning algorithm.
Ten ANN models were created, using a different 10% of the data as a test set each time. For each of the ten test sets, the mean square error was calculated for each weight update. An average of the mean square errors for the ten test sets was calculated for each weight update. The number of weight updates corresponding to the lowest average test set error was defined as the stopping point.
The results from the cross validation analysis showed that only mean annual rainfall and the percentage of residential land use lead to improvements in both the standard error of estimate and absolute average percentage error. Therefore, only these two variables were deemed to be significant on the 965 data point set.

Regression equations were then developed on the regional subset consisting of 374 storm events. Results from the analysis of the larger data set justified the use of total phosphorus concentration as the dependent variable.
The variables found to be significant in the study by Driver and Tasker were total storm rainfall, total contributing drainage area, impervious area and maximum 24 hour precipitation intensity that has a 2 year recurrence interval. These variables were combined with mean annual rainfall and the percentage of residential land use. Theoretical considerations combined with information extracted from stepwise regression models determined the order of variable entry into the final regression model.
The cross validation analysis isolated drainage area as the only variable that did not improve either the average absolute percentage error or standard error of estimate. Therefore, drainage area was removed from the model. Impervious area and total event rainfall only reduced one error measure. However, when impervious area and total event rainfall were added together, both error measures reduced. Total event rainfall was also the only available variable in the data set capable of describing storm-to-storm variability at a site. Therefore, total event rainfall and impervious area were left in the model.
Regression and ANN models were compared on the regional subset. The results suggest that regression and ANN models constructed on the regional subset had very similar accuracies.

The regression model constructed using regional data was more accurate than the model constructed using all the available data. It was anticipated that a more complicated combination of relationships between variables was present within the larger data set. The lack of significant inputs restricted the ability of the regression model to replicate the complicated relationships.
Data limitations in the current study were exacerbated by violations of data independence for the bulk of variables. Instead of analyzing a large dataset equal to the number of storm events, a smaller subset equal to the number of catchments was effectively analyzed. The effective size of the data set was approximately an order of magnitude smaller than the actual data set size. This made the modeled relationships tenuous, thereby decreasing the likelihood that ANN and regression models would accurately predict water quality at unmonitored sites. Inaccurate predictions are inevitable without the inclusion of a significant descriptor of storm-to-storm variability at a single site. Total event rainfall was not able to accurately define such variability. The comparable accuracies of the regression and ANN models

constructed on the regional dataset inferred that the ANN model was not more adept at defining storm-to-storm variability at a site. This inferred that ANN models constructed on the total dataset would probably require additional storm descriptors, which were generally unavailable at a large proportion of the studied catchments. The inclusion of additional storm descriptors would have further reduced the size of the dataset, thereby limiting the applicability of applying ANN. The construction of an ANN model on the entire dataset using all available variables might produce more accurate results. However, the potential inclusion of superfluous variables was perceived to reduce the accuracy of the final models and make it difficult to isolate significant variables. The identification of additional synergistic relationships between the existing variables was considered to be overly time consuming compared to the benefit extracted from the identification of such relationships.

It was found that models using concentration as the dependent variable were more accurate than those using load. This was an important finding considering that the majority of current computer simulation models require estimates of concentration rather than load. When load was used as the dependent variable, the regression models were forced to simulate the known relationship existing between load and runoff volume, leading to an unnecessary increase in the complexity of the models. However, if the volume of runoff is not accurately known, load models might provide better estimates of the total load than the concentration models. Regression models constructed using the total data set were less accurate than those constructed on the regional subset of data. The reduced data complexity combined with the use of additional variables contributed to the increased accuracy of regression models constructed on the regional subset.
Violation of the assumption of data independence significantly reduced the applicability of constructing models on the larger data set. Total event rainfall was the only variable capable of describing storm-to-storm variation at a single catchment. However, total event rainfall was deemed to be insignificant on the larger data set. This meant that the effective size of the larger data set was too small to successfully apply ANN. Even though regression and ANN models yielded similar predictions, regression modelling was considered to be a more applicable approach. The simple form of regression models made them quick to construct and less likely to over fit the data.

### 4.4.3. Impact of annual daily traffic on highway runoff pollutant concentrations (Kayhanian, Singh, Suverkropp and Borroum, 2003)

The California Department of Transportation (Caltrans) is engaged in a multi-year program studying the environmental effects of storm water quality from transportation facilities, and in this course it is characterising highway runoff in California. The information presented in this paper is based on a four-year highway storm water runoff characterization study carried out in the rainy seasons between 1997 and 2001.
The objective of the study was to evaluate correlations between AADT and storm water runoff pollutant concentrations generated from the Caltrans highway sites.

Therefore, representative highway sites and storm events where selected to represent the full range of physical parameters. During four years, 83 highway sites were monitored. During storm events producing at least 2.54 mm of rainfall (7.62 mm in Northern California) up to 50 samples were obtained to capture a representative composite sample during each event. The results of the analysis of the samples were assumed to represent the event mean concentration for runoff for a given rainfall event. The data has been imported in a database containing the main tables sample description (laboratory results, analytical methods, date information), event description (start and end time, maximum intensity, antecedent dry period of precipitation; total flow volume, peak flow rate, and start and end time of runoff), and site description (location, physical characteristics). The database was used to extract all information for statistical analysis. Data sets containing non-detects were treated regression on order statistics (ROS) developed by Shumway (2002).

Multiple linear regression (MLR) and analysis of covariance (ANCOVA) were used to address the impact of AADT on pollutant concentrations. The distributions of runoff quality data for each constituent were evaluated for approximate normality using normal cumulative probability plots of untransformed and log-transformed data. The transformation providing the best $R^2$ regression statistic was selected as the appropriate starting point for additional analysis. The distributions of other continuous predictor variables (precipitation factors, antecedent dry periods, AADT, and contributing drainage area) were evaluated for approximate normality by inspection of cumulative probability plots, and were transformed to natural logarithms or cube roots. MLR and ANCOVA methods were used to evaluate the effect of precipitation factors, antecedent conditions, AADT, contributing drainage area, and surrounding land use on each constituent.

Because the origin of cadmium, copper, lead, zinc, oil, and grease can be easily related to traffic, a correlation of these pollutants and the AADT was expected.

However, oil and grease were the only pollutants, for which the average concentration had a strong correlation with the AADT and which, quantitatively, can be related to transportation activity.

On the other hand, pesticides, nitrogen and phosphorus compounds are expected to have little or no correlation with AADT.

Several studies performed by Chui (1982), Stolz (1987), or Driscoll (1990) were unable to confirm strong correlations between pollutant concentrations in highway runoff and AADT. Others, like Dorman in 1988,or Mc Kenzie and Irwin in 1983 regarded the correlations between the AADT and some constituents as well fitting.

Some investigators like Chui (1982) and Kerri in (1985) suggest that traffic levels during storm events would be a better independent variable for estimating total runoff loads for certain pollutants.

Kayhanian et al. came to the conclusion, that AADT should only be considered as a very general indicator of pollutant concentration when it is used as only predictor. Possible reason for the lack of simple linear correlation could be found in the limitation of accumulation through wind, vehicle turbulence, volatilisation and oxidation as mentioned by Irish in 1995 and Wistrom and Matsumoto in 1999.

Therefore, multiple linear regression models using more than one independent variable were taken into consideration.

Kayhanian, et al. used precipitation factors, antecedent conditions, AADT, and contributing drainage area as effects influencing the accumulation of pollutants.

This multilinear regression model was developed for 33 to 36 constituents with statistically significant adjusted $R^2$ values ranging from 0.085 to 0.648 ($p<0.05$).

All of the observed effects had a statistically significant effect on pollutant concentration and were generally consistent for most pollutants.

As the most important factors were considered:

- Event rainfall:
  Event rainfall had a significant negative correlation to the pollutant concentration. As total event rainfall increases, the concentrations decrease.

- Maximum rainfall intensity:
  Higher rainfall leads mainly to higher pollutant concentration in runoff. It seems as if higher rainfall intensities mobilize particle-associated pollutants, whereas dissolved pollutants tend to have a negative correlation.

- Antecedent dry period:
  In most cases this factor had a significant positive effect on the model, which is consistent with the "build-up" of pollutants during dry periods.

- Cumulative seasonal precipitation:
  Also known as the "first flush effect". It has a negative coefficient in most cases.
  This indicates that the pollutant concentrations are higher in the early wet season and tend to decrease thereafter.

- Drainage area:
  Sites with larger contributing drainage areas tend to show higher pollutant concentrations for particle-associated constituents and lower concentrations for dissolved parameters.

- AADT:
  AADT has a significantly positive slope for all constituents except $NO_2$-N.
  Its importance was assessed by comparing the numbers of constituents significantly affected by AADT and by comparing the relative magnitude of the effects.

AADT, event rainfall, cumulative season precipitation and antecedent dry period have been significant in 73% of all models. Contributing drainage area and rainfall intensity tend to have smaller effects (33-45%).

The ANCOVA method for analysing the effect of predominant land use came to the conclusion that contributing land use appears to significantly effect concentrations of many pollutants in highway runoff, but that additional data is needed to conclusively establish the specific effects for different land uses.

Conclusions for the use of AADT in models:

- In general, the average pollutant concentrations in runoff from urban highways (AADT>30000) were found to be ten times higher then those from nonurban highways (AADT<30000).

- No simple linear correlation could be found between the pollutant event mean concentration and AADT.

- AADT is not the only factor capable of influencing the accumulation and runoff of pollutants from highways.

- AADT, total event rainfall, seasonable cumulative rainfall, and antecedent dry period were significant for more than 70% of constituents evaluated using multiple linear regression analysis. The effects of drainage area and maximum rainfall intensity were smaller and less frequently significant.

- AADT and other factors evaluated in this paper can be used as a practical tool for planning and prioritizing efforts for managing runoff quality in highly urbanized areas. Contributing land use seems to be less important and consistent than AADT and the other parameters evaluated in this paper.

# 5. Testing Models for Water Quality Prediction on Portuguese Conditions

## 5.1. Framework

Chapter five results from a three month lasting stay at the Laboratório Nacional de Engenharia Civil (Portugal), which was so kind to invite me to participate at one of their research projects.
It is part of the Portuguese study “Méthodo de previsão da qualidade das águas de escorrência de estradas em Portugal” (Methods for the prediction of the runoff water quality from Portuguese highways).

The study which the Laboratório Nacional de Engenharia Civil carried out for the Instituto das Estradas de Portugal is part of the overall project called: “Aguas de Escorrência de Estradas. Sistemas para minimização de impactes” (Systems to minimize the impacts of highway runoff water).

This project is divided into four parts:

A) Qualidade das aguas de escorrência de estradas em Portugal (Quality of runoff from Portuguese highways).
B) Méthodo de previsão da qualidade das águas de escorrência de estradas em Portugal (Methods for the prediction of the runoff water quality from Portuguese highways).
C) Análise de sistemas de controlo de derrames acidentais de substâncias tóxicas (Analyze of the control systems of the accidental escape of toxic substances).
D) Directrizes para a definição de programas de monitorização que permitem avaliar a eficácia de sistemas de tratamento (Directives for the definition of monitoring programs to evaluate the efficiency of highway runoff water treatment facilities).

In Portugal, the characterization of highway runoff water quality is needed in the scope of environmental impact studies and for the evaluation of appropriate runoff treatment measures. Therefore, a modeling approach is used.

In this diploma thesis a model which is able to replace the inefficient methods used, until now, to estimate pollutant loads from Portuguese highways is searched.
At present, pollutant loads are obtained by multiplying the estimated AADT by emission factors for different pollutants and then transforming them into loads under help of arbitrary chosen precipitation values.
The emission factors represent an element of uncertainty for the calculation, as in Portugal, they are not standardized, but differ according to their origin (different studies, measurements obtained from sites with different conditions to the site of interest, etc.) (Barbosa A.E., 2003).

## 5.2. Requirements for the Wanted Model

### 5.2.1. Special requirements

Special requirements for a model to use are to be reliable and applicable on the Portuguese situation. It shall be inexpensive and less time consuming in its application.
Because of the complex Portuguese climatic situation, the model also has to be flexible in its use on highly variable hydrologic input data.

Future models should consider the special characteristics of highway runoff and provide an answer to certain discrete phenomena (e.g., the pollution related to a certain storm event) with a certain rank of confidence (Barbosa A.E., Santos D., 2004).

### 5.2.2. General requirements

General model requirements which should be considered in the choice for a model to use in Portugal, are:

- Usability

  The model should work accurate, reliable and less time consuming.

- Costs

  The modeler should minimize the costs for obtaining the information in operation.

- Data requirements (Donigian A.S. et al., 1991)

  The data needed to make the model work. This comprises of input parameters and time series data for the model. It typically includes precipitation (rainfall) and other meteorological information, drainage area, imperviousness, runoff coefficients or other quantity prediction parameters, and (or) quality prediction parameters such as constant concentration, constituent median and coefficient of variation (CV), regression relationships, buildup and wash off parameters, soil/chemical characteristics, partition coefficients, reaction rates, etc.

  The data needed for calibration and verification of more complex models are sets of measured runoff and quality samples (coincident with the input precipitation and meteorological data) with which to test the model.
  Such data often exist, but seldom for the site of interest. If the project objectives absolutely require such data (e.g., if a model must be calibrated in order to drive a receiving water quality model), expensive local monitoring could become necessary.

  Data needs for specific methods are given in Table 23.

