Discharges of copper, zinc and lead to water and soil - analysis of the emission pathways and possible emission reduction measures

Executive Summary

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I. Background

Copper, zinc and lead are chemical elements which are used to a considerable extent in the technosphere because of their special features. They alloy well with other metals so that the material properties can be altered and adjusted as desired. But even in a pure, non-alloyed state, they play an important technical role. Their applications range from the electrical industry, transport or mechanical engineering through to construction and civil engineering. As far as the building sector is concerned, they are traditionally used materials for roof constructions, gutters, drainpipes, chimneys, roof flashings and coverings. There is also a long tradition of covering entire roofs with these materials.

The use of these substances in open applications (i.e. exposed to the atmosphere or rainwater) results in emissions to the environment which ultimately contribute to polluting water and soil. With regard to water, the available monitoring data of recent years show constantly high, even slightly increasing pollution when compared with the targeted water quality class II limits. The River Basin Commissions of the Rhine and the Elbe have stated that the targets set for these substances are not being achieved. Comparing the discharge inventories to water for the years 1985 and 2000 show that the non-point emission sources for the pollution of the environment with these substances make up a continuously increasing share in total pollution, even if the absolute emission amount has decreased. In contrast to the considerable progress achieved during this period with regard to emissions via industrial wastewater and municipal sewage treatment plants, the progress made in non-point sources was slight - with the exception of lead because of the use of lead-free fuels.

There are various pollution causes contributing to these non-point emissions. One important application is the use of metallic building products which has clearly increased over the last 20 years. The specialist material characteristics of these products as well as optical design reasons are responsible for this growth. Other causes for the non-point emissions are emissions from transport (mechanical wear and tear of brake pads and tyres of cars, overhead lines of rail vehicles etc.) as well as the large number of galvanized products which are exposed to the weather. Furthermore, pollution emissions to water as well as soil also result from the use of these materials in household plumbing. However, up to now, only insufficient information was available about the significance of these various emission sources and their share in the total pollution of the environment with copper, zinc and lead.
II. Objective

There is a basic need for action to reduce the environmental pollution due to diffuse emissions of copper, zinc and lead because of the pollution situation for these heavy metals and due to the significance of the diffuse emission sources. An improved database is essential in order to be able to estimate the significance of individual sources for pollution and to be able to develop suitable strategies for reducing the discharge of these metals into water and soil. Therefore the aim of the project was to first quantify the application-based emissions of these heavy metals to water and soil.

In the first stage, a rough survey was compiled of the stock flows for copper, zinc and lead for Germany. Based on this, the emissions to water and soil for the areas household plumbing, open applications in the building sector, vehicles (brake pads, tyres) as well as for other applications (galvanized products, overhead lines etc.) were calculated. To verify the results, plausibility checks were done for the emissions to water based on existing information about total pollution. In addition, for the individual areas, the future development of the emissions was estimated.

Within the scope of this research project, it was also intended to develop approaches for specific strategies to reduce the emissions to water. To do so, the individual emission pathways were differentiated as were the different instruments which could be used for these strategies. An important element of the project was to draw up a guideline for architects and builders for open applications in the building sector. This guideline should supply practicable information and aids on the environmentally-compatible use of copper, zinc and lead. Additionally, existing life cycle assessments for the use of various roofing materials were examined. It was also examined how significant the results were concerning the environmental pollution caused during the service life of these materials.

The objective of the work conducted was to demonstrate the different possibilities to reduce the emissions of the heavy metals copper, zinc and lead, taking into account the relevant boundary conditions. This information may also serve as the basis for elaborating a programme of measures within the scope of a future river basin management: if deficiencies are revealed in meeting the quality targets of these three heavy metals within the scope of a river basin management, suitable measures can be selected using this information and the respective regional conditions in the river basin.

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1 Heavy metals are those with densities over 5 g/cm³ (there are varying definitions between 3.5 to 6 g/cm³). Some are essential trace elements, some highly toxic even at small quantities.
III. Calculating the emissions for copper, zinc and lead

The different emission sources included in the survey and the relevant emission pathways are summarized in Figure 1. For the individual applications, first the resulting environmental pollution (total emissions) was always calculated and then the resulting substance discharges into water and soil. The most important statistical base data for the calculations are:

- data on the degree of connection to the municipal sewer network or wastewater purification,
- data on stormwater treatment and discharge (share of combined and separate sewer system, stormwater overflow rate of combined systems, paved areas, share of discharged polluted water in combined sewers),
- degree of separation of heavy metals in municipal sewage treatment plants and
- disposal route of the sewage sludge.

Figure 1: Sources of heavy metals considered, transport pathways and sinks
(SWTP: stormwater treatment plant, SOT: stormwater overflow tank, SO: stormwater overflow)
Emissions and entries to water and soil from the drinking water supply

The drinking water used in households contains heavy metals originating from various sources. There are already small quantities of heavy metals present in the raw water used for the drinking water supply, which are predominantly of geogenic origin. In addition, the materials used for water treatment and distribution (pipelines, household plumbing: pipe materials, pipe connections, fittings) may lead to a clear increase of the copper, lead and zinc concentrations found in the drinking water. Household plumbing plays a particularly important role: copper and galvanized iron materials are or were used in Germany to a large extent. Lead, in contrast, only remains in old constructions in some towns and will be completely replaced in the next few years because of the standards set in the German Drinking Water Ordinance. Overall, there is a tendency towards a greater use of plastic as a plumbing material.

