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# Non-point pollution with cadmium

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## NON-POINT POLLUTION WITH CADMIUM

by

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The Kiel Institute of World Economics

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# CONTENT:

# 1. INTRODUCTION

Cadmium is one of the most toxic heavy metals in the human environment. Although it does not serve any particular function in biological processes, it is part of the industrial activities, either in the production of chemicals, batteries, plated metal products, glass, and ceramics or as a contamination of raw material inputs in production, most notably Zinc, Lead, and Copper, but also coal, iron and sand (KLEPPER/MICHAELIS 1991). Therefore, these activities present a continuous potential health threat as long as the material flow of Cadmium in the economy is not controlled.

The control problem is exemplified by the fact that the throughput of Cadmium in Germany is about 3.000 t/a of which approximately 1.000 t/a are added to the existing stock. Of those 1.000 t/a, emissions into the environment in the early 1990s amount to between about 30 and 40 t/a which are composed of air emissions with between 13 and 23 t/a and aqeous emissions of approximately 16 t/a (KLEPPER/MICHAELIS 1991). The total amount of Cadmium emissions reveals little about the environmental impact and the threat to human health which these emissions can cause. It is therefore necessary to relate total emissions to the impact. E.g., the WHO has set the critical exposure level for humans at a tolerable weekly intake of 0.5 mg which predominantly comes from food intake and through smoking (EWERS 1990).

The material flow of Cadmium leading to the increase in the stock in the environment does not end with air emissions, water emissions, and waste disposal; the final media in which Cadmium ends are the soil and lakes and the sea. Information about the material flows in these media is unequally distributed and some puzzles still remain to be solved. In KLEPPER/MICHAELIS (1991) it is estimated that about 16 t/a of Cadmium leave Germany through rivers. However, only about 4.2 t/a can be identified as point sources such as municipal and industrial waste water treatment plants. The other approximately 12 t/a can originate from the

- direct atmospheric deposition of air emissions to surface waters,
- run off from atmospheric deposition on soils,
- run off from the application of sewage sludge on agricultural and other soils,
- run off from the use of phosphate fertilizers containing Cadmium, and
- the erosion of contaminated soils.

Given the small share of rivers and lakes on the total surface area of Germany, the direct impact of atmospheric deposition is probably quite low. However, for the other non-point sources this question can not be as easily answered by simply looking at the deposition of Cadmium on soils, since rather complex processes take place after Cadmium has

entered the soil. The dynamics of these processes then determine the final fate of Cadmium either in the run off - on the surface and in the groundwater -, its fixation in the soil, or the further removal through the harvesting of crops which have assimilated the Cadmium. This paper tries to summarize the information about the impact of non-point cadmium deposition on soils, the subsequent dynamic processes in the soil, and of non-point emissions into the water.

## 2. PHOSPHATE FERTILIZERS

### 2.1 FERTILIZER CONSUMPTION

For a long time, the dominating Phosphate fertilizer in German agriculture was Thomas Phosphate, a by-product of the traditional iron and steel production. Because of the high temperatures of these processes, the Cadmium which is originally contained in the raw phosphate is removed from it - and emitted into the atmosphere or collected in dust arresters - such that the basic slag is practically free of Cadmium. New processes for producing iron and steel have replaced the use of Phosphate such that the supply of Thomas phosphate as a fertilizer amounting to about 50 per cent of Phosphate fertilizer consumption in Germany in the 1960s has been reduced to less than 10 per cent in 1990/91 (see Table 2.1). Parallel to this development the use of other Phosphate fertilizer has increased until the early 1970s and has been falling most pronounced in the 1980s. However, the overall input of fertilizers containing Cadmium has fallen even though their share in the total consumption of Phosphate fertilizers has been rising (see Tables 2.2 and 2.3). This reduction in the use of inorganic fertilizers stems from the downward trend in the prices of agricultural commodities which has lowered the derived demand for inputs and the increase in the planned use of nutrients in manures, i.e. the rational use of organic fertilizers (WICHMANN 1988; SCHINDLER 1986).