**Table 23:** Data needs for various quality prediction methods (Donigian A.S. et al., 1991)

| Method | Data | Potential Source |
|---|---|---|
| Unit Load | Mass per time unit tributary area | Derive from constant concentration and runoff, Literature values |
| Constant concentration | Runoff prediction mechanism (simple to complex)<br>Constant concentration for each constituent | Existing model; runoff coefficient or simple method.<br>NURP; local monitoring |
| Spreadsheet | Simple runoff prediction mechanism<br><br>Constant concentration or concentration range<br>Removal fractions for control | e.g., runoff coefficient, perhaps as function of land use<br>NURP; local monitoring<br><br>NURP; Schueler (1987); local and publications |
| Statistical | Rainfall statistics<br><br><br>Area, imperviousness<br>Pollutant median and CV<br><br>Receiving water characteristics and statistics | NURP; Driscoll et.al.(1989); Woodward-Clyde (1989); EPA SYNOP model<br>NURP; Driscoll (1986); Driscoll et al. (1989); local monitoring<br><br>Local or generized data |
| Regression | Storm rainfall, area, imperviousness, land use | Local data |
| Rating curve | Measured flow rates/volumes and quality EMC's/loads | NURP; local data |
| Buildup | Loading rates and rate constants<br>Street cleaning removals | Literature values*<br>Literature value |
| Washoff | Power relationship with runoff | Literature value* |

*Usually must be calibrated using end-of-pipe monitored quality data

- Operational requirements (Donigian A.S. et al., 1991)

  Documentation: Which should include a user's manual, explanation of theory and numerical procedures, data needs, data input format, etc.
  Documentation of computer models most often separates the many computerized procedures found in the literature from a model that can be accessed and easily used by others.

  Support: Is sometimes provided by the model developer or by a federal agency.

  Experience: Every model must be used a first time, but it is best to rely on a model with a proven track record. However, new methods and models are constantly under development and should not be neglected.

- Logistical requirements (Tasker G. D., Granato G. E., 2000)

  Availability: The availability of hardware and software to implement the model of choice; of trained modelers to manipulate the model if needed, to develop sound input parameters with an understanding of how they are used by the model, and to critically evaluate model results.

  Organizational requirements: Organizational commitment to establish and support a model, and to oversee subsequent applications of the model so that methods and results can be reviewed and accepted as valid, current, and technically defensible; organizational expertise with the model, to apply the model and to review applications of the model to maintain credibility of results.

- Political requirements (Shoemaker L. et al., 1997; quoted by Tasker G. D., Granato G. E., 2000)

  Acceptance: The most successful and sophisticated modeling effort will fail if results are not accepted by the various interest groups and decision makers involved in a project.

  Understanding: The most successful and sophisticated modeling effort will fail, if results are not understood by decision makers.

## 5.3. A Definition of Hydrologic and Demographic Characteristics of Portugal

The Portuguese motorway network consists of 4385 kilometers per lane, extending all over the land. Even though the country, with a dimension of 88.226 square-kilometers and 850 kilometers of coastline, is small in comparison to other European countries, its climatic situation is complex. The causes for these differences are manifold. Main reasons are the different altitudes of the sites, the latitude, the distance to the sea, and the influences of the mayor cities.

For a better understanding of the Portuguese climate, the distributions of average annual climate values observed between 1961 and1990 are given in Figure 12, Figure 13, and Figure 14 (Instituto de Meteorologia, 2004).

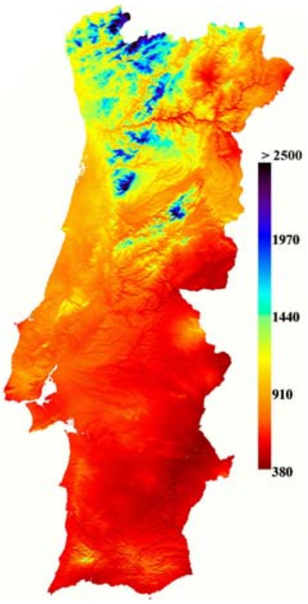


**Figure 12:** Average annual precipitation height in Portugal [mm]

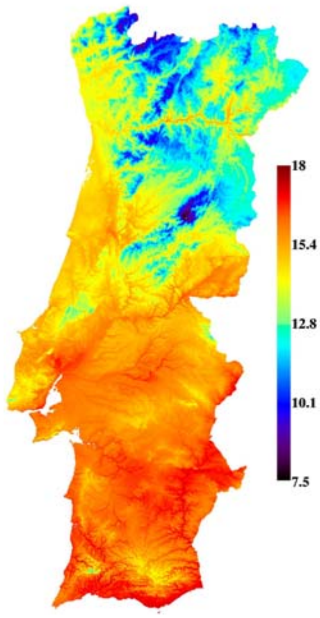


**Figure 13:** Average annual temperature in Portugal [C°]

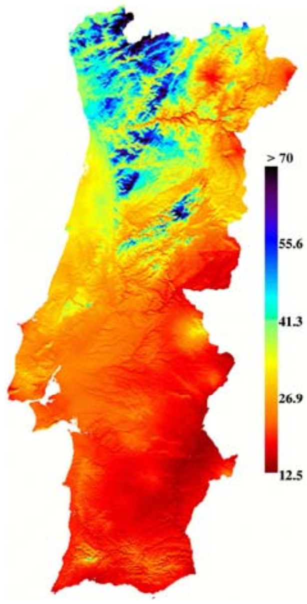


**Figure 14:** Number of days with a precipitation >10mm per year

## 5.4. Data Requirements for Testing the Chosen Models

### 5.4.1. Input data

For input data hydrologic, land use, and traffic related data were available.
From this data, only the AADT has not been used in the following calculations. The input data were provided by Dr. Ana Estela Barbosa.
Two different total yearly average precipitation values for highway A1 and A6 are used because of missing exact local information. Therefore, data from sites nearby were taken.

Input data from in totally 4 Portuguese highways were investigated. They are given in Table 24.

**Table 24:** Input data for testing the chosen models on Portuguese highways (Barbosa A. E., 2004)

| Variables | Units | IP5 | A 1 | A 1 | A 2 | A 6 | A 6 |
|---|---|---|---|---|---|---|---|
| | | | (Minde) | (Alcobaça) | | (Elvas) | (Vila Viçosa) |
| Total impervious area | [m²] | 250 | 26600 | 26600 | 1287 | 4650 | 4650 |
| Total catchment area | [m²] | 250 | 64600 | 64600 | 1287 | 4650 | 4650 |
| Land use | | water | forest | forest | bridge | bushes | bushes |
| Total rainfall volume | [mm] | 6 | 4.1 | 4.1 | 6.8 | 4.6 | 4.6 |
| Storm duration | [min] | 5 | 9 | 9 | 5 | 7 | 7 |
| Intensity of the maximum precipitation during a 24h rainfall | [mm/h] | 51.5 | 54.3 | 54.3 | 46.7 | 44.9 | 44.9 |
| Total yearly average precipitation | [mm/a] | 928.6 | 1157 | 1080.6 | 574.6 | 593.5 | 758.2 |
| Minimum average temperature in January | [C°] | 6.3 | 5.5 | 5.5 | 5.2 | 4.2 | 4.2 |
| AADT | [v./d] | 27448 | 30299 | 30299 | 16344 | - | - |

### 5.4.2. Measured data for comparison

The measured data were taken from sampling programs carried out by Dr. Ana Estela Barbosa.
For observing regional differences, sampling sites were chosen all over the county.
In the following tables, the sites are listed according to their situation, from the north to the south. The term A stands for highway, the term IP for main road.

The origin of the measured data can be specified exactly for highway A1, A2, and A6.

Place of sampling:

- A1: Entry of a retention pond near Fatima
- A2: Collector (Diameter: 20 cm) of a drainage system of a bridge passing the Sado River near Alcácer do Sal
- A6: Entry of a retention pond for the pre-treatment of runoff water near Borba
- IP5: Dyke near Aveiro

Data collection was effectuated by an automatic sampling equipment manufactured by ISCO, which took samples every 15 minutes during a storm event, and equipment for measuring the flow (model 730, ISCO). Also, the event rainfall depth was measured.

Samples were taken from highway A1 for 6 storm events between May the 3rd and 23rd, 2002 and from highway A2 for 3 storm events between April the 14th and 25th, 2003.
For the main road IP5 (5 storm events) and highway A6 (6 storm events) the period of sampling is uncertain. The sampling of highway A6 was carried out in summer 2004.

The mean concentrations and mean annual loads stated in Table 25 and Table 26 were obtained by these sampling programs.

**Table 25:** Mean concentrations from Portuguese highways (Barbosa A. E., 2004)

| Constituent | IP5 | A1 | A6 | A2 |
|---|---|---|---|---|
| | [mg/l] | [mg/l] | [mg/l] | [mg/l] |
| TSS | 44.7 | 84.5 | 19.635 | 7.4 |
| Zn | 0.205 | 0.159 | 0.346 | 0.208 |
| Pb | 0.005 | 0.012 | 0.0018 | 0.004 |
| Cu | 0.014 | 0.034 | 0.00813 | 0.033 |
| Fe | 1.482 | 0.724 | 0.353 | 0.333 |
| Cr | 0.004 | - | - | - |
| Ni | 0.004 | - | - | - |

**Table 26:** Mean annual loads from Portuguese highways (Barbosa A. E., 2004)

| Constituent | IP5 | A1 | A6 | A2 |
|---|---|---|---|---|
| | [mg/m$^2$*a] | [mg/m$^2$*a] | [mg/m$^2$*a] | [mg/m$^2$*a] |
| TSS | 38427 | 70453 | 14942 | 4256 |
| Zn | 177 | 133 | 263 | 120 |
| Pb | 5 | 10 | 1 | 2 |
| Cu | 12 | 29 | 6 | 19 |
| Fe | 1275 | 604 | 269 | 192 |

## 5.5. Comparison of Austrian and German Limit Values and Average Pollutant Concentrations with Measured Data from Portuguese Highways

Mean pollutant concentrations from Portuguese roads, as already mentioned in chapter 5.4.2, are stated in Table 27.

**Table 27:** Mean concentrations from Portuguese roads (Barbosa A. E., 2004)

| Constituent | IP5 | A1 | A6 | A2 |
|---|---|---|---|---|
| | [mg/l] | [mg/l] | [mg/l] | [mg/l] |
| TSS | 44.7 | 84.5 | 19.635 | 7.4 |
| Zn | 0.205 | 0.159 | 0.346 | 0.208 |
| Pb | 0.005 | 0.012 | 0.0018 | 0.004 |
| Cu | 0.014 | 0.034 | 0.00813 | 0.033 |
| Fe | 1.482 | 0.724 | 0.353 | 0.333 |
| Cr | 0.004 | - | - | - |
| Ni | 0.004 | - | - | - |

They are compared to several legal limits.
Legal limits which are applicable on road runoff are, e.g., the “Allgemeine Abwasseremissionsverordnung” (AAEV) (BMLF, 1996) (limits for sewage emissions) and the “Allgemeinen Güteanforderungen für Fliessgewässer” (1991) (AGA) (general quality standards for rivers) in North Rhine- Westphalia. Furthermore, the UVPVwV (1995), a guideline for the evaluation of impacts in water bodies can be consulted in the scope of environmental impact studies.
The strictest values provide the “Trinkwasserverordnung” (TWV) (BMLF, 2001) (limits for drinking water).

A summary of different limit values is outlined in Table 28.

**Table 28:** Different Austrian and German pollutant limits (BMSSG, 2001; BMLF, 1996; MU-NRW,1991; UVPVwV, 1995)

| Constituent | TWV Austria, 2001 | AAEV Austria, 1996 | AGA Germany, 1991 | UVPwV Germany, 1995 |
|---|---|---|---|---|
| | [mg/l] | [mg/l] | [mg/l] | [mg/l] |
| TSS | - | 30 | - | - |
| Zn | - | 2 | 0.3 | - |
| Pb | 0.01 | 0.5 | 0.02 | 0.05 |
| Cu | 2 | 0.5 | 0.04 | 0.05 |
| Fe | 0.2 | 2 | 2 | - |
| Cr | 0.05 | 0.5 | 0.03 | 0.05 |
| Ni | 0.02 | 0.5 | 0.03 | - |

Comparing the mean pollutant concentrations from Portuguese roads to these limits, it can be seen that most of the values do not exceed pollutant limits, even for drinking water. For iron the values exceed drinking water limits at all sites and for lead at highway A1. Comparing Portuguese values to immission and emission limits, zinc at highway A6 exceeds the limits of the AGA, and total suspended solids at the A1 and the main road IP5 the AAEV.

For comparing Portuguese pollutant concentrations to German ones, a summary of 9 sampling programs was chosen.

The respective minimum, maximum and median values of flow-weighted mean concentrations from 9 studies (13 catchment areas) in Germany are summarized in Table 29. The studies were performed by Krauth and Klein (1982), Klein (1982), Krauth and Stolz (1993), Xanthopoulos (1992), Paulsen (1984), Sieker and Grottker (1987), ifs (1997), and Dannecker et al. (1988) (quoted by Grotehusmann D., 1999).

**Table 29:** Overview of flow-weighted mean concentrations from different studies(Grotehusmann D., 1999)

| Constituent | Minimum [mg/l] | Maximum [mg/l] | Median [mg/l] |
|---|---|---|---|
| TSS | 84 | 564 | 158 |
| COD | 36 | 141 | 88 |
| Cl | 4 | 357 | 88 |
| Total P | 0.25 | 0.49 | 0.31 |
| NH4-N | 0.2 | 2.31 | 0.56 |
| Pb | 0.08 | 0.34 | 0.18 |
| Ca | 0.0014 | 0.0064 | 0.0031 |
| Cr | 0.0052 | 0.0242 | 0.011 |
| Cu | 0.04 | 0.14 | 0.1 |
| Zn | 0.16 | 0.62 | 0.3 |
| Ni | 0.008 | 0.057 | 0.02 |
| PAH | 0.00024 | 0.00297 | 0.00251 |

It can be seen, that the Portuguese values are very low in comparison to German values. Only zinc for the main road IP5 and the highways A2 and A6 and total suspended solids for highway A1 exceed minimum values. For iron, no values for comparison are given.