How metals corrode in plumbing installations depends on many different factors. With regard to the corrosion of metallic surfaces, usually a conversion coating is formed first which partly protects against further corrosion. High concentration of carbonic acid may result in the conversion coating breaking up. In particular, the pH value and the acidity/alkalinity (as a measure for the carbonic acid content) are used as decision criteria for the application areas of metallic materials. Other factors of influence are the degree of water hardness, the concentration of organic substances and neutral salts, the temperature and the age of the pipes.

The environmental surveys of drinking water in Germany were referred to when quantifying the metal emissions in drinking water. A distinction was made between:

1. the load in the drinking water after delivery from the waterworks and
2. the emissions due to metallic household plumbing, due to corrosion of fittings as well as due to metallic materials in the supply pipes from the waterworks to the households.

Emissions and entries to water and soil from materials used in roofs and facades

The use of copper, zinc and lead on the outsides of buildings results in emissions to water and soil via rainwater due to the weathering of surfaces and the runoff of soluble and insoluble metallic compounds. Copper and zinc are still traditionally used materials in the building sector especially for roofs, guttering and facing materials. Lead, in contrast, plays only a subordinate role due to its more limited outdoor use.

The corrosion of the metals is the process causing the emissions. The corrosion rates may vary widely. Climatic factors influence these (temperature, humidity etc.), above all the presence of corrosive gases (sulphur dioxide, nitrogen oxide, ozone etc.) but also
the nearby used building materials (for example bitumen roof sheetings). Due to the sharp fall in SO\textsubscript{2} emissions in Germany, there has also been a marked decrease in corrosion rates. The metal on the surface is transformed via the corrosion process into corrosion products, during which the thickness of the metal decreases. While one part of the corrosion product remains on the metal's surface (protective layer, patina), the other part is washed away by rain. The runoff rate refers to the total amount of substances formed through the corrosion processes of the metallic material which are washed away by rainwater from a surface of defined size during a certain period of time.

Current measurement results were evaluated to determine the average runoff rates. These examinations were carried out via natural experiments for a test sample of selected roof areas. There is hardly any data available for entire roof areas or for entire buildings which also account for actual technical conditions. Therefore, the runoff rates used are rather low estimates. To determine the erosion-relevant metal surfaces estimates by industrial associations were used. The total emissions in roof runoff water could be determined using these figures and the emissions to surface water and soil could be calculated from this.

**Emissions and discharges to water and soil from vehicles**

Substance emissions caused by traffic are complex and dependent on many parameters which vary by locality, time and substance. In principle, substances can be emitted by vehicles, the road surface and by road maintenance. Emissions of copper, zinc and lead are mainly caused by wear and tear of tyres and brake pads. In addition, surveys have shown that balance weights on wheels, carbon brushes of electric motors and road surface wear also represent additional relevant emission sources. The reference figures of the environmental emissions are usually the kilometres driven per vehicle. The emissions can then be calculated based on the road performance.

- **Tyre wear and tear:**
  Zinc oxide is used as an activator to accelerate vulcanisation when manufacturing tyres. The zinc oxide thus contained in the tyre is contaminated with lead and cadmium oxide. The extent of tyre abrasion depends on the material properties (rubber used, degree of reinforcement, ageing resistance), the construction and the interplay of vehicle and tyre. From the existing data, an emission factor per vehicle kilometre was calculated from the tyre wear and the metal content. Taking road performance into account, the annual metal emissions due to tyre abrasion can then be calculated.

- **Brake pad wear and tear:**
  Brake pads are designed for wear; their lifespan depends on factors such as traffic conditions, individual driving behaviour, type of vehicle use, condition of the braking system and wear behaviour of the brake pad. The main components of most brake pads are iron and copper, which together often make up 40 - 50 % of the total mass. Copper or copper alloys serve to increase the mechanical stability as well as to con-
duct heat between the direct friction layer and the back plates of the pads. Zinc is also present in brake pads albeit in much smaller concentrations. The brass shavings used in the pads may contain lead. In addition, lead and lead compounds (such as e.g. lead sulphide) may be added as solid lubricants. In the future, vehicles will be fitted with lead-free brake pads in accordance with the EU End-of-life Vehicle Directive 2000/53/EC.

The average metal contents in brake pads were calculated from the current studies available of metal concentrations in brake pads. The vehicle-specific emission factors could be derived from these data using the available figures on specific wear factors, and the emissions then calculated.

- **Balance weights:**
  In the past, the vast majority of balance weights contained lead. If the balance weights were lost and then pulverised by traffic and distributed as fine lead dust, these quantities of lead could end up in the environment. In addition, lead emissions occurred due to the surface corrosion of the balance weights. According to the standards set by the Directive 2000/53/EC of the European Parliament and the Council on end-of-life vehicles, this use of lead will be phased out in the future. Calculating the emissions is done by using an average number of balance weights for the various types of vehicle, an estimation of the share of lost weights and the corrosion rate.

- **Road surface wear:**
  The annual road surface wear averages approx. 1 mm on motorways and approx. 0.8 mm on main roads. It can be assumed that very rough particles are involved here which are first deposited on the road surface and then shifted or washed to the edge of the road partly due to the air turbulence caused by passing vehicles. The emissions were calculated using study results on the heavy metal content in abrasion.

Electric motors could be another emission source for lead from vehicles since lead is one of the components in the copper/carbon brushes. However, there are no detailed figures available on the total amounts used or the resulting emissions, so that a more accurate estimation of the environmental pollution was not possible.