Table 2.1 — Production and Consumption of Phosphate Fertilizers in West Germany 1955/56 - 1990/91 (1000 t Phosphate ($P_2O_5$))

|  | Total | P-Fertilizers (single nutrient) | | N-P-K-Fertilizers (compounds) |
|---|---|---|---|---|
|  |  | Total | Thomas Phosphate |  |
| Production |  |  |  |  |
| 1955/56 | 498.1 | 404.3 | 298.6 | 93.8 |
| 1960/61 | 767.9 | 552.0 | 41.2 | 215.9 |
| 1965/66 | 948.7 | 622.2 | 414.5 | 326.4 |
| 1970/71 | 945.8 | 497.0 | 317.7 | 448.8 |
| 1975/76 | 649.0 | 349.6 | 74.9 | 299.4 |
| 1980/81 | 686.7 | 358.4 | 153.7 | 328.3 |
| 1985/86 | 446.2 | 158.7 | 60.5 | 287.6 |
| 1990/91 | - | - | - | - |
| Consumption |  |  |  |  |
| 1955/56 | 479.1 | 362.8 | 291.9 | 116.3 |
| 1960/61 | 662.4 | 419.5 | 366.6 | 242.8 |
| 1965/66 | 833.2 | 445.5 | 400.5 | 387.8 |
| 1970/71 | 913.1 | 351.3 | 302.8 | 561.8 |
| 1975/76 | 779.7 | 250.0 | 176.8 | 529.7 |
| 1980/81 | 837.5 | 194.7 | 130.4 | 642.8 |
| 1985/86 | 736.8 | 125.7 | 49.3 | 611.2 |
| 1990/91 | 509.1 | 89.9 | 42.3 | 419.2 |

Source: STATISTISCHES BUNDESAMT (1987a, 1991).

## 2.2 SOURCES OF PHOSPHATE FERTILIZERS

Since Raw Phosphate and Phosphate fertilizers from different locations have different Cadmium contaminations an assessment of the Cadmium input into agriculture needs to take into account the regional structure of imports of Raw Phosphate - the input in the production of fertilizer - and of phosphate fertilizers which are imported as finished products. Table 2.2 shows the regional structure of the German imports of Raw Phosphate which then is processed in Germany and turned into Phosphate fertilizer. Since the different sources of supply correspond to different Cadmium contents, the Cadmium load of these imports can only be estimated with the help of the average concentration of Cadmium in the Raw Phosphates. In Table 2.3 Cadmium concentrations of different Raw Phosphates and of Phosphoric acids are presented which show that especially African supplies have relatively high concentrations. Most notably Phosphoric acid but also Raw Phosphate from Senegal, Togo, and Tunesia have contributed significantly to the Cadmium load. Therefore German producers of fertilizer have voluntarily restricted imports (BECKER 1989) in order to maintain reasonably low Cadmium concentrations as it is evident from Table 2.2.

Table 2.2 — German Imports of Natural Phosphates and Phosphatic Chalk by Country of Origin (1000 t)

| | 1980 | 1982 | 1984 | 1986 | 1988 |
|---|---|---|---|---|---|
| Developed Market Economies | | | | | |
| USA (+ Ruerto Rico) | 1443 | 905 | 828 | 718 | 496 |
| Belgium-Luxembourg | - | - | - | - | 4 |
| Netherlands | - | - | - | 2 | 13 |
| Israel | 133 | 161 | 192 | 156 | 176 |
| South African Custom Union | - | 6 | 167 | 257 | 204 |
| Centrally Planned Economies | | | | | |
| USSR | 387 | - | - | 20 | 75 |
| China | 1 | - | - | - | - |
| Developing Market Economies | | | | | |
| Morocco | 339 | - | 22 | 224 | 158 |
| Algeria | 4 | - | 4 | 46 | 28 |
| Tunesia | - | - | 8 | 4 | - |
| Senegal | 91 | - | - | (56)* | - |
| Togo | 170 | 45 | 53 | 7 | - |
| Jordan | - | - | - | 37 | 3 |
| Syria | 4 | - | - | - | - |
| Others | - | 810 | 646 | 101 | - |
| Total | 2572 | 1927 | 1920 | 1572 | 1154 |
| * 1985. | | | | | |

Sources: UNITED NATIONS, current issues.