## 5.6. Selection of Existing Models and Application to Portuguese Roads

### 5.6.1. Models that accomplish the requirements stated in chapter 5.2.

Most of the models mentioned in chapter 4.2 are hardly applicable on Portuguese highway runoff. Responsible therefore is a lack of data needed to run prediction models or the lack of traffic related variables in the models.

The multiple linear regression equation used by the California Department of Transportation (Caltrans) is the only equation derived from regression models which was made for predicting highway runoff water quality.
Furthermore the program “Wasser”, designed for the BMVIT was made for providing a decision frame for highway runoff water treatment measures.
Regarding simulation models, the Source Loading and Management Model (WinSLAMM) alone includes traffic related model variables.

Models that are inapplicable on the Portuguese situation are:

- Simple empirical models, as they depend on the knowledge of accurate mean pollutant concentrations, which can not be provided.

- Statistical models, which require measurements of statistical tendencies and the variability of available data.

- Build up and wash off models which cannot be used for prediction of absolute values of concentrations and loads without adequate calibration of the model for which data is not available. They perform better in predicting single storm events.

- Continuous curve number models cannot be used since, conceptually, a curve number is a measure of the infiltration capacity of the soil. Therefore, there is little theoretical justification for using the Curve Number Procedure on urban land (Mandel R. et. al., 1997) or highways.

- *S*imulation models, as they are dependent upon a robust model calibration with site-specific data. This data can not be provided. Most of them focus on water quantity modeling and therefore do have objectivities invalid for water quality modeling. They focus on extreme events whereas in water quality modeling the total amount of a pollutant that is discharged during a number of events corresponding to the period considered is from interest.

- A better part of equations derived from regression models, as they do not include traffic related model variables and require data for calibration.

- Regression models, as they require a large amount of data.

- Artificial neural networks, as they require a large amount of data.

Nonetheless, an application of a simple empirical model, the Simple Method, as well as equations derived from regression models, the U.S. Geological Survey regression equations for estimating pollutant load, has been carried out.

### 5.6.2. Application of the Simple Method to Portuguese highways

The Simple Method is an easy to use empirical equation for estimating pollutant loadings in urban watersheds. It estimates storm water pollutant loads as the product of mean pollutant concentrations and runoff depth over specified periods of time.
An accurate description of the Simple Method is given in chapter 4.2.1.

The Simple Method was applied to estimate annual pollutant loads for suspended solids, zinc, copper, and lead.
As input data the size of the area, the percent of site imperviousness, the rainfall depth over the desired time interval, the fraction of rainfall events that produce runoff, and the flow-weighted mean concentration of the pollutant in urban runoff load need to be known.
From these five variables, only the size of the area and the rainfall depth over the desired time interval could be specified.

Through a lack of information from Portuguese highways, it was necessary to assume a flow-weighted event mean pollutant concentration. These values where taken from a study conducted by Driscoll (1990) and are outlined in Table 30.
Driscoll ran field measurements on rural and urban highways between 1975 and 1985 in the USA. For the estimation on Portuguese highways, the values for 50% of all sites having a median concentration ($C_{med}$) less than the indicated concentration have been used.

**Table 30:** Range of site medium concentrations in rural highway runoff
(Driscoll E. D. et al., 1990; adapted by the FHWA, 1996)

| Rural Highways: Average daily traffic usually less than 30000 vehicles per day | | | | | |
|---|---|---|---|---|---|
| Site Median Concentration ($C_{med}$) in mg/L | | | | | |
| Percent of sites having a median EMC less than indicated concentration | | | | | |
| Pollutant | 10% of Sites | 20% of Sites | 50% of Sites | 80% of Sites | 90% of Sites |
| TSS | 12 | 19 | 41 | 90 | 135 |
| Zinc | 0.035 | 0.046 | 0.08 | 0.139 | 0.185 |
| Copper | 0.01 | 0.013 | 0.022 | 0.038 | 0.05 |
| Lead | 0.024 | 0.036 | 0.08 | 0.179 | 0.272 |

Furthermore, the fraction of rainfall events that produce runoff had to be estimated. It was set to 0.9, according to Schueler (1987).
The percentage of site imperviousness was estimated with 90%, except for highway A1, for which it was set to 41%.
Results from the application of the Simple Method are given in chapter 5.7.1.

### 5.6.3. Application of the equation for estimating storm runoff loads and storm runoff volumes to Portuguese highways

The equation for estimating storm runoff loads and storm runoff volumes is a basic regression formula using physical and land use variables, as well as climatic variables. It provides values for the event pollutant load and the event runoff volume.

An accurate description of the USGS regression equations is given in chapter 4.2.7.

For different climatic regions different regression coefficients have to be used. The regions are divided in:

I) States with a mean annual rainfall of less than 508 mm
II) States with a mean annual rainfall between 508 and 1020mm
III) States with a mean annual rainfall of more than 1020 mm

Regression coefficients are outlined in Table 31.

**Table 31:** Summary of regression coefficients for the equation for estimating storm-runoff loads and volumes (adapted from Driver N. E., Tasker G. D., 1990)

| Response variable and region | $\beta_0$ | $\beta_3$ $H_t$ | $\beta_1$ A | $\beta_2$ I+1 | $\beta_8$ LUI+1 | $\beta_9$ LUC+1 | $\beta_{10}$ LUR+1 | $\beta_{11}$ LUN+1 | $\beta_4$ $t_r$ | $\beta_5$ INT | $\beta_6$ $H_{mar}$ | $\beta_7$ $T_j$ | BCF |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | - | [mm/25.4] | [km²/2.59] | [%] | [%] | [%] | [%] | [%] | [min] | [mm/25.4] | [mm/25.4] | [°C*(5/a)+32] | - |
| SS I | 1518 | 1,211 | 0.735 | - | - | - | - | - | -0.463 | - | - | | 2.112 |
| SS II | 2032 | 1,233 | 0.439 | 0.274 | - | - | - | - | - | - | - | -0.59 | 1.841 |
| SS III | 1990 | 1,017 | 0.984 | - | 0.226 | 0.228 | - | -0.286 | - | - | - | - | 2.477 |
| ZN I | 224 | 0,745 | 0.792 | - | - | 0.172 | -0.195 | -0.142 | - | - | -1.355 | - | 1.444 |
| ZN II | 0.002 | 0,796 | 0.667 | 1.009 | - | - | - | - | - | - | - | 1.148 | 1.754 |
| ZN III | 4.355 | 0,83 | 0.555 | - | 0.402 | 0.287 | -0.191 | - | - | - | - | -0.5 | 1.942 |
| CU I | 0.141 | 0,807 | 0.59 | - | 0.424 | 0.274 | - | -0.061 | - | 0.28 | - | - | 1.502 |
| CU II | 0.013 | 0,504 | 0.585 | 0.816 | - | - | - | - | - | - | - | - | 1.534 |
| CU III | 4.508 | 0,896 | 0.609 | - | 0.648 | 0.253 | - | -0.328 | - | -2.071 | - | - | 2.149 |
| PB I | 478 | 0,764 | 0.918 | - | -0.161 | 0.276 | | -0.282 | - | - | -1.892 | - | 1.588 |
| PB II | 0.076 | 0,833 | 0.381 | - | - | 0.243 | 0.087 | -0.181 | - | - | 0.574 | - | 1.587 |
| PB III | 0.081 | 0,852 | 0.857 | 0.999 | - | - | - | - | - | - | - | - | 2.134 |
| RUN I | 1123052 | 1.016 | 0.916 | 0.677 | - | - | - | - | - | - | -1.312 | - | 1.299 |
| RUN II | 62951 | 1.127 | 0.809 | 0.522 | - | - | - | - | - | - | - | - | 1.212 |
| RUN III | 32196 | 1.042 | 0.826 | 0.669 | - | - | - | - | - | - | - | - | 1.525 |

A variation of land use variables was conducted to evaluate the influence of using different land use variables for substituting a non-existing transportation land use.
To calculate mean concentrations, the obtained values for event pollutant loads had to be divided by the runoff volume.
Annual pollutant loads could not be determined under use of this equation because the number of annual storm events producing runoff was not known.

A comparison of the estimated with the measured values is given in chapter 5.7.2.

### 5.6.4. Application of the equation for determining mean seasonal or annual loads to Portuguese highways

There exist several equations developed by the USGS for estimating seasonal or annual loads. FHWA (1996) stated one applicable equation for determining annual loads. In contrast to the equation for estimating storm runoff loads and storm runoff volumes, regression coefficients are not differed by regions of different mean annual rainfall.

The equation, as well as the different variables used in the equation, is explained in detail in chapter 4.2.7.

For calculation, coefficients derived from ordinary least squares (OLS) models were used to determine event loads.

Table 32 lists the regression coefficients for these constituents.

**Table 32:** Regression coefficients of mean loads of a storm for indicated constituents based on physical, land use, or climatic characteristics of the watershed (adapted from DriverN. E., Tasker G. D., 1990)

| Response variable | Method | Regression constant | Regression coefficients for indicated explanatory variables | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | $A^{0,5}$ | I | $H_{MAR}$ | $T_j$ | X2 | BCF |
| | | $\beta_0$ | $\beta_1$ [km²/2.59] | $\beta_2$ [%] | $\beta_3$ [mm/25.4] | $\beta_4$ [C°(9/5)+32] | $\beta_5$ [1 or 0] | - |
| COD | OLS | 1.1262 | 2.0004 | 0.0049 | - | - | - | 1.301 |
| | GLS | 1.1174 | 2.0069 | 0.0051 | - | - | - | 1.298 |
| SS | OLS | 1.4627 | 1.6021 | - | 0.0299 | -0.0342 | - | 1.67 |
| | GLS | 1.543 | 1.5906 | - | 0.0264 | -0.0297 | - | 1.521 |
| DS | OLS | 1.8656 | 2.5501 | - | - | -0.0244 | - | 1.278 |
| | GLS | 1.8449 | 2.5468 | - | - | -0.0232 | - | 1.251 |
| TN | OLS | -0.2398 | 1.6039 | 0.0065 | - | - | | 1.332 |
| | GLS | -0.2433 | 1.6383 | 0.0061 | - | - | -0.4442 | 1.345 |
| TKN | OLS | -0.7326 | 1.5991 | 0.0067 | 0.0219 | -0.0199 | -0.4553 | 1.264 |
| | GLS | -0.7282 | 1.6123 | 0.0064 | 0.0226 | -0.021 | -0.4345 | 1.277 |
| TP | OLS | -1.4443 | 2.0918 | - | 0.0246 | -0.0211 | - | 1.33 |
| | GLS | -1.3884 | 2.0825 | - | 0.0234 | -0.0213 | - | 1.314 |
| DP | OLS | -1.3898 | 1.4316 | - | - | - | - | 1.508 |
| | GLS | -1.3661 | 1.3955 | - | - | - | - | 1.469 |
| CU | OLS | -1.4861 | 1.7646 | - | - | -0.0136 | - | 1.457 |
| | GLS | -1.4824 | 1.8281 | - | - | -0.0141 | - | 1.403 |
| PB | OLS | -2.0676 | 1.988 | 0.0081 | 0.0121 | - | - | 1.477 |
| | GLS | -1.9679 | 1.9037 | 0.007 | 0.0128 | - | - | 1.365 |
| ZN | OLS | -1.6504 | 2.0267 | 0.0073 | - | - | - | 1.356 |
| | GLS | -1.6302 | 2.0392 | 0.0072 | - | - | - | 1.322 |

To obtain annual loads, the calculated event loads need to be multiplied by the number of storm events per year. As the number of storm events producing runoff was not known, annual loads could not be determined.

Therefore, estimated mean concentrations were compared to measured ones. These mean concentrations were obtained by dividing the event load by a runoff volume.

The runoff volume was calculated by multiplying the drainage area by the total storm rainfall and a mean runoff coefficient, expressing the fraction of rainfall converted into runoff. The runoff coefficient was taken from the Simple Method.

Results of the application of the equation for determining annual loads are given in chapter 5.7.3.

# 5.7. Comparison of the Estimated Values with the Measured Values

## 5.7.1. Comparison of the measured data with the Simple Method

The Simple Method has been used to predict annual pollutant loads.
The results of its application to 6 investigated sites are given in Table 33.

**Table 33:** Comparison of the application of the Simple Method with measured data, annual load

| Location | E. | M. | E. | M. | E. | M. | E. | M. |
|---|---|---|---|---|---|---|---|---|
| | Suspended Solids | | Zinc | | Copper | | Lead | |
| | [mg/m²*a] | | [mg/m²*a] | | [mg/m²*a] | | [mg/m²*a] | |
| A 1, Alcobaça | 34732 | 70453 | 68 | 133 | 19 | 29 | 68 | 10 |
| A 1, Minde | 37187 | 70453 | 73 | 133 | 20 | 29 | 73 | 10 |
| A 2 | 27840 | 4256 | 54 | 120 | 15 | 19 | 54 | 2 |
| A 6, Elvas | 28756 | 14942 | 56 | 263 | 15 | 6 | 56 | 1 |
| A 6, V. V. | 36736 | 14942 | 72 | 263 | 20 | 6 | 72 | 1 |
| IP 5 | 44992 | 38427 | 88 | 177 | 24 | 12 | 88 | 5 |

It is obvious that the variability of the estimated values (E.) is much lower than the variability of the measured values (M.), except for lead.
The best concordance of values could be gained for copper.

## 5.7.2. Comparison of the measured data with the equation for estimating storm runoff loads and storm runoff volumes

### 5.7.2.1. Comparison of mean concentrations

Table 34, Table 35, Table 36, and Table 37 compare the mean pollutant concentrations obtained by using the equation for estimating storm runoff loads and storm runoff volumes with the measured data.
Except for total suspended solids and zinc at highway A1 all estimated values turned out to be over estimated.
The biggest differences were observed for the constituent lead, for which estimated values tuned out to be up to 209 times as high as measured ones.
For zinc and copper at the highway A1 values are most close to measured ones. For zinc the difference between estimated and measured values is 12%.