Figure 2 shows the material flows and sinks and the different conditions which apply to roads within built-up areas and roads outside such areas, which also have to be taken into account when quantifying the discharges to soil and water resulting from vehicles’ emissions.
Steel surfaces are frequently coated with zinc as a protection against corrosion. A distinction is made between galvanic and thermal processes of applying the zinc coating. Continuous (e.g. strip galvanizing, wire galvanization) and discontinuous (e.g. individual pieces, thermal spray) processes are common in both the thermal and galvanic zinc coating methods. The thickness of the zinc coat applied varies to a wide extent depending on the process used and the demands made of the galvanized product. The range of galvanized products is very large. It extends from small mass-produced products (e.g. mounting parts, screws, springs), sheet metals, tapes and wire for varied applications through to pipes, large steel elements (e.g. grids, poles, steel railings, street furniture) and large steel constructions in the building sector, in large plant construction or in bridge constructions.

The zinc coating of individual pieces and wire coating are especially relevant for the possible environmental emissions from this sector and are not covered by the other application areas. Calculating the relevant area for piece-coated products was done specifically for the individual applications using the quantities, the specific surface and the weathered share less the organically coated share (duplex coating). The runoff relevant surfaces were calculated based on the statistics available for wire galvanization on the amount of iron and steel wire used. The zinc emissions from this sector end up almost entirely in the soil because of how the products are used.
Use of copper as a contact wire material in electric rail vehicles

The contact wires (overhead contact lines) of electrically-powered rail vehicles consist of a moulded copper wire with a diameter of 100 to 120 mm². The electricity is collected by the contact strip attached to the pantograph. There is mechanical stress on the contact wire due to the sliding contact. In addition, electrically induced wear of the contact wire takes place at the point of contact which far outweighs the mechanical wear. The amount of copper emitted can be calculated using the lifetime of the contact wires and the average wear. These amounts of copper are partially deposited in the close vicinity of the rails, but are also partially spread over a wider area and then enter the soil or water surfaces through wet and dry deposition. A distinction was made between trains and trams when calculating the emissions, since the share of copper emissions which are deposited directly on surfaces connected to sewers is much larger in the case of trams.

Use of copper to protect plants in farming

On account of its toxic effects, copper is used in agriculture as a fungicide. Copper oxychloride and copper hydroxide are the most common active ingredients used today. The most important use is for the specialized crops wine and hops, but these agents are also used in fruit and potato farming. The amount used can be estimated using the specific application rate in the individual applications. Furthermore, data on the amount of copper in circulation in plant protection products is available from the German Federal Office of Consumer Protection and Food Safety (Bundesamt für Verbraucherschutz und Lebensmittelsicherheit – BVL), based on information from the producers and distributors in accordance with §19 of the German Plant Protection Act. The amount of copper used is predominantly applied to farmland.

Less significant applications

Within the scope of the project, other potential emission sources were examined with regard to their relevance (copper emissions from wood protection products, copper emissions from detergents and zinc emissions from the use of zinc compounds as pigments). The results showed that these applications are only of secondary importance.

Summary of the results of the emission calculations

The results on the environmental emissions from the application areas described and on their retention in the various environmental compartments are shown in Figure 3. The review for copper shows the high importance of environmental emissions from vehicles (brake pads). This sector is also the most significant for emissions to soil, fol-
lowed by pesticides, drinking water distribution and overhead power cables. For emissions to water, drinking water distribution and roof runoffs are the most important sources after vehicles.

For zinc the environmental emissions from vehicles are also the highest by far (especially tyre wear). The second most important are galvanized products. There is the same order for emissions to soil, but roofs and facade materials are the most significant for emissions to water. This is because most of the emissions here end up in water, whereas soil is much more affected by the other emission pathways.

Of the applications examined in more detail, it is also true for lead that the biggest environmental emissions stem from vehicles. Similar to the other two metals, the predominant share here enters the soil. With regard to emissions to water, those from roofs and facades are the largest. Lead plays only a minor role in drinking water distribution.

In addition, Figure 4 shows the results of the emissions to water in detail, supplemented by the results of the emission pathway-related balance sheets for Germany. This comparison highlights the significance of the application fields examined for the total pollution of water, especially for copper and zinc. For lead, in contrast, their significance is lower due to the high other emissions (predominantly from farming).

The emissions to soil are shown separately in Figure 5. The comparison with the other relevant emission sources for soil included in the figure shows a mixed picture with regard to the most important emission sources (for copper: farmyard manure, for zinc: sewage sludge and for lead: the atmospheric deposition). In relation to the emissions from the predominantly agriculturally determined sources, the application areas examined within the scope of this project are only of secondary importance. The exception is emissions of copper from vehicles, which takes second place after manure.
Figure 3: Total emissions and discharges to water and soil from the applications areas examined for copper, zinc and lead.
Figure 4: Comparison of the emissions calculated for the individual applications to water with the emission pathway-related emissions 2

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2 according to Fuchs et al. (2002) and Böhm et al. (2001)
Figure 5: Comparison of the calculated emissions to soil for the individual applications with other emission sources

### Copper Emissions

- **Direct Emission Sources:**
  - DW roof
  - Roof vehicles
  - Overhead c.l.
  - Plant protection

- **Other Emission Sources:**
  - Mineral fertilizer
  - Compost
  - Sewage sludge
  - Manure
  - Atmos. deposition

### Zinc Emissions

- **Direct Emission Sources:**
  - DW roof
  - Roof vehicles
  - Galvanized prod.