The import structure of Raw Phosphates only determines the final Cadmium content of Phosphate fertilizers produced in Germany. Since an increasing share of the Phosphate fertilizers consumption is satisfied through imports the total Cadmium input from the use of fertilizer needs to take into account the concentration of these imports as well. Table 2.4 makes evident the increasing importance of imported fertilizer and the trend towards the use of compound fertilizers. The Cadmium inflow through these imports is predominantly due to the compound fertilizers since the imports of single nutrient - Phosphate fertilizer are dominated by Thomas Phosphate which is not contaminated with Cadmium.

5

Table 2.3 — Phosphate and Cadmium Content of Raw Phosphates and Phosphoric Acids by Country of Origin

| Country of Origine | P-Content (per cent) | Cd-Content ( ppm) |
|---|---|---|
| *Raw Phosphates* | | - |
| USA | | 7.0 - 9.0 |
| USSR | | < 1.0 |
| Morocco | | 12.2 - 15.3 |
| Algeria | | 17.0 - 23.0 |
| Togo | | 59.1 - 61.9 |
| South-Africa | · | 0.03 - 1.7 |
| Israel | | 18.4 - 28.7 |
| Jordan | | 5.3 - 8.2 |
| Syria | | 7.5 |
| *Phosphoric Acids* | | |
| Morocco | 56.0 - 57.8 | 15 - 24 |
| Togo | 28.8 - 28.4 | 33 - 42 |
| Senegal | 39.9 | 54 - 120 |
| North Carolina | 51.0 - 54.0 | 30 - 36 |
| Florida | 29.6 | 6 |

Sources: FRANKENFELD/RUSCHKE (1985); BÖHM/SCHÄFERS (1990).

Table 2.4 — German Imports of Phosphatic Fertilizer Containing Cadmium (1000 t $P_2O_5$)

| | Total (incl. Thomas Phosphate) | Total (excl. Thomas Phosphate) | Single Nutrient (excl. Thomas Phosphate) | Compound Fertilizers |
|---|---|---|---|---|
| 1980/81 | 270.6 | 196.1 | 27.7 | 169.1 |
| 1981/82 | 277.3 | 228.1 | 14.9 | 213.1 |
| 1982/83 | 321.3 | 294.4 | 24.9 | 269.5 |
| 1983/84 | 354.9 | 299.3 | 30.2 | 269.1 |
| 1984/85 | 327.4 | 282.9 | 39.7 | 243.2 |
| 1985/86 | 397.7 | 385.0 | 46.5 | 311.5 |
| 1986/87 | 404.1 | 363.2 | 38.4 | 324.8 |
| 1987/88 | 451.0 | 408.7 | 29.0 | 379.7 |
| 1988/89 | 398.9 | 353.4 | 37.3 | 316.1 |
| 1989/90 | 398.3 | 365.9 | 33.4 | 332.5 |

Sources: STATISTISCHES BUNDESAMT (1987a); FOOD AND AGRICULTURE ORGANISATION (1991).

Unfortunately, it is not possible to determine the structure of German imports of compound fertilizers by country of origin in terms of the amount of Phosphate fertilizer, i.e. in tons of $P_2O_5$. Only the total weight of the N-P-K fertilizers is reported in the statistics, but the composition of the different components is not reported. Therefore one can only assess in a rough calculation the likely Cadmium concentrations of those imports. In order to estimate these loads one needs to know the cadmium concentration of the the Raw Phosphates which the major suppliers of N-P-K fertilizers to Germany use in the production of these fertilizers. Table 2.5 summarizes the major exporters through

which German consumption is served. The largest suppliers of compound fertilizers are the Benelux countries, the Unites States, and Denmark. Single nutrient P-fertilizer imports are dominated by Belgium and Luxembourg for which one can suspect that a large proportion of those imports consists of Thomas Phosphates from the Belgian steel industry, i.e. without Cadmium.