**Table 34:** Comparison of the measured data with the equation for estimating storm runoff loads and volumes for total suspended solids, mean concentration

| Location | E. | M. |
|---|---|---|
| | [mg/l] | [mg/l] |
| A 1, Alcobaça | 23.9 | 84.5 |
| A 1, Minde | 23.9 | 84.5 |
| A 2 | 414.1 | 7.4 |
| A 6, Elvas | 253.6 | 19.6 |
| A 6, Vila Visçosa | 253.6 | 19.6 |
| IP 5 | 729.0 | 44.7 |

**Table 35:** Comparison of the measured data with the equation for estimating storm runoff loads and volumes for zinc, mean concentration

| Location | E. | M. |
|---|---|---|
| | [mg/l] | [mg/l] |
| A 1, Alcobaça | 0.140 | 0.159 |
| A 1, Minde | 0.140 | 0.159 |
| A 2 | 2.166 | 0.208 |
| A 6, Elvas | 1.952 | 0.346 |
| A 6, Vila Visçosa | 1.952 | 0.346 |
| IP 5 | 3.006 | 0.205 |

**Table 36:** Comparison of the measured data with the equation for estimating storm runoff loads and volumes for copper, mean concentration

| Location | E. | M. |
|---|---|---|
| | [mg/l] | [mg/l] |
| A 1, Alcobaça | 0.041 | 0.034 |
| A 1, Minde | 0.041 | 0.034 |
| A 2 | 0.197 | 0.033 |
| A 6, Elvas | 0.188 | 0.008 |
| A 6, Vila Visçosa | 0.188 | 0.008 |
| IP 5 | 0.307 | 0.014 |

**Table 37:** Comparison of the measured data with the equation for estimating storm runoff loads and volumes for lead, mean concentration

| Location | E. | M. |
|---|---|---|
| | [mg/l] | [mg/l] |
| A 1, Alcobaça | 0.265 | 0.012 |
| A 1, Minde | 0.265 | 0.012 |
| A 2 | 0.550 | 0.004 |
| A 6, Elvas | 0.363 | 0.002 |
| A 6, Vila Visçosa | 0.418 | 0.002 |
| IP 5 | 1.516 | 0.005 |

Table 38, Table 39, Table 40, and Table 41 illustrate the influence of using different land use variables for substituting a non-existing transportation land use.

**Table 38:** Comparison of using different land use variables for total suspended solids, mean concentration

| Location | No land use | Industrial land use | Non-urban land use | Measured |
|---|---|---|---|---|
| | [mg/l] | [mg/l] | [mg/l] | [mg/l] |
| A 1, Alcobaça | 23.9 | 55.6 | 20.6 | 84.5 |
| A 1, Minde | 23.9 | 55.6 | 20.6 | 84.5 |
| A 2 | 414.1 | 414.1 | 414.1 | 7.4 |
| A 6, Elvas | 253.6 | 253.6 | 253.6 | 19.6 |
| A 6, Vila Visçosa | 253.6 | 253.6 | 253.6 | 19.6 |
| IP 5 | 728.9 | 728.9 | 728.9 | 44.7 |

**Table 39:** Comparison of using different land use varibles for zinc, mean concentration

| Location | No land use | Industrial land use | Non-urban land use | Measured |
|---|---|---|---|---|
| | [mg/l] | [mg/l] | [mg/l] | [mg/l] |
| A 1, Alcobaça | 0.140 | 0.629 | 0.140 | 0.159 |
| A 1, Minde | 0.140 | 0.629 | 0.140 | 0.159 |
| A 2 | 2.166 | 2.166 | 2.166 | 0.208 |
| A 6, Elvas | 1.952 | 1.952 | 1.952 | 0.346 |
| A 6, Vila Visçosa | 1.952 | 1.952 | 1.952 | 0.346 |
| IP 5 | 3.006 | 3.006 | 3.006 | 0.205 |

**Table 40:** Comparison of using different land use variables for copper, mean concentration

| Location | No land use | Industrial land use | Non-urban land use | Measured |
|---|---|---|---|---|
| | [mg/l] | [mg/l] | [mg/l] | [mg/l] |
| A 1, Alcobaça | 0.041 | 0.46 | 0.034 | 0.034 |
| A 1, Minde | 0.041 | 0.46 | 0.034 | 0.034 |
| A 2 | 0.197 | 0.197 | 0.197 | 0.033 |
| A 6, Elvas | 0.188 | 0.188 | 0.188 | 0.008 |
| A 6, Vila Visçosa | 0.188 | 0.188 | 0.188 | 0.008 |
| IP 5 | 0.307 | 0.307 | 0.307 | 0.014 |

**Table 41:** Comparison of using different land use variables for lead, mean concentration

| Location | No land use | Industrial land use | Non-urban land use | Measured |
|---|---|---|---|---|
| | [mg/l] | [mg/l] | [mg/l] | [mg/l] |
| A 1, Alcobaça | 0.265 | 0.265 | 0.256 | 0.012 |
| A 1, Minde | 0.265 | 0.265 | 0.256 | 0.012 |
| A 2 | 0.55 | 0.55 | 0.239 | 0.004 |
| A 6, Elvas | 0.363 | 0.363 | 0.157 | 0.002 |
| A 6, Vila Visçosa | 0.417 | 0.417 | 0.182 | 0.002 |
| IP 5 | 1.516 | 1.516 | 0.658 | 0.005 |

For suspended solids, zinc and copper, in regions with a mean annual rainfall of more than 1020 mm, higher values were obtained using industrial land use instead of neglecting the land use variable. For using non-urban land use slightly lower values, in regions with a mean annual rainfall of more than 1020 mm, resulted for suspended solids and copper.

### 5.7.2.2. Comparison of event mean concentrations and loads

The equation for estimating storm runoff loads and storm runoff volumes has been used to compare predicted event mean concentrations and loads with measured data for the highways A1 and A2.

- Highway A1

Representative for all three events, the results for the event mean concentrations and loads for the event which took place at the 17.05.2002 are stated in Table 42 and Table 43.

**Table 42:** Comparison of the measured data with the equation for estimating storm runoff loads and volumes for lead , event mean concentration, Highway A1

| | SS | Zn | Cu | Pb |
|---|---|---|---|---|
| | [mg/l] | [mg/l] | [mg/l] | [mg/l] |
| Estimated | 23.252 | 0.111 | 0.035 | 0.215 |
| Measured | 237 | 0.247 | 0.035 | 0.029 |

**Table 43:** Comparison of the measured data with the equation for estimating storm runoff loads and volumes for lead, event load, Highway A1

| | SS | Zn | Cu | Pb |
|---|---|---|---|---|
| | [kg] | [kg] | [kg] | [kg] |
| Estimated | 8.702 | 0.0416 | 0.013 | 0.081 |
| Measured | 5 | 0.0053 | 0.00076 | 0.00061 |

Predicted event mean concentrations, except for copper, are lower than the measured ones. Regarding loads, only for suspended solids estimated values came close to measured ones.

- Highway A2

Because of complete measured data is available only for the event of the 22.04.2003, comparison only therefore can be provided. The comparison is outlined in Table 44 and Table 45.

**Table 44:** Comparison of the measured data with the equation for estimating storm runoff loads and volumes for lead using different sets of variables, event mean concentration, Highway A2

| | SS | Zn | Cu | Pb |
|---|---|---|---|---|
| | [mg/l] | [mg/l] | [mg/l] | [mg/l] |
| Estimated | 414.13 | 2.166 | 0.197 | 0.55 |
| Measured | 2.4 | 0.00007 | 0.000014 | 0.0000001 |

**Table 45:** Comparison of the measured data with the equation for estimating storm runoff loads and volumes for lead using different sets of variables, event load, Highway A2

| | SS | Zn | Cu | Pb |
|---|---|---|---|---|
| | [kg] | [kg] | [kg] | [kg] |
| Estimated | 4.534 | 0.0237 | 0.00216 | 0.00603 |
| Measured | 0.011 | 0.0013 | 0.00026 | 0.0000019 |

All of the predicted values clearly exceed the measured ones. There exist no correlation between the measured and the predicted data.

### 5.7.3. Comparison of the measured data with the equation for determining mean seasonal or annual loads

Table 46, Table 47, Table 48, and Table 49 compare values obtained by using the equation for determining mean seasonal or annual loads with measured data.
(E.) stands for estimated values, (M.) for measured ones.

**Table 46:** Comparison of the measured data with the equation for determining mean seasonal and annual loads for total suspended solids, mean concentration

| Location | E. | M. |
|---|---|---|
| | [mg/l] | [mg/l] |
| A 1, Alcobaça | 118.8 | 84.5 |
| A 1, Minde | 146.1 | 84.5 |
| A 2 | 385.7 | 7.4 |
| A 6, Elvas | 266.1 | 19.6 |
| A 6, Vila Visçosa | 322.1 | 19.6 |
| IP 5 | 4800.8 | 44.7 |

**Table 47:** Comparison of the measured data with the equation for determining mean seasonal and annual loads for zinc, mean concentration

| Location | E. | M. |
|---|---|---|
| | [mg/l] | [mg/l] |
| A 1, Alcobaça | 0.25 | 0.159 |
| A 1, Minde | 0.25 | 0.159 |
| A 2 | 6.127 | 0.208 |
| A 6, Elvas | 2.754 | 0.346 |
| A 6, Vila Visçosa | 2.754 | 0.346 |
| IP 5 | 33.732 | 0.205 |

**Table 48:** Comparison of the measured data with the equation for determining mean seasonal and annual loads for copper, mean concentration

| Location | E. | M. |
|---|---|---|
| | [mg/l] | [mg/l] |
| A 1, Alcobaça | 0.048 | 0.034 |
| A 1, Minde | 0.048 | 0.034 |
| A 2 | 0.572 | 0.033 |
| A 6, Elvas | 0.269 | 0.008 |
| A 6, Vila Visçosa | 0.269 | 0.008 |
| IP 5 | 2.982 | 0.014 |

**Table 49:** Comparison of the measured data with the equation for determining mean seasonal and annual loads for lead, mean concentration

| Location | E. | M. |
|---|---|---|
| | [mg/l] | [mg/l] |
| A 1, Alcobaça | 0.363 | 0.012 |
| A 1, Minde | 0.395 | 0.012 |
| A 2 | 5.65 | 0.004 |
| A 6, Elvas | 2.588 | 0.002 |
| A 6, Vila Visçosa | 3.100 | 0.002 |
| IP 5 | 45.915 | 0.005 |

The equation for determining mean seasonal or annual loads produces values that differ highly from the measured ones for areas beyond the application limits. For highway A1, the only highway whose area lies within the application limits, the equation produces results that are, except for lead most close to measured ones.

## 5.8. Discussion of the Results

### 5.8.1. Comparing the Simple Method with the measured data

Most significant is that the variability of estimated values was smaller than of measured ones. This may originate from the use of constant concentrations.
The best concordance between estimated and measured values was gained for copper. The reason therefore could be an accurate estimation of the flow-weighted mean concentration.
The overestimated values for lead compared to the measured ones may originate from the introduction of unleaded fuel, introduced after the study by Driscoll et al. (1990), from which the values for the flow-weighted mean concentration were taken, was conducted.
An accurate estimation of the flow-weighted mean concentration seems to be the base for the correct use of the equation.

### 5.8.2. Comparing the USGS regression equation for estimating storm runoff loads and storm runoff volumes with the measured data

The USGS regression equation for estimating storm runoff loads and storm runoff volumes was not specially developed for estimating pollutant concentrations and loads of highway runoff. Applying it leads to series of problems.

In general, the predicted values turned out to be overestimated.
As USGS regression equations were not developed for impervious areas, like highways, but can even be used on, e.g., agricultural sites, it seems as if the regression coefficient for this variable is set to high when used on almost impervious sites. For highway A1, which consist of only 41% of impervious area, the results turned out to be more realistic then for the sites having 90% of impervious area.
Modifying one variable, like e.g., land use or storm duration, often has an immoderate influence on the results.

One of the problems detected is, that certain for highway runoff water quality prediction most influential variables, like e.g., the AADT, or the antecedent dry period, are not integrated in the equation. These variables should have a high influence on the results, and therefore may be one reason for the differences between measured and predicted data.

Moreover, the land use variables integrated in the USGS regression equation do pose a problem. Transportation land use is not a stated land use. This brings up the question if instead of transportation land use another, most proximate, land use should be chosen or if the whole variable should be neglected.
Therefore, the two most different land uses, industrial land use and non-urban land use, were tested on the given data.

Substituting no land use with industrial land use, higher values were obtained for suspended solids, zinc and copper in regions with a mean annual rainfall of more than 1020 mm.

For using non-urban land use slightly lower values, in regions with a mean annual rainfall of more than 1 020 mm, resulted for suspended solids and copper.
This shows that land use variables are only conditionally influencing the outcome of the equation.

Finally, as the regression equations have been designed in the U.S.A in 1990, the predicted values for the constituent lead were overestimated. Since the introduction of unleaded fuel in Europe, the concentrations of lead in highway runoff reduced.

For this reasons, it cannot be recommended to use the USGS Regression Equation for estimating storm runoff loads and storm runoff volumes in decision processes, in which accurate results are needed. It can only provide an order-of-magnitude estimate of pollutant concentrations and loads.

### 5.8.3. USGS Equation for determining mean seasonal or annual loads

The USGS equation for determining mean seasonal or annual loads could not be used in its original way on the base of the given data. For obtaining mean concentrations the obtained event loads were divided by a runoff volume calculated under help of a runoff coefficient taken from the Simple Method.

However, applied under these conditions and for areas lying in the range of model limits, it provides the best concordance between measured and estimated values for suspended solids and zinc of all the tested methods.
Except for highway A1, all of the monitored sites possessed areas smaller than the limit set for the use of the equation. It seems that results become more unreliable with a decreasing area size.

Also, in this equation transportation land use is no stated land use.

Therefore, no general statement to the applicability of the equation can be given on the base of available data.