- **Other Emission Sources:**
  - Mineral fertilizer
  - Compost
  - Sewage sludge
  - Manure
  - Atmos. deposition

### Lead Emissions

- **Direct Emission Sources:**
  - DW roof
  - Roof vehicles

- **Other Emission Sources:**
  - Mineral fertilizer
  - Compost
  - Sewage sludge
  - Manure
  - Atmos. deposition

The bar charts illustrate the comparison of calculated emissions for copper, zinc, and lead to soil for the individual applications with other emission sources.
Plausibility checks

To check the plausibility of the emission calculations, reference was made to the results of Fuchs et al. (2002), who quantified the point source and non-point source heavy metal emissions to surface waters based on emission pathways for Germany for the balance year 2000. In detail, the results available for the emission pathways "sewage plant effluents" and "stormwater sewers of separate systems" were used to check the order of magnitude of the calculated source-specific emissions to surface waters. In spite of the existing uncertainties, there is very good agreement between the data calculated using the different methods.

Future development of water emissions

The anticipated emission development from the various sources must be taken into account when evaluating possible emission reduction measures. The estimations listed in Table 1 show that a decrease or only slight changes are anticipated for water supply systems, galvanized products and overhead lines. An emission increase is expected both for emissions from roofing and facade materials because of the growth in the relevant surface areas and for the emissions of copper and zinc from vehicles.

Table 1: Future trends of emission development in the most important fields of application

<table>
<thead>
<tr>
<th>Sector</th>
<th>Developments</th>
<th>Overall tendency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drinking water supply</td>
<td>Drop in the use of metallic materials, standards set for the use of copper,</td>
<td>Slow decrease in emissions</td>
</tr>
<tr>
<td></td>
<td>replacement of lead pipes</td>
<td></td>
</tr>
<tr>
<td>Roof/facade materials</td>
<td>Definite growth in the relevant surfaces to be expected (for lead, however,</td>
<td>Definite growth in emissions if boundary conditions otherwise</td>
</tr>
<tr>
<td></td>
<td>mostly coated)</td>
<td>remain the same</td>
</tr>
<tr>
<td>Vehicles</td>
<td>Emissions dependent on road performance; forecasts for D: definite increase</td>
<td>growth in emissions; exception lead: decrease due to EU Directive</td>
</tr>
<tr>
<td></td>
<td>especially in the transport of goods</td>
<td></td>
</tr>
<tr>
<td>Galvanized surfaces</td>
<td>Zinc demand relatively constant for piece galvanization, increase in duplex</td>
<td>Slightly falling zinc emissions</td>
</tr>
<tr>
<td></td>
<td>coating</td>
<td></td>
</tr>
<tr>
<td>Overhead contact lines</td>
<td>slow increase in the length of contact wires, technical approaches to reduce</td>
<td>Only small changes</td>
</tr>
<tr>
<td></td>
<td>the wear</td>
<td></td>
</tr>
</tbody>
</table>
IV. Approaches to reduce the emissions to water

To reduce the copper, zinc and lead pollution of water, various starting points were described and assessed using the following criteria:

- Technical description: description of process, applicability, boundary conditions, technical pros and cons.
- Practicability: availability of the emission reduction technology, existing experiences.
- Effectiveness or reduction potential: specific emission reduction, total reduction potential.
- Economic impacts: costs of measure, as far as possible specific costs or cost-effectiveness (related to the emission reduction to be achieved).
- Possible instruments for implementation e.g. information programmes, voluntary industrial initiatives/commitments, economic instruments, command-and-control instruments.

This information can be used as a basis for implementing the Water Framework Directive if the audits in river basins reveal deficiencies in complying with good chemical quality and programmes of measures are to be developed to reduce the water pollution.

The basic starting points for reducing the emissions are, on the one hand, the avoidance or reduction of emissions by using substitute substances, modified metalliferous materials or, in the agricultural sector, through modified farming methods. On the other hand, there is the possibility of post-segregation of the substances by treating the polluted water flows. Measures were included which have the potential to reduce the emissions to water to a noticeable degree. In addition, only those measures are treated in more detail which are technically mature and have been tested in practice. The following measures were included:

- **Measures related to more than one substance:**
  - Building sector: use of substitutes or coated materials in new buildings/renovations
  - Treatment of stormwater runoff:
    a) decentralized: filter systems for individual buildings
    b) in the sewers: stormwater overflow tanks in combined sewer systems as well as soil filters in combined or separate sewer systems;
  - stormwater percolation;
  - reducing erosion in farming.

- **Measures related to specific substances:**
  - Copper:
- household plumbing: changing the composition of drinking water to reduce the rate of corrosion;
- in transport sector: use of substitute materials for copper in brake pads.

- Zinc:
  - Duplex coating of galvanized materials.

- Lead:
  - in transport sector: use of substitute materials for lead in brake pads
  - in transport sector: use of substitutes in balance weights.

### Use of substitutes or coatings in the building sector

There are alternative materials available for the majority of the applications of copper, zinc and lead in the building sector or coatings can be applied so that the copper, zinc or lead emissions can be avoided or significantly reduced. For example, substitutes include materials such as stainless steel, aluminium, plastics, tin-plated copper or organically coated zinc or lead. However, the use of these alternative materials may interfere considerably with the structural and architectural design of the affected building. Furthermore, it must be checked whether the technical functions linked with the use of copper, zinc or lead can also be fulfilled by the substitute or the coated materials. It is therefore necessary to make a differentiated examination of the various applications including the respective boundary conditions and to consider the ecological impacts associated with the alternatives. In additional studies, therefore, the applications in the building sector were examined in detail taking into account the advantages and drawbacks of the various materials (see Section V.).