Table 2.5 — German Imports of Fertilizer by Country of Origin (1987)

| | P-Fertilizer (1000 t) | N-P-K-Fertilizer (1000 t) | P-Fertilizer (%) | N-P-K-Fertilizer (%) |
|---|---|---|---|---|
| Netherlands | 36.0 | 270.6 | 5.9 | 14.8 |
| USA | - | 264.0 | - | 14.4 |
| Belgium-Luxembourg | 422.5 | 229.0 | 69.5 | 12.5 |
| Denmark | 0.8 | 229.0 | 0.1 | 12.5 |
| Italy | - | 158.6 | - | 8.6 |
| Austria | - | 158.6 | - | 8.6 |
| Yugoslawia | - | 131.5 | - | 7.2 |
| France | 85.4 | 125.3 | 14.0 | 6.8 |
| Hungary | - | 85.5 | - | 4.7 |
| Rumania | - | 50.7 | - | 2.8 |
| Great Britain | - | 22.7 | - | 1.2 |
| Turkey | - | 19.6 | - | 1.1 |
| Norway | - | 18.1 | - | 1.0 |
| Tunesia | 39.0 | 17.5 | 6.4 | 0.9 |
| Sweden | - | 13.9 | - | 0.8 |
| Portugal | - | 12.8 | - | 0.7 |
| Poland | - | 10.7 | - | 0.6 |
| Spain | - | 9.8 | - | 0.5 |
| Switzerland | - | 2.0 | - | 0.1 |
| Jordan | - | 1.0 | - | 0.05 |
| Israel | - | 0.6 | - | - |
| South-Africa-Custom-Union | - | 0.1 | - | - |
| Irak | 15.0 | - | 2.5 | - |
| Morocco | 8.3 | - | 1.4 | - |
| Total | 608 | 1834 | 100 | 100 |

Source: UNITED NATIONS (1987).

The Raw Phosphate sourcing of these exporters is clear for the USA which have their own Phosphate ore deposits with low Cadmium contents for Phosphates from Florida and higher for those from North-Carolina (see Table 2.3). Since the shares of the two sources are unknown one can not deduct the likely Cadmium concentrations of the fertilizer. Still, it is clear that they will be lower than those from other suppliers. The Raw Phosphate imports of the other major suppliers of N-P-K fertilizers are summarized in Table 2.6. These countries buy their inputs predominantly from Morocco, the United States, and to a lesser extent from South Africa. Since all these supplies of Raw Phosphates have relatively low Cadmium contents, the average Cadmium content of the

Table 2.6 — Structure of Raw Phosphate Imports of Major Fertilizer Suppliers to Germany (1987)

| | Total Imports of Raw Phosphates (SITC 271.3) | South-African Custom-Union | Algeria | Morocco | Tunesia | Togo | Senegal | Israel | Jordan | Syria | USA | Others |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Netherlands (14.8%)* | 2213 | 171 | 26 | 615 | - | 181 | - | 515 | - | - | 695 | |
| Belgium-Luxembourg (12.5%) | 2522 | 354 | 4 | 1589 | 43 | 25 | 9 | - | 10 | - | 362 | |
| Denmark (12.5%) | 228 | 67.3 | 13.1 | 124 | - | - | | - | - | - | - | 12.5 |
| Italy (8.6%) | 578 | - | | - | - | - | - | - | - | - | - | |
| Austria (8.6%) | 271 | - | - | - | - | - | - | - | - | - | - | |
| Yugoslawiia (7.2%) | 1374 | - | 47 | 530 | | 128 | 82 | - | 365 | 183 | 5 | 19.5 |
| France (6.8%) | 3755 | 13 | 208 | 851 | 194 | 266 | 212 | 959 | 18 | 163 | 857