# 6. Conclusion

Nowadays it is essential to take an integral approach to pollution resulting from diffuse sources. In this context, a precise determination of highway runoff water characteristics in the scope of environmental impacts and for evaluating possible treatment measures is of particular importance. Therefore, a definition of the nature of highway runoff water, its environmental impacts and legal basics regarding the treatment of runoff water is necessary. Currently, infiltration is standard practice for the treatment of highway runoff water.

Describing the nature of highway runoff water is a difficult task, as its main characteristic is the high variability of loads and volumes.
In practice, it is not even possible to identify details of the sources for road runoff (Hvitved-Jacobsen T., Vollertsen J., 2003). They can be atmospheric or traffic related and are classified as diffuse sources. Processes of accumulation, loosening, transport, and removal of pollutants from the road surface are additional aspects contributing to variability. For the accumulation process, no general explanation can be given, whereas the loosening, transport and removal of pollutants is basically dependent on the intensity of a storm event.

Regarding the impact runoff water is causing to water bodies, different approaches have to be taken. Focusing on acute pollution effects extreme events are crucial, whereas for accumulative effects the focus is on the total amount of a pollutant discharged during a number of events corresponding to the period considered.
From higher interest in water quality observation are accumulative effects caused by persistent substances. They are divided into heavy metals and organic micropollutants.
To a better part, road runoff constituents are associated with particulate material. According to Ball (1997) most of the constituent load is sorbed to the fine fraction of this material.
To evaluate potential risks to the biota, it is therefore necessary to carry out a selective analysis of mobile and possible mobile fractions in the runoff water, receiving water and (or) soils. The toxic impact of accumulative substances moreover is dependent on their mobility, their concentration, their particle size and their exposure time.
With regard to these aspects, an emission oriented definition of total pollutant loads, which so far has been used, is considered incompletely for the evaluation of environmental impacts.

However, a direct discharge of certain substances into a water body is prohibited or bound to an approval, according to EU-directives. Therefore, a purification of highway runoff water is compulsory. Exceptions can be made, if the impacts to water bodies remain insignificant.
Total concentrations of pollutants in undiluted highway runoff regularly do not exceed wastewater pollutant limits or formal in-stream criteria for protection of aquatic life. Considering dilution, it is possible that concentrations will be well below levels of concern. Crucial therefore is the background pollution of the receiving waters.

To define environmental impacts and to evaluate possible runoff treatment measures, runoff water quality modeling is considered to gain in importance. Therefore, this work includes an introduction to water quality modeling and an overview of applicable mathematical models.

Albeit the search for applicable models unfolded a great variety in this field, certain limitations regarding their credibility and the usefulness of results for the given purpose were detected.

Generally, the simplest model fulfilling the projects objectivities should be used.
Resulting from this investigation, the use of regression models would be the best choice for an accurate estimation of highway runoff water quality.
In practice, the appliance of data-driven methods, like regression models, requires a tremendous effort. For the use of these models a large data set is conditional, as evidenced by May and Sivakumar (2004). Furthermore, regression models have been criticized as poor predictors when applied beyond the original data set used to create a model (Driscoll E. D. et al., 1990). Therefore, no credibility to model results generated on data with differing site conditions can be given.

The biggest challenge for highway runoff quality modeling is the possession of reliable data, as the quality of model interpretations depends directly upon the quality and representativeness of available data (Tasker G. D., Granato G. E., 2000).
The data has to be made up of input data, data for calibration, and data for validation of a model and will have mostly stochastic nature. Therefore, data will inevitably be subject to a high variability.
According to Montgomery and Sanders (1985) (quoted by Tasker G. D., Granato G. E., 2000) models, at best, are only as good as the uncertainty in the input data.
Input data for highway runoff water quality modeling should include at least precipitation data and data related to traffic and highway conditions.
Also data for calibration and validation is indispensable. Donigian (1991) stated that no method currently available (or likely to be available) is able to predict absolute (accurate) values of concentrations and loads without local calibration data. He stated the need for one set of data for calibration and another independent set for verification.
Keeping in mind the high costs associated with the collection and analysis of storm water quality sampling data, which are needed for calibration and validation, every modeling effort will be a cost and time consuming process.

Regarding model variables in use, each model designer will have his own opinion on the processes leading to highway runoff generation and on the importance of single variables.
As, according to Donigian (1991), an error in prediction will occur regardless of the method in use, there may be no point in compiling many hypothetical input parameters for a more complex model lacking a guarantee of a better prediction.
Ball (1992) even proposed to develop, instead of one model of reality, alternative models with differing degrees of complexity and computational effort to describe highway runoff water generation processes.

Regardless of which model to use, as no model is truly deterministic in the sense of fully characterizing the physical, chemical and biological mechanisms that underlie conceptual buildup, erosion, transport and degradation processes (Donigian A.S. et al., 1991), these processes cannot be replicated mathematically with exact certainty.

Therefore, an appliance of mathematical models guaranteeing an acceptable rank of confidence under tolerable expenses is difficult to realize. Without this level of confidence, no model can be used in decision-making processes.

Following an invitation of Dr. Ana Estela Barbosa to write one part of my thesis at the Laboratório Nacional de Engenharia Civil (Portugal), two models, the Simple Method and regression equations developed by the U.S. Geological Survey have been tested on data from Portuguese roads.
Problems that emerged applying these equations are stated in chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**.
On the base of the available Portuguese data, no general statement to the applicability of these equations can be given.

In Austria, the program "Wasser" is used in decision processes regarding runoff water treatment facilities. It is a tool for planning preventive measures for water bodies and allows an order of priorities for these measures. The program provides a general overview of the influencing site parameters and their importance for the respective local situation. It represents an economical alternative to mathematical models.

# Table Directory

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# References


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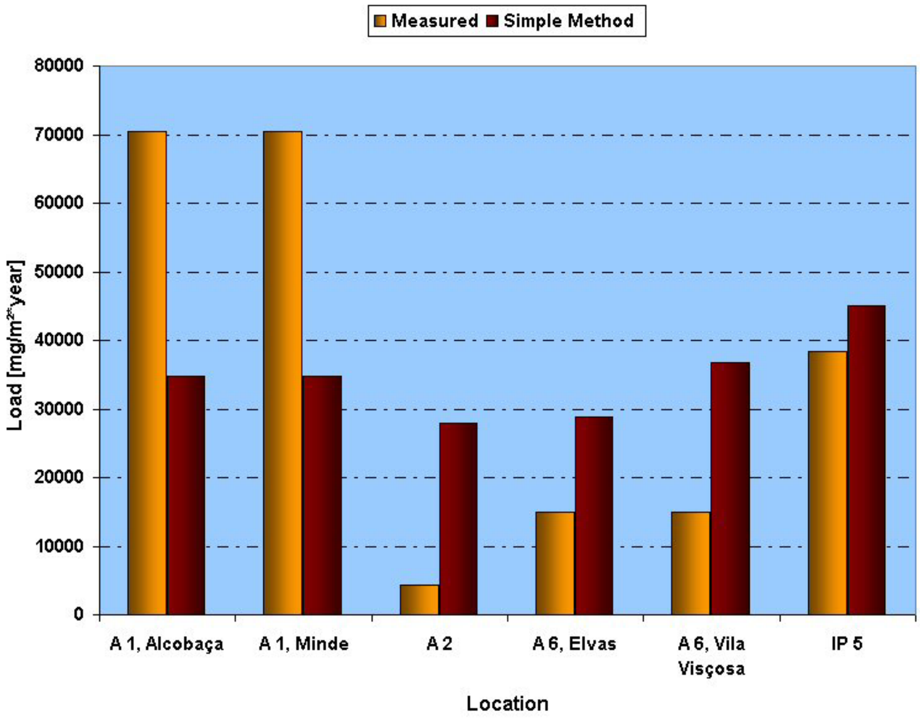
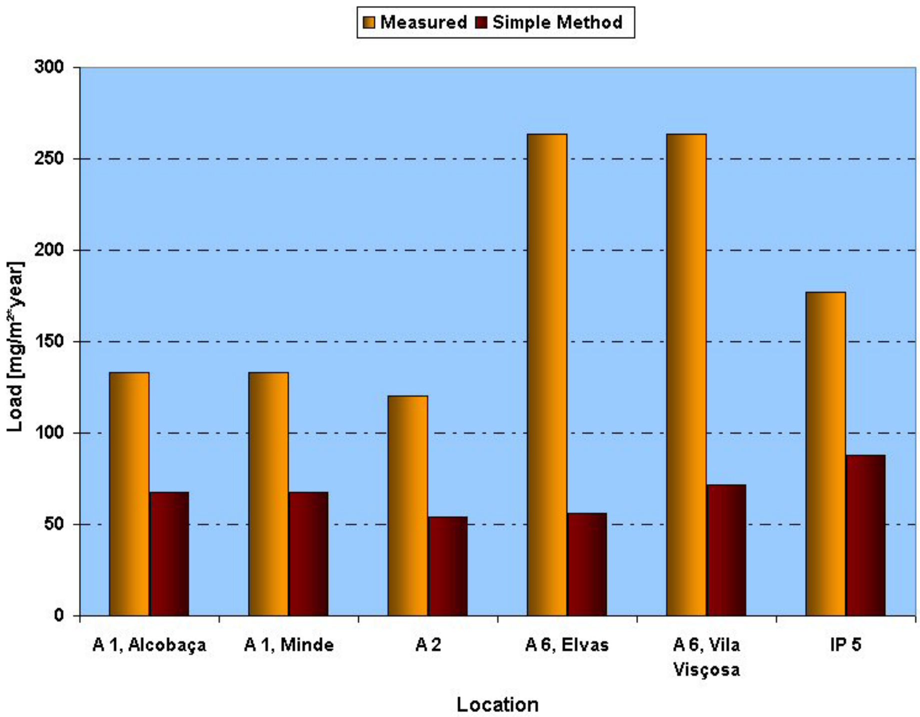
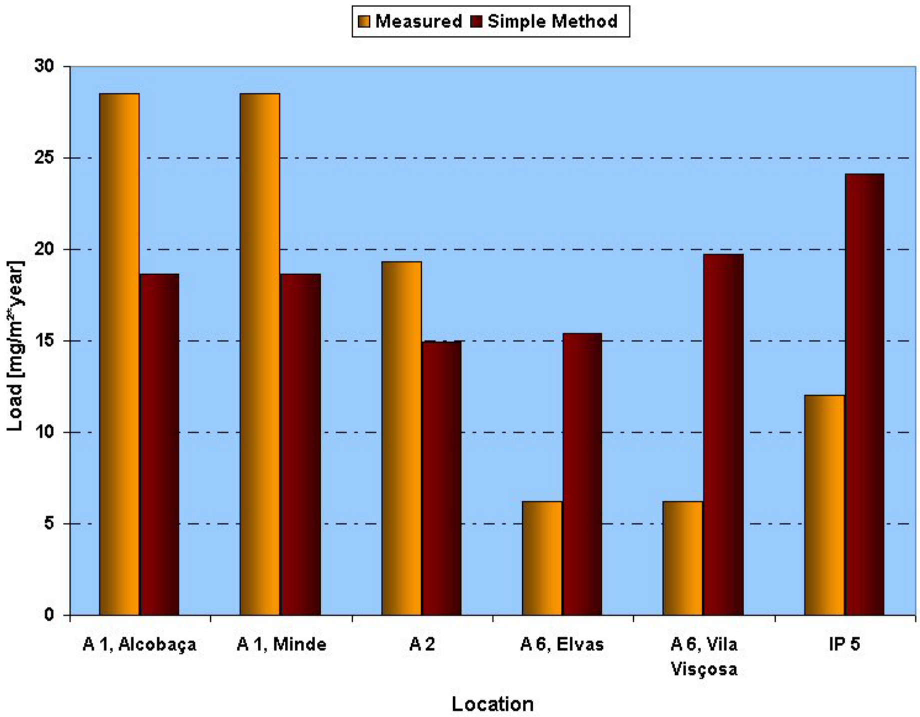
# Annex 1: Comparison of the measured data with the Simple Method