### Decentralized treatment of stormwater before the discharge – filter systems for individual buildings

The stormwater running off metal roofs or facades is much more polluted than rainwater. To reduce the emissions to soil (taking place through rainwater percolation) or to the sewer system, it is possible to treat the water in a decentralised way. The main problem in treating roof runoffs is the variability of the loads: the hydraulic load fluctuates widely, extremely high quantities of runoff water can occur during heavy showers or thaws. The material load also varies widely; there are high material concentrations to start with, which can then decrease swiftly, at least for some substances (first-flush effect). Depending on the climate, long dry periods can also occur. In the past few years, different systems have been developed for the decentralised treatment of roof runoff. Some of these systems are equipped with integrated underground percolation (generally in shaft percolation systems), some serve to eliminate pollutants independent of the further discharge of the stormwater.
Treatment of stormwater in the sewer network – use of stormwater overflow tanks (combined system) or soil filters (combined and separate system)

If polluted stormwater is drained off via the sewer network, there are various possibilities to reduce the pollutant load carried by the water. Up to now, stormwater overflow tanks are often used as flood control storage in combined sewer systems. These can temporarily store combined water and then regulate its further discharge on to the sewage treatment plant in order to relieve the strain on the system during beginning rainy weather. In the separate system, in contrast, there is generally no stormwater treatment. Recently, there has been an increasing use of soil filter systems as one technology to treat stormwater. These can be used in both combined and separate systems. These systems usually consist of earth basins with several different layers of filters. By constructing stormwater overflow tanks or soil filter systems, not only heavy metal emissions to water are reduced, but also the hydraulic load (especially relevant for smaller water bodies), the emissions of other pollutants (nitrogen, phosphorous, organic pollutants etc.) and epidemic-hygienic relevant pollution. However, the actual degradation of the pollutants and thus the discharge to the environment is not avoided by the downstream treatment of the polluted water.

Stormwater percolation

Another possibility to reduce the substance inputs to water resulting from polluted stormwater lies in decoupling paved surfaces from the sewer system and allowing percolation of the rain falling on these areas. Rainwater which is allowed to seep away remains part of the natural local water cycle and reduces the load on sewer networks, sewage treatment plants and on watercourses serving as receiving water (hydraulic peak loads). Stormwater percolation, at least to some extent, is technically possible even in built-up areas and less permeable ground. Here, however, percolation has to be understood not as an isolated measure, but as part of a stormwater disposal system comprising (decentralised) percolation, (decentralised) storage and (regulated) discharge (concept of "natural" stormwater management). In the stock, unsealing surfaces can also be an important component of suitable concepts, for example for less used (traffic) areas. Various systems are available for stormwater percolation which differ especially with regard to the amount of space they require (e.g. surface, trough or trench percolation). The cleansing effect of the percolation depends on the filtration effect of the layers of soil through which the water seeps. Retained, non-degradable pollutants such as heavy metals remain in the soil.

Measures to reduce erosion in farming

Considerable heavy metal emissions enter water bodies from farming. The most important emission pathways are erosion and surface runoffs. The amount of emissions is strongly dependent on location-specific conditions such as the slope of the land, the
erosion strength of the rainfall and soil conditions. In addition, the erosion varies greatly over time (sediment entry to water predominantly during strong rainfall). Important single measures to reduce erosion are mulch or catch crops, adjusting crop rotation, soil-preserving land management and the minimization of mechanized field work. Erosion-minimizing measures are always in the self-interest of the landowner since the loess areas, which are particularly threatened by erosion, are very fertile. Therefore, a reduction of erosion can already be achieved through increased consultation. Another possibility is the imposition of farming conditions for erosion-endangered areas in combination with compensation benefits for the landowners. Obviously, it only makes sense to use such measures in regions really threatened by erosion.

**Copper in household plumbing – modification of drinking water properties**

Copper is extensively used in Germany as a material for household drinking water pipes. Due to the corrosion processes in metallic pipes, there is a continuous removal of small amounts of metal which end up in the drinking water. The corrosion behaviour of the metallic materials is influenced by many factors. The centralized softening of hard to medium hard water represents one possibility for a targeted adjustment of the properties of drinking water to reduce the corrosion rate where necessary. The corrosion processes in plumbing and thus also the emissions to drinking water and the pollutant load in wastewater, sewage sludge and water could be clearly reduced by softening the water and the related change in the pH value and the acidity/alkalinity. A current study of the advantages and drawbacks associated with centralised softening of hard water shows both ecological advantages (reduction of the emissions of copper and detergent degradation products) and economic advantages, if the savings possible in the households due to the softening are also taken into account (among others reduced use of washing and cleaning products and lower energy and water costs).

**Use of copper-free brake pads**

Up to now, copper is used in large quantities in brake pads, although there are copper-free brake pads offered on the market. However, so far these products are not being used to equip new vehicles, but only in the aftermarket sector. According to the manufacturer, copper is replaced by a combination of mineral and ceramic fibres. In contrast, according to the Association of the German friction material manufacturers (Verband der Reibbelagindustrie), there are no known alternatives in the sector which are on a par with copper. It is thought that replacing copper would be a major effort.