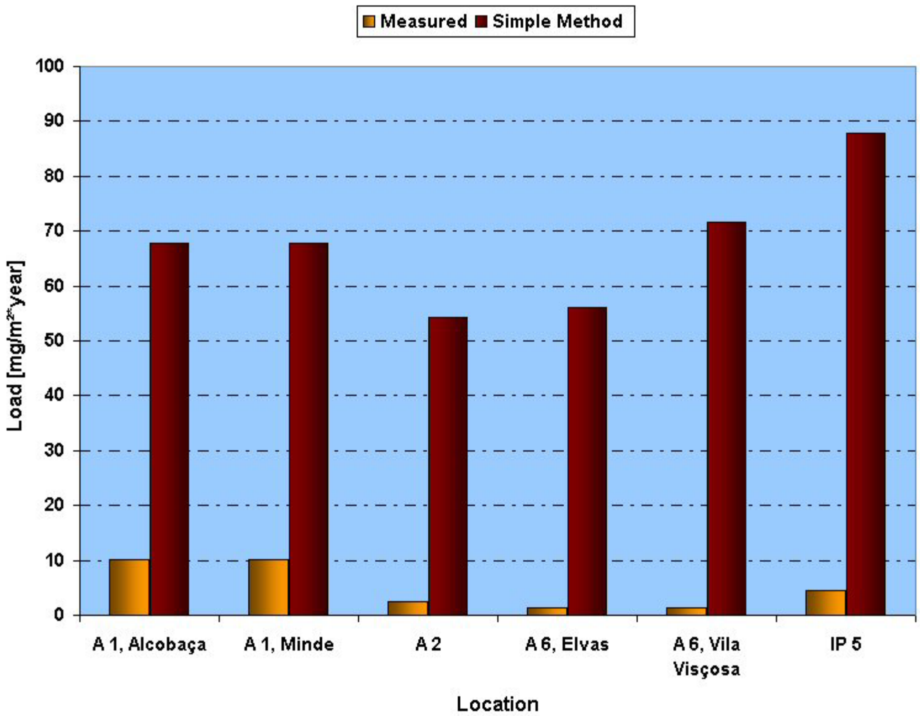

**Comparison of the measured data with the Simple Method**
**Suspended solids, annual load**




**Comparison of the measured data with the Simple Method**
**Zinc, annual load**



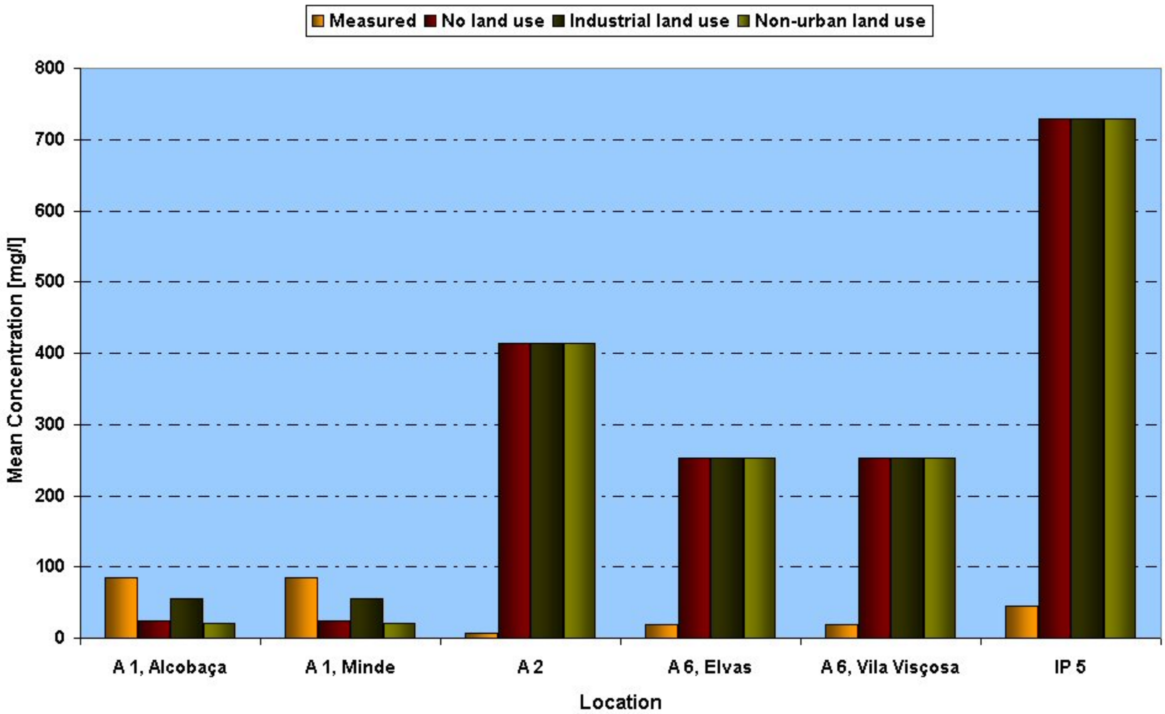

**Comparison of the measured data with the Simple Method**
**Copper, annual load**



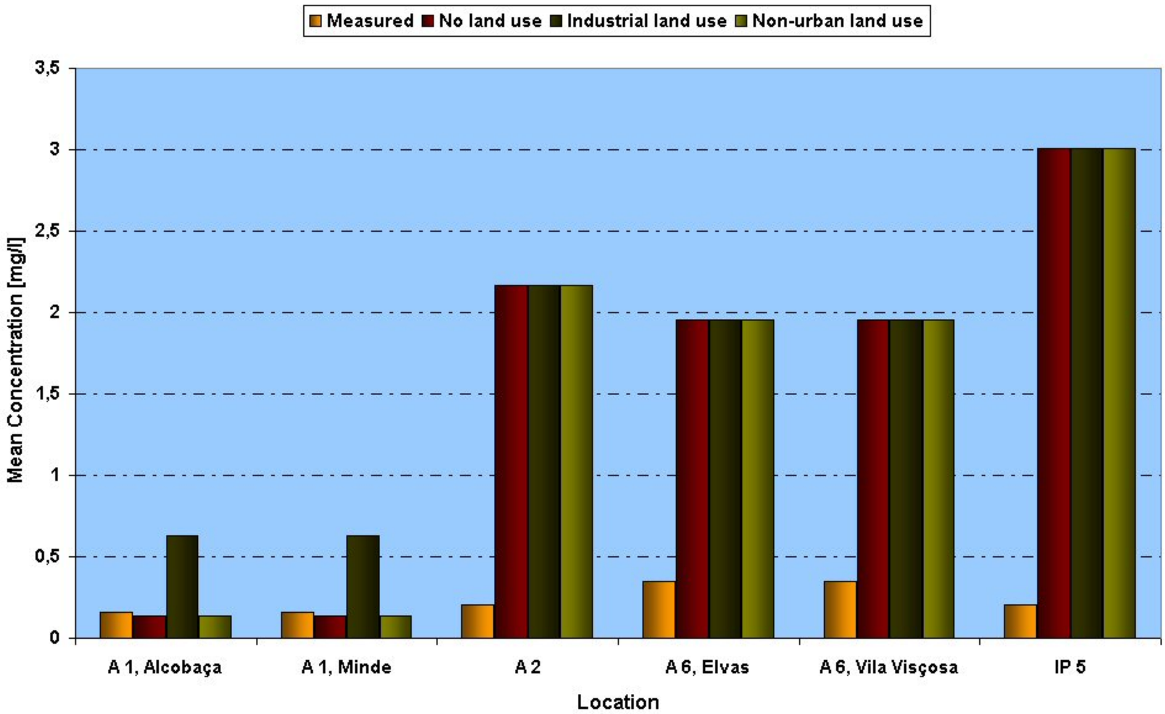

**Comparison of the measured data with the Simple Method**
**Lead, annual load**

# Annex 2: Comparison of the measured data with the Equation for Estimating Storm Runoff Loads and Storm Runoff Volumes

- **Comparison of mean concentrations, variation of land use types**




**Comparison of the measured data with the equation for estimating storm runoff loads and volumes**
**Different land use parameters**
**Suspended solids, mean concentration**

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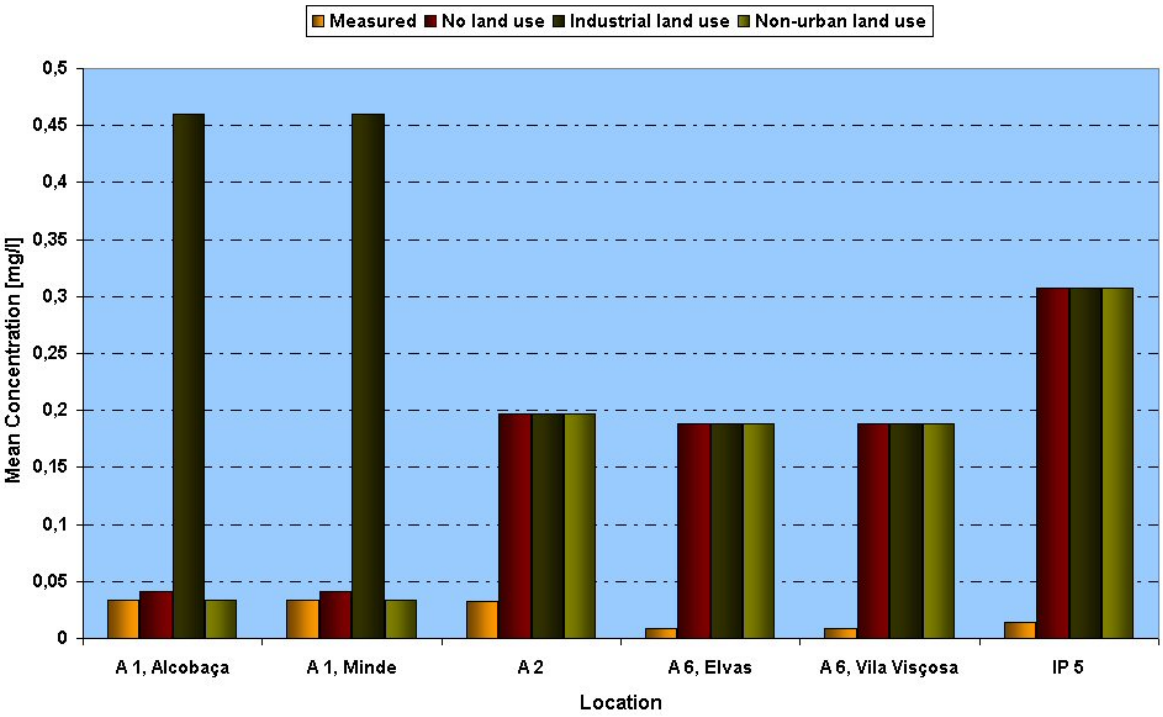
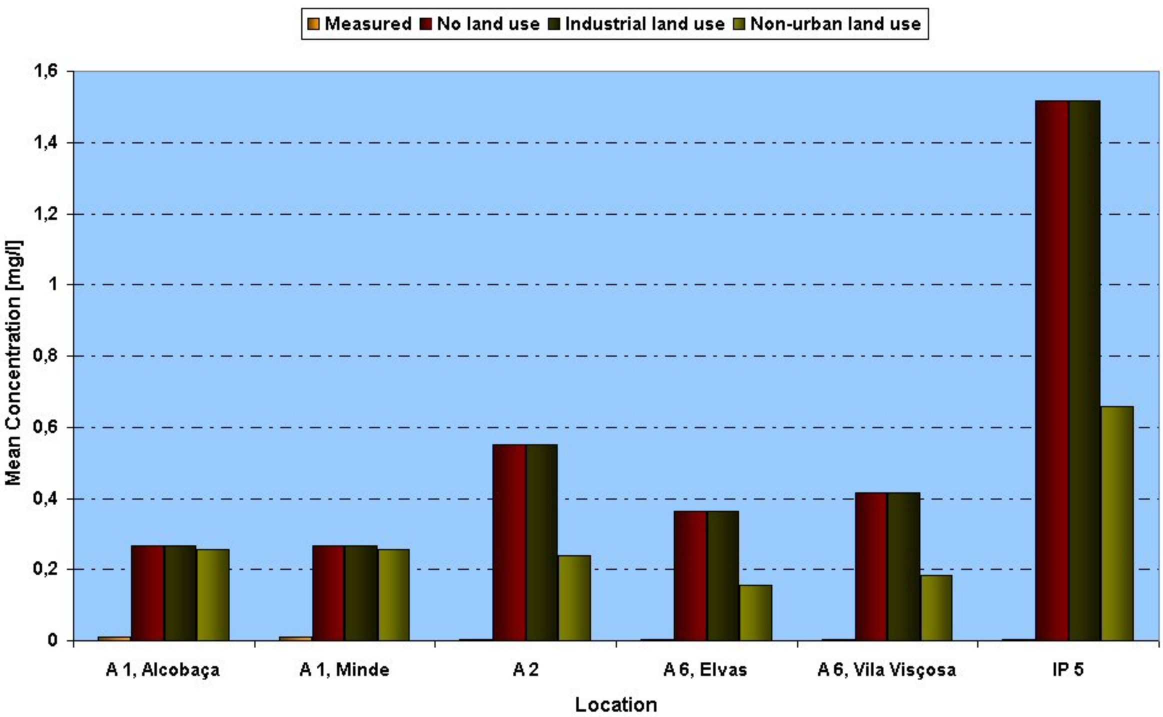
**Different land use parameters**
**Zinc, mean concentration**

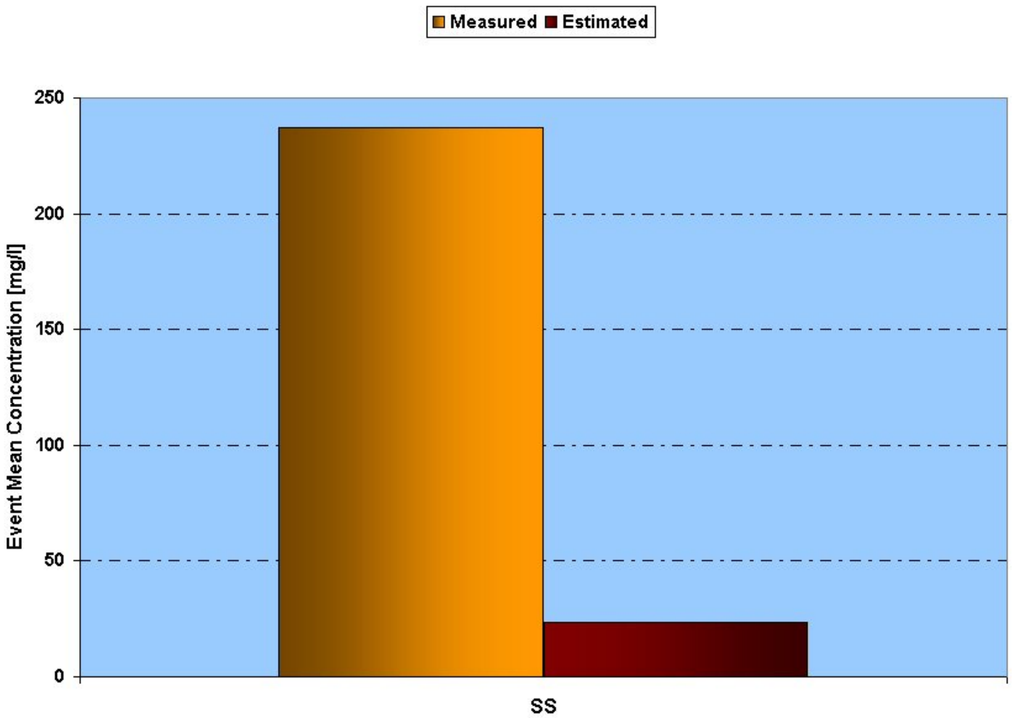



**Comparison of the measured data with the equation for estimating storm runoff loads and volumes**
**Different land use parameters**
**Copper, mean concentration**

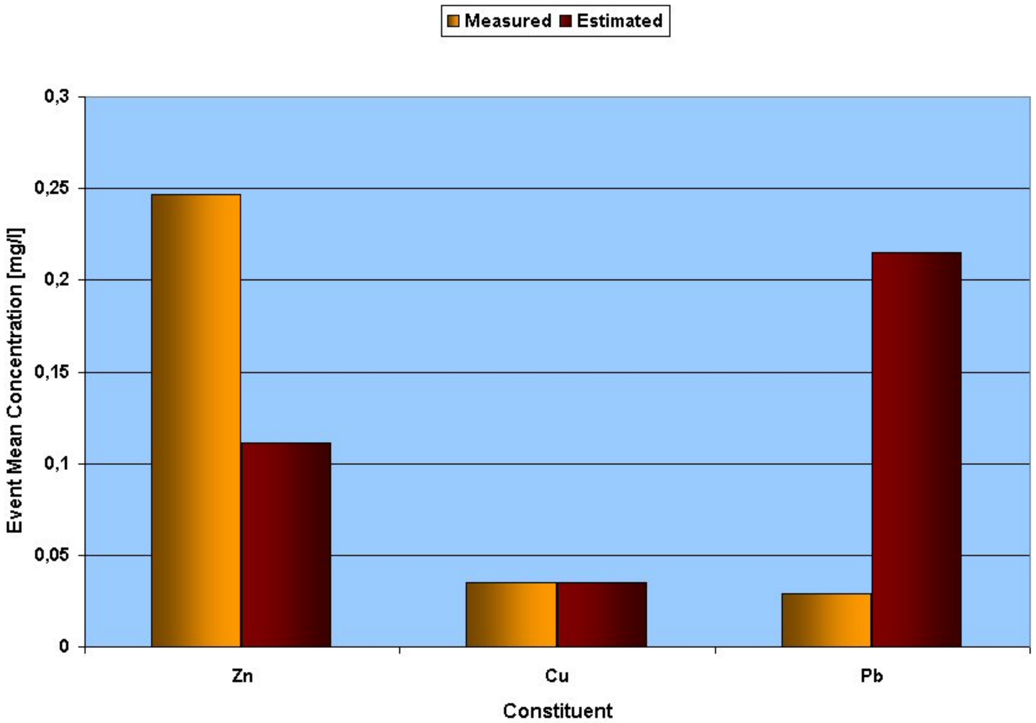



**Comparison of the measured data with the equation for estimating storm runoff loads and volumes**
**Different land use parameters**
**Lead, mean concentration**

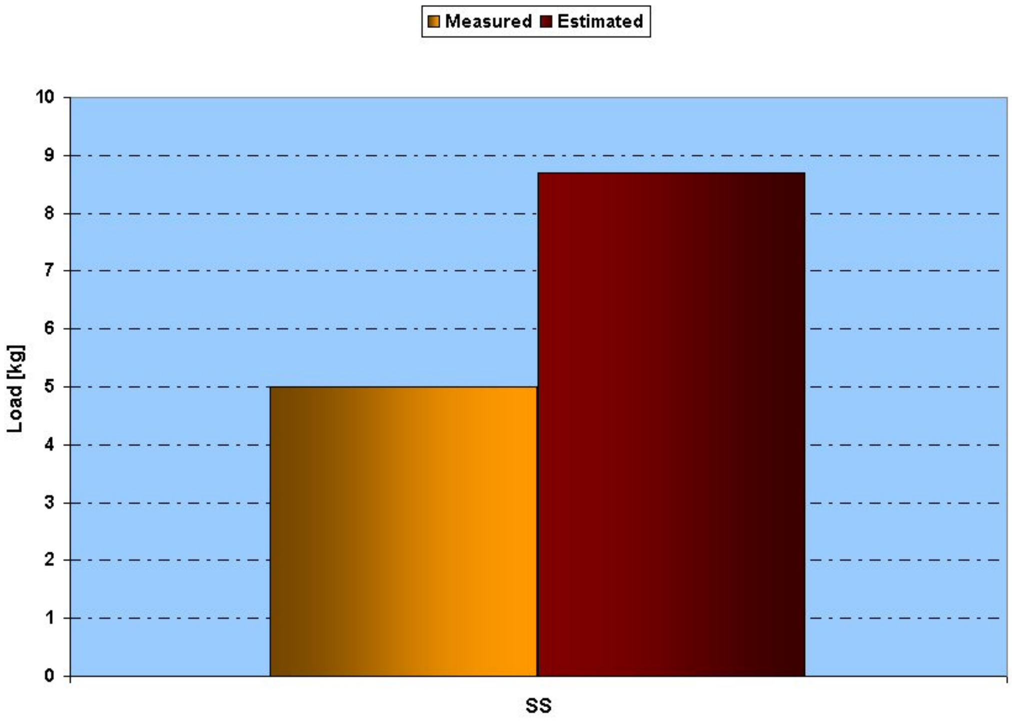
- **Comparison of event mean concentrations and loads**



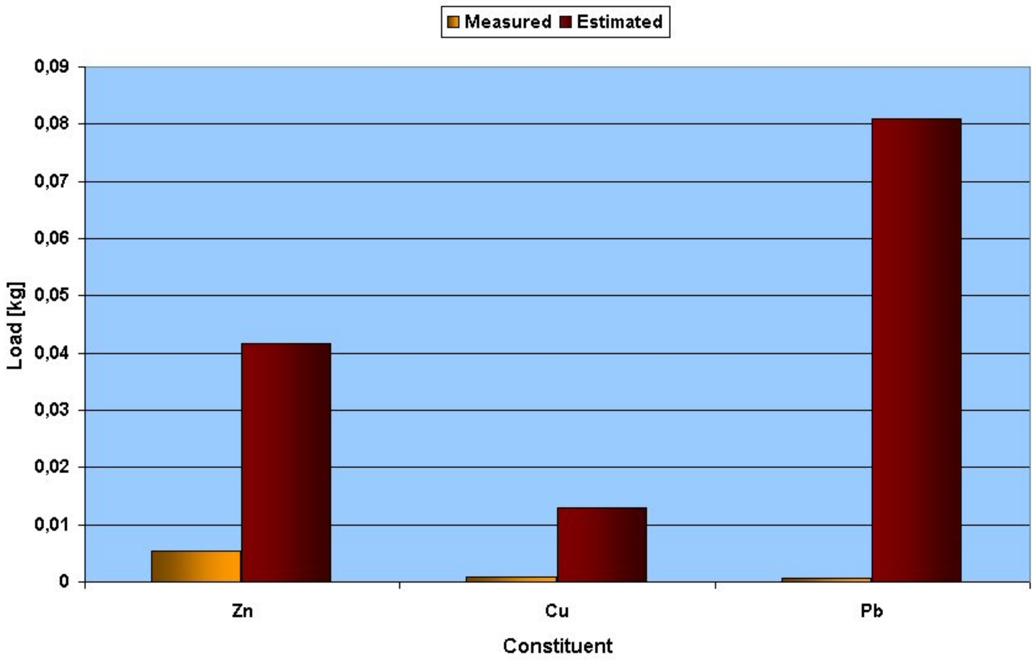

**Comparison of the measured data with the equation for estimating storm runoff loads and volumes**
**Highway A1**
**Suspended solids, event mean concentration**



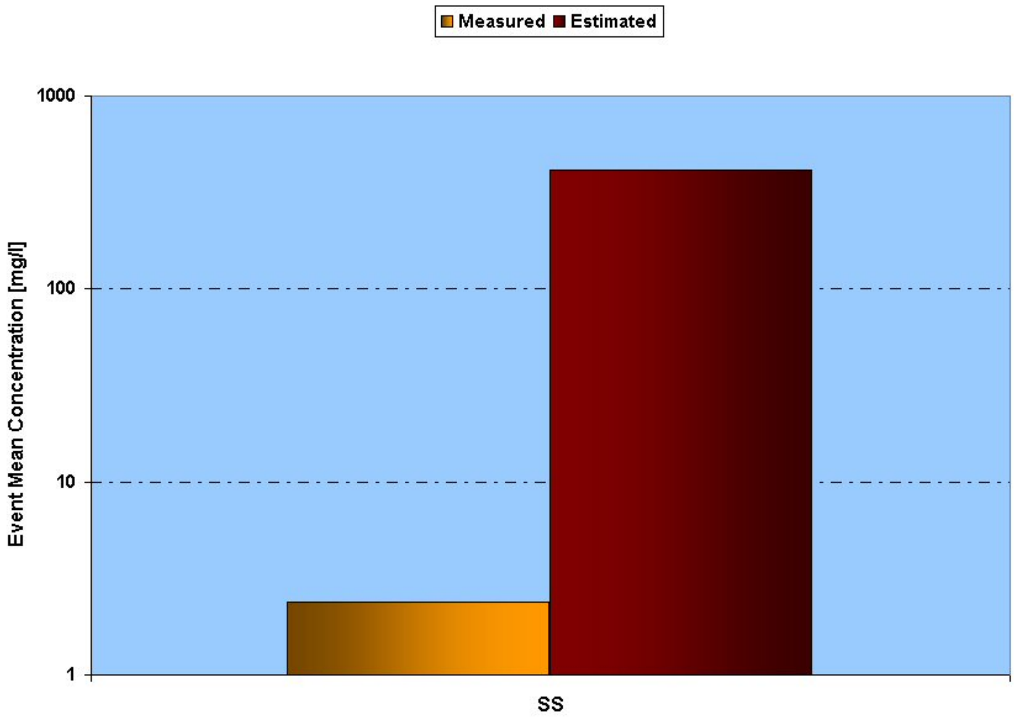

**Comparison of the measured data with the equation for estimating storm runoff loads and volumes**
**Highway A1**
**Zinc, copper, lead, event mean concentration**



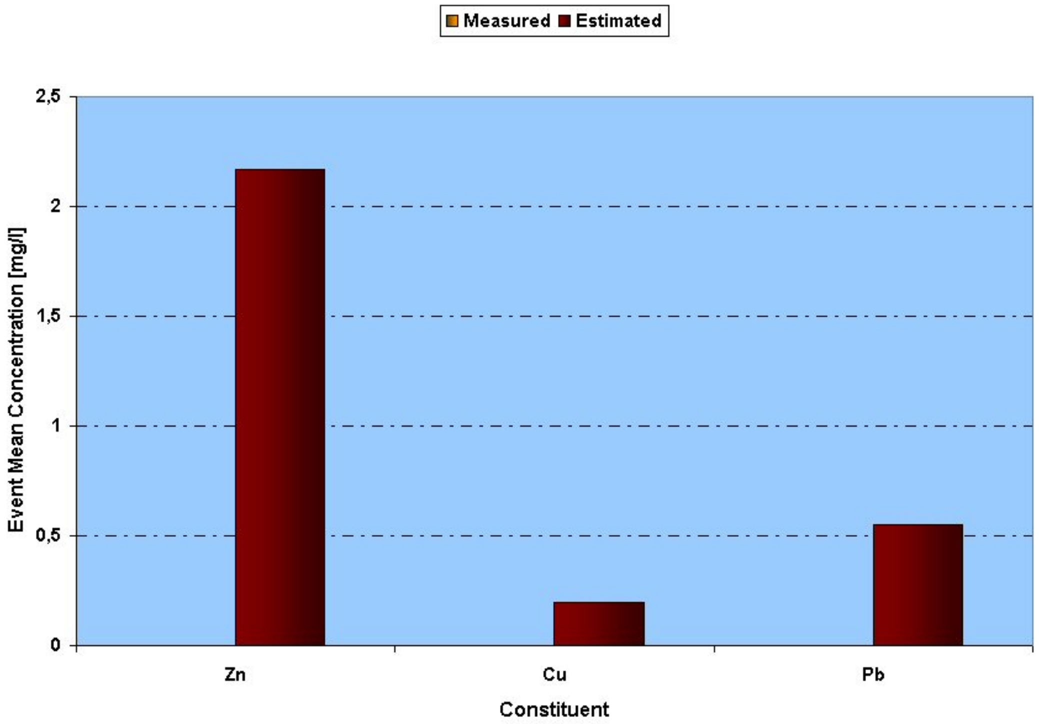

**Comparison of the measured data with the equation for estimating storm runoff loads and volumes**
**Highway A1**
**Suspended solids, event load**



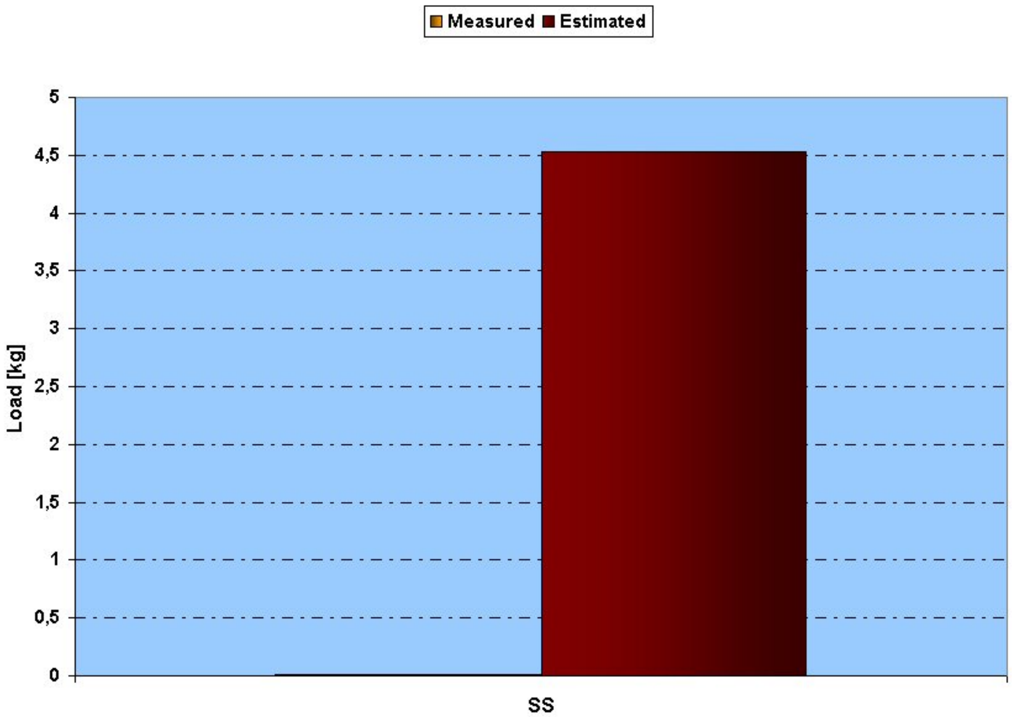

**Comparison of the measured data with the equation for estimating storm runoff loads and volumes**
**Highway A1**
**Zinc, Copper, Lead, event load**