**Duplex-coating of galvanized materials**

The zinc removal from galvanized building components can be extensively reduced if an organic coat (varnish) is applied to the layer of zinc. Such duplex coatings have been used for many years. The tendency is increasing and is currently estimated at
30% of the galvanized goods produced. The zinc surface of duplex systems has to be pre-treated to achieve a good bonding of the organic coat. A wide range of varnishes can be used as organic coating substances. Single-pack or two-pack coatings of various compositions are processed (e.g. epoxy lacquers, PU lacquers, solvent- or water-based acrylic resin lacquers). Environmentally-compatible powder lacquers are increasingly being used for high quality coatings.

**Use of lead-free brake pads**
A conversion to lead-free brake pads is currently taking place. According to the End-of-Life Vehicle Directive 2000/53/EC from the year 2002, only lead-free brake pads are to be used in future. An exception is made for vehicles approved before 1.7.2003. Lead-free linings are already in widespread use in Germany. Due to the expected complete conversion to lead-free products, the emissions from this sector can be completely avoided.

**Use of lead-free balance weights**
The EU End-of-Life Vehicle Directive also sets requirements for balance weights: balance weights containing lead will only be permitted in vehicles which were approved before the 1\textsuperscript{st} July 2003. Corresponding substitutes for lead are available, for example zinc, tin and stainless steel are all used. The switch to these alternative materials is currently taking place; lead-free products are being offered on the market. Because of the higher prices of the alternative products, however, it can be assumed that garages will continue to use predominantly lead products until these are no longer available on the market.

The most important information for the measures described is summarised in Table 2. Cost-effectiveness analyses were used to assess the economic effects of the measures. The monetary costs were related to measures valuated in non-monetary terms. For this study the avoided emissions of copper, zinc or lead were used as reference values. To ensure the comparability of the results, the costs were calculated based on standardized parameters as far as possible (i.e. cost accounting method, technical service life, capital and operational cost). The results obtained on the cost-effectiveness of the measures show that:

- Savings are possible for stormwater percolation under favourable conditions. This also basically applies to the use of substitutes in the building sector, although additional requirements have to be taken into account here which could considerably restrict the choice of material (see chapter V.).
- The cost-effectiveness of the decentralised treatment of stormwater in filter systems is comparatively cheap, even if a wide margin exists here. In comparison to this, treatment in the sewer system is much more expensive.
• The data for erosion reduction in agriculture through increased consultation are of a comparable order of magnitude as the cost-effectiveness of decentralized stormwater treatment.

• To some extent, the measures related to individual substances also represent a cost-effective option to reduce the emissions of the respective substance (lead or copper-free brake pads, duplex coating of galvanized materials).

When evaluating the results, it should be considered that additional effects are connected with many of the measures which cannot be captured in the cost-effectiveness appraisal presented, but which may be of decisive importance when assessing the measures (e.g. additional effects of stormwater treatment in the sewer network or the erosion reduction in agriculture).
<table>
<thead>
<tr>
<th>Measure</th>
<th>Effect</th>
<th>Costs</th>
<th>Boundary conditions/comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Building sector: 1a) Use of substitute materials 1b) Use of coated materials</td>
<td>high effectiveness; only low reduction potential short-term (new buildings, renovations); avoids an increase in pollutant emissions</td>
<td>some alternative materials more expensive, some cheaper; differences in processing, technical features, service life etc. (-&gt; see Guideline)</td>
</tr>
<tr>
<td>2</td>
<td>Treatment of stormwater before the discharge – filter systems for individual buildings for 2a) extensive and 2b) small metal applications</td>
<td>high effectiveness; only low reduction potential short-term (new buildings, renovations); avoids an increase in pollutant emissions</td>
<td>Building costs between 3 - 15 €/m²; first estimates of operating costs</td>
</tr>
<tr>
<td>3</td>
<td>Treating stormwater in the sewer network - 3a) use of stormwater overflow tanks (combined system) 3b/c) use of soil filters (combined + separate system)</td>
<td>stormwater overflow tanks: medium effectiveness; soil filter: high effectiveness; high reduction potential; reduction of pollutant emissions from other sources as well as reduction of hydraulic stress</td>
<td>large fluctuation (among others, dependent on size of installation)</td>
</tr>
<tr>
<td>4</td>
<td>Percolation of stormwater</td>
<td>high effectiveness, but pollutants shifted to soil; high reduction potential; additional effect with regard to other pollutants and hydraulic stress</td>
<td>heavily dependent on boundary conditions; additional costs for disposing of polluted soil; savings possible under favourable conditions (sewer network, sewage treatment plant)</td>
</tr>
<tr>
<td>5</td>
<td>Erosion reducing measures in agriculture: 5a) increased consultation 5b) imposed conditions</td>
<td>high effectiveness for locations threatened by erosion; high reduction potential; also effective for other pollutants</td>
<td>5a) consultation approx. 5 - 10 €/ha•a 5b) compensation payments 60 - 130 €/ha•a</td>
</tr>
<tr>
<td>Measure</td>
<td>Effect</td>
<td>Costs</td>
<td>Comments</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>---------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Copper:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Household plumbing: modifying the drinking water properties (centralised softening)</td>
<td>high effectiveness under favourable conditions, but depends on boundary conditions; average reduction potential; short-term effect;</td>
<td>costs of centralised softening approx. 0.1 to 0.5 €/m³; but: compensation of additional costs through household savings</td>
<td>only applicable under certain conditions (drinking water properties, share of copper fittings); also effective for existing stock</td>
</tr>
<tr>
<td>7 Use of copper-free brake pads</td>
<td>high effectiveness; high reduction potential;</td>
<td>no additional costs for copper-free products in aftermarket</td>
<td>evaluation of substitute materials necessary; current change-over to lead-free products; approach necessary at a national level</td>
</tr>
<tr>
<td><strong>Zinc:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Duplex-coating of galvanized items</td>
<td>high effectiveness; high reduction potential; already used today for about 30 % of products</td>
<td>costs: 7 - 12€/m² (depending on coating system, quality of corrosion protection, etc.)</td>
<td>ecological assessment of the duplex process necessary; implementation possible in the field of public procurement</td>
</tr>
<tr>
<td><strong>Lead:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Use of lead-free brake pads</td>
<td>high effectiveness; high reduction potential; impact only medium-term;</td>
<td>no additional costs for lead-free pads</td>
<td>measure already being implemented</td>
</tr>
<tr>
<td>10 Use of lead-free balance weights</td>
<td>high effectiveness; low reduction potential;</td>
<td>costs of lead-free products much higher, but still a low proportion of total costs of tyres</td>
<td>measure already being implemented</td>
</tr>
</tbody>
</table>
Figure 6: Cost-effectiveness of the various measures for copper, zinc and lead