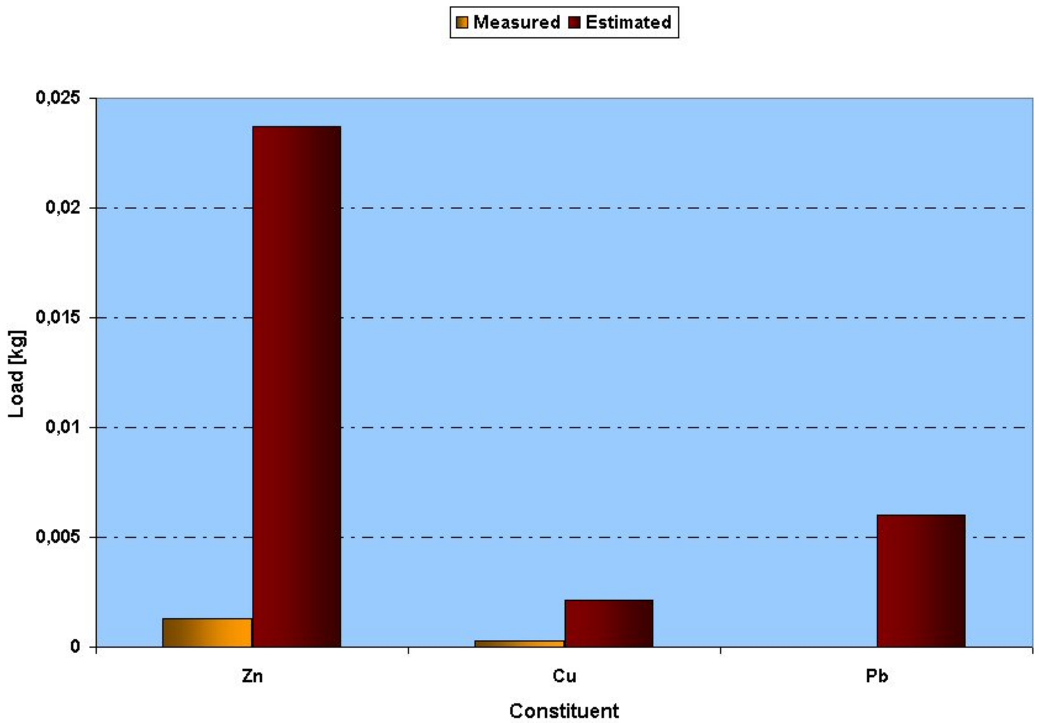

**Comparison of the measured data with the equation for estimating storm runoff loads and volumes**
**Highway A2**
**Suspended solids, event mean concentration**




**Comparison of the measured data with the equation for estimating storm runoff loads and volumes**
**Highway A2**
**Zinc, copper, lead, event mean concentration**

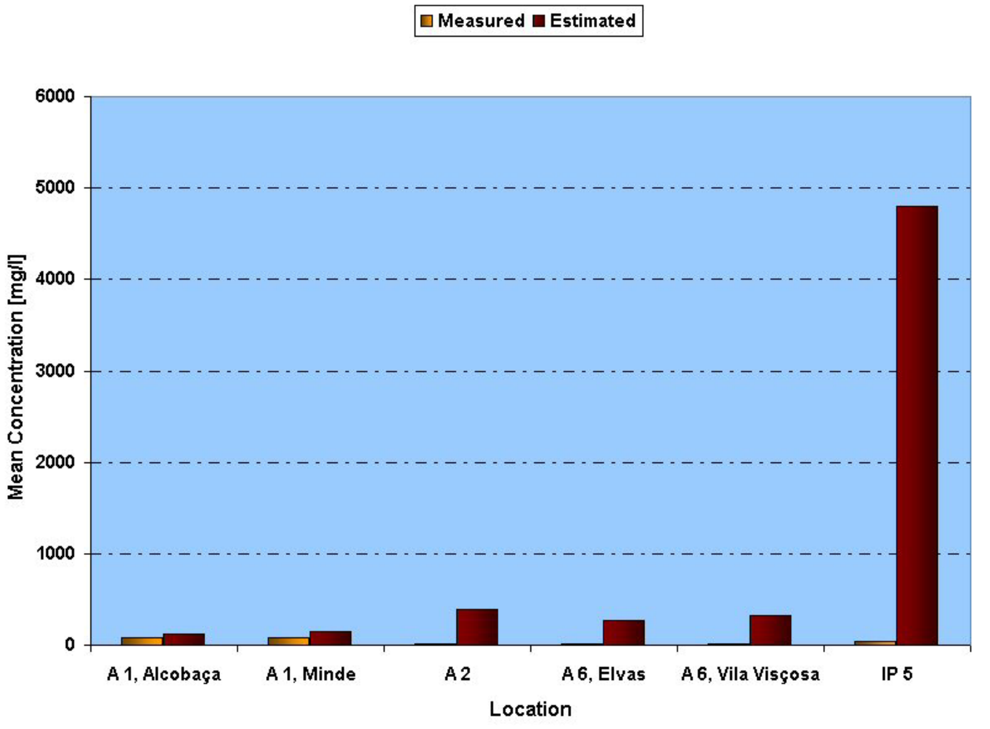



**Comparison of the measured data with the equation for estimating storm runoff loads and volumes**
**Highway A2**
**Suspended solids, event load**

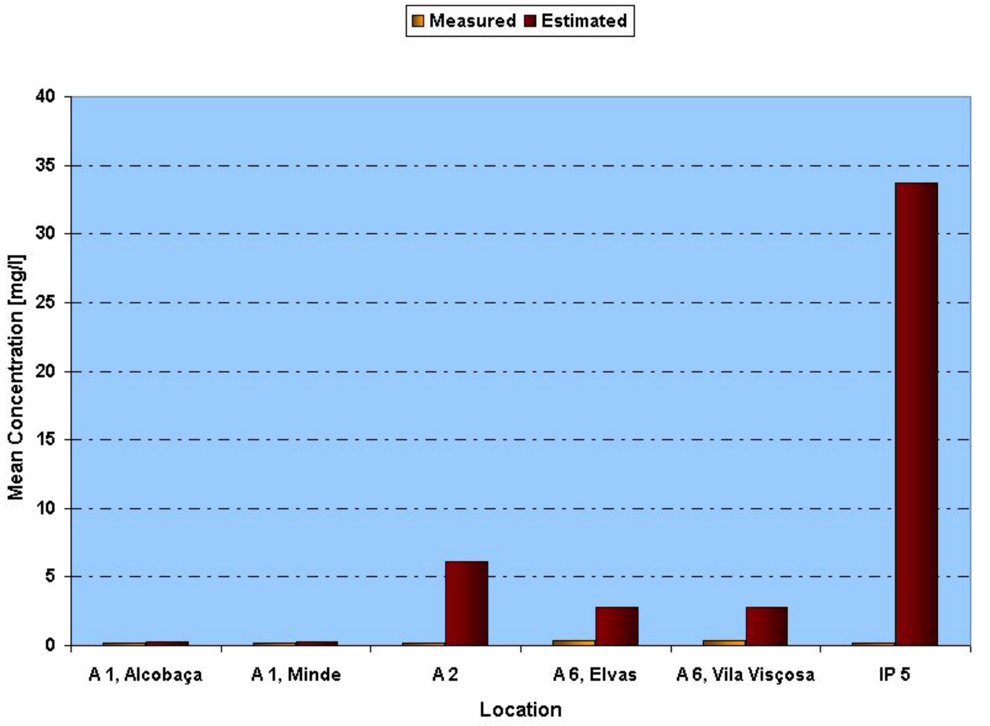



**Comparison of the measured data with the equation for estimating storm runoff loads and volumes**
**Highway A2**
**Zinc, Copper, Lead,. event load**

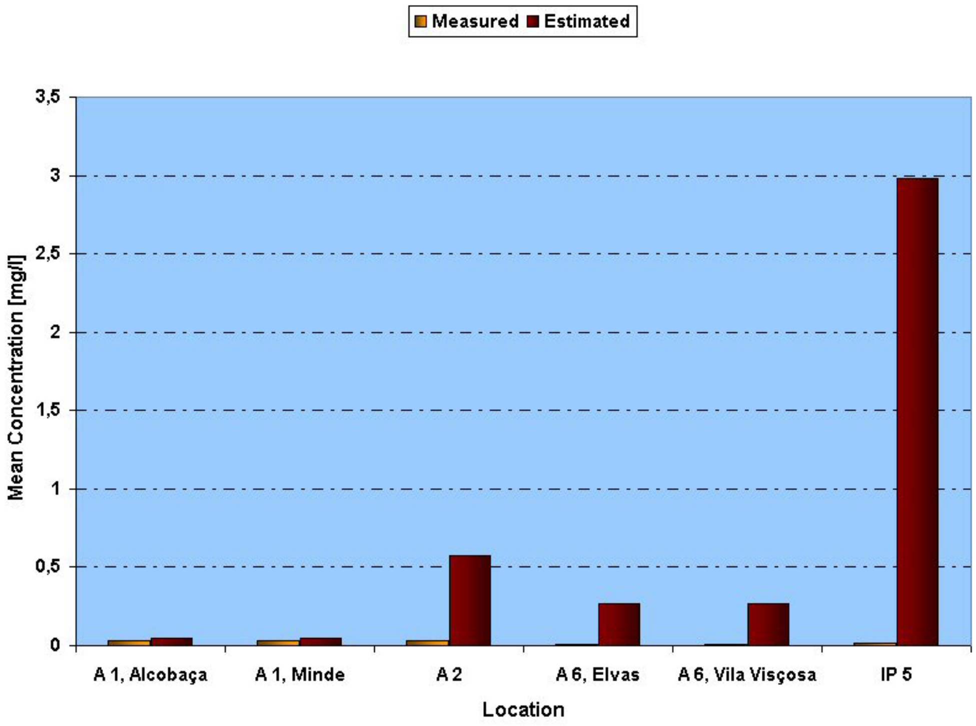
# Annex 3: Comparison of the measured data with the Equation for Determining Mean Seasonal or Annual Loads



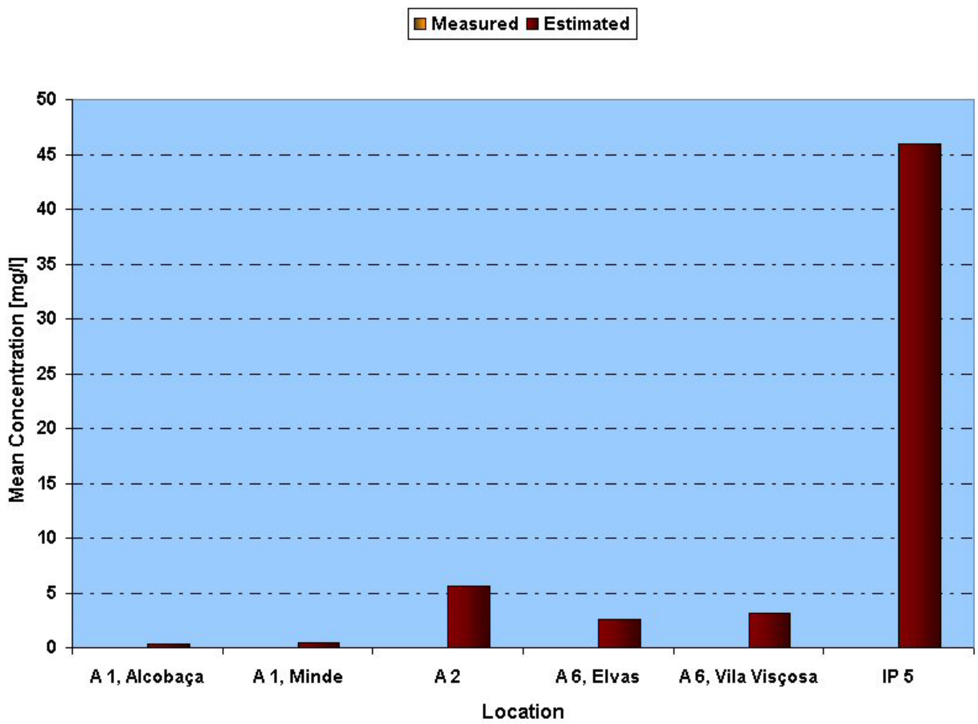

**Comparison of the measured data with the equation for determining mean seasonal and annual loads**
**Suspended solids, mean concentration**




**Comparison of the measured data with the equation for determining mean seasonal and annual loads**
**Zinc, event mean concentration**




**Comparison of the measured data with the equation for determining mean seasonal and annual loads**
**Copper, mean concentration**




**Comparison of the measured data with the equation for determining mean seasonal and annual loads**
**Lead, mean concentration**