<table>
<thead>
<tr>
<th>Measure</th>
<th>Copper Cost-effectiveness [€/g]</th>
<th>Zinc Cost-effectiveness [€/g]</th>
<th>Lead Cost-effectiveness [€/g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building sector - substitute/coated materials</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>Treatment of stormwater - decentralized filter systems</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>Treatment of stormwater - combined sewer system</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>Treatment of stormwater - soil filters (combined system)</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>Treatment of stormwater - soil filters (separated system)</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>Stormwater percolation</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>Erosion reducing measures (consultation)</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>Erosion reducing measures (imposed conditions)</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>Household plumbing: Drinking water properties</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>Duplex-coating of galvanized materials</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
</tbody>
</table>

Notes:
- Copper: 0-25 €/g
- Zinc: 0-6 €/g
- Lead: 0-30 €/g
- Under favorable terms: savings in the household
- No additional costs in the aftermarket sector
- Compensation by savings in the household
- No general data
V. Explanatory report on the guideline for the building sector

In urban areas, the use of zinc, copper and lead in the building sector (with the exception of copper abrasion from brake pads) is the largest single source for heavy metal emissions in household and stormwater drains. Individual regulations in the federal states such as, e.g. in Bavaria and Baden-Württemberg, acknowledge this fact by requiring a permit to dispose of the stormwater on a site. However the regulations are of a general nature and the functional and design contexts of the buildings are not considered. For this reason, methods to reduce the emissions of heavy metals in the building sector are to be supplied in the form of a guideline for town planners, for architects and builders, which take into account both water protection and the building issues. The following objectives with regard to content were set for this guideline:

- The application of zinc, copper and lead in flashings exposed to the weather should be reduced to a technically justifiable amount.
- Important and proven standards for the application of zinc and copper in small auxiliary functions of roofing should remain possible.
- Care should be taken that any substitution in auxiliary building functions does not result in solutions which are in turn connected with unacceptably high economic burdens.
- Alternative products and constructions to avoid heavy metal emissions during the service period should not on their part be connected with considerable environmental burdens during the extraction and production (including recycling) in order to avoid merely shifting environmental impacts to other categories.
- Treatment options of the stormwater runoff should also be included.
- The creative design work of the architects should be restricted as little as possible.

To start with, the common uses of zinc and copper sheets are divided into 5 building component groups with varying significance for the targeted reduction. The most frequent substitutes were then assigned to the building component groups.

1. **Large-area roofs and metal coverings**: aluminium sheets, tin-plated copper sheets and stainless steel.
2. **Small-area roof and facade elements**: aluminium sheets, coated aluminium sheets, tin plated copper sheets and stainless steel.
3. **Small purely functional metal sheets**: aluminium sheets and tin-plated copper sheets.
4. **Rainwater systems**: PVC, cast iron, galvanized steel, aluminium sheets, tin-plated copper sheets and stainless steel.
5. **Free standing galvanized building components**: corrosion protection via coating systems according to DIN EN ISO 12944, powder coating, stainless steel and wood.

Lead in its non-coated and thus unprotected form was not considered since this should always be substituted because of its fewer technical applications (with the exception of the preservation of monuments and historic buildings) and its particularly ecotoxicological importance.

A mathematically weighted reference area was defined in order to make the very diverse application areas of zinc and copper sheets recordable, assessable and comparable in a guideline with regard to the weathered surfaces, the slope involved and the building orientation. The planned or real metal surfaces are converted into an imaginary horizontal reference surface in m² with correction factors for the slope, building overhang and orientation. The factors were derived on the one hand from building codes of practice and roofing regulations, on the other hand, the conversion of the slope and orientation-dependent runoff rates were based on corresponding field trials.

### Slope and orientation factors

<table>
<thead>
<tr>
<th>Building component feature</th>
<th>Σ Net visible area</th>
<th>Slope factor</th>
<th>Orientation factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>flat sloping metal surfaces, outdoor exposure e. g. attic coverings, roof flashings below 20° etc.</td>
<td>m²</td>
<td>1</td>
<td>0.0</td>
</tr>
<tr>
<td>sloped metal surfaces, outdoor exposure, e. g. roof flashings, bay window coverings, 20° to 70°</td>
<td>m²</td>
<td>0.7</td>
<td>0.0</td>
</tr>
<tr>
<td>sloped metal surfaces, outdoor exposure, e. g. roofing and facade sheets, bay window coverings 70° to 90°</td>
<td>m²</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>........ one-side to main weather side</td>
<td>m²</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>........ peripheral orientation, or orientation to all sides</td>
<td>m²</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>........ diagonally or away from main weather side</td>
<td>m²</td>
<td>0.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

In order to be able to take into account each of the respective existing building sizes for the evaluation, the targeted restriction of the reference surface is based on the building base area BA.

The result of the calculations is the "rated surface" ($S_R$) = amount m²/m² BA of the planned reference surface. The evaluation and the estimation of the necessary substitutions or planning modifications results from the comparison with a "limited surface" ($S_L$) = amount m²/m² BA of a limited reference surface.
A concrete value was estimated to set the necessary tolerance limit for the application of zinc and copper sheets based on 100 m² building base area as the building-dependent surface variable. This tolerance value is derived from structural-engineering criteria on the one hand and, on the other, from the estimated runoffs to be tolerated by the surfaces. An acceptable tolerance limit of 10 m² $S_L / 100$ m² base area BA resulted from the virtual calculation of several typical building projects. For the subsequent determination on location, a table was proposed citing what is washed away from the tolerance area for different regionally given amounts of stormwater and weather directions. In this way, the tolerance limit can be adjusted to local conditions.

The comparative ecological assessment of the common material alternatives in the individual building component groups is done using life-cycle data on the manufacturing of the materials (updated data sets on the resource indicators of renewable and non-renewable energy sources and on five selected impact categories) under qualitative consideration of the emissions during the service period. All building component groups were regarded in turn; the life-cycle data were presented for the relevant material alternatives based on the respective functional equivalents. The data show that fewer environmental effects result for the manufacture of zinc products and, somewhat restricted also of copper products in comparison to the alternative materials such as aluminium or stainless steel. However, the lower pollution during the manufacturing phase has to be set against the environmentally-relevant pollution during the service period from the heavy metal emissions to water and soil.

The guideline for town planning authorities, architects and builders consists of five consecutive steps:

1. In the first step of the preliminary check, the builder or planner has to determine whether the regulations of the guideline apply to his building project. In this way, plans which do not incorporate any appreciable shares of zinc or copper sheeting can be excluded.

2. During the initial inspection of the building plan, it is determined whether the tolerance limit underlying the guideline is surpassed. If it is not reached, no further steps are necessary, although there are restrictions on the percolation of stormwater. If it is reached or even exceeded, there are further restrictions for the percolation of the runoff water. For projects without the application of large areas of heavy metal sheets, sometimes the set targets can be met by undertaking only a small substitution of material.

3. Emissions can be avoided by treating the stormwater e.g. using a filter system.
4. Preliminary purification using a filter system will not always be able to avoid emissions to water or soil, e.g. from a historic metal covering. For listed buildings, a balance has to be found between the public interests in protecting the environment and protecting historic buildings.

5. In the fifth step, the alternatives for the originally planned but no longer realisable zinc or copper covering have to be examined. Depending on the roof form and its use, there are technically suitable and ecologically reasonable variants available. In the specific concrete case, a life-cycle assessment of the roof variants should be done taking into account regional boundary conditions.

For each step, aids are included to help with the guideline. These include explanations of the application areas with a simplified table for calculating the reference areas resulting from each planning stage. Information is also provided on the alternative possibility of wastewater treatment using filter technology. Different consequences are possible when applying the guideline depending on the planning requirement; these range from restrictions of stormwater percolation to targets for stormwater purification up to exchanging the planned roofing and facade materials. Test applications show that single-family homes are not or are hardly affected, but that clearer restrictions may arise for larger buildings or purpose built blocks, e.g. in the selection of other materials, coated metal sheets or stormwater purification.

VI. Documentation and further development of ecological assessment methods in roofing materials

In the field of building or building materials various life-cycle studies have been made recently on the level of building substance, building component and whole building. However, the problems associated with the selection and assessment of roofing and facade materials incorporating copper, zinc and lead have only been dealt with in very few cases. These cases especially emphasised the environmental pollution associated with the corrosion taking place with these materials during the service period. As a result, in Switzerland, for example, it is advised to do without their application as far as possible. However, so far, there has been no comprehensive life-cycle evaluation of the relevant roofing materials in the building products sector taking into account the special boundary conditions (e. g. high significance of the service period, influence of the installation and other frame conditions, and the fact that the useful life is only partly determined by the product features).
Since especially copper and zinc are used for a wide variety of applications, there are, corresponding life cycle inventory data available for the manufacture and processing of these materials. According to the life-cycle methodology, the heavy metal emissions occurring during use should be considered under the impact categories human toxicity and ecotoxicity. There are as yet no widely recognized aggregation methods available for the aggregation of these emissions with other human- or eco-toxically relevant emissions (such as e.g. heavy metal emissions during production or pollutant emissions during the generation of the energy necessary for production). In addition, it should be noted that there are particular methodological problems associated with the assessment of essential heavy metals such as copper and zinc (e.g. speciation of the metal, bioavailability, effects dependent on the concentration range).

Comparing the heavy metal emissions from the service period with the production phase and the available data on the ecological prioritisation shows the large significance of the emissions resulting during the useful life of metallic roofing materials. These are significant both in comparison with the other ecotoxically relevant emissions in the life cycle of these materials, as well as in relation to the other impact categories relevant in ecological assessments. In an ecological comparison of different materials, therefore, these emissions should each be assessed separately as individual indicators, even if the methodological base for an aggregation and an ecological prioritisation of the impact categories of human and ecological toxicity is not yet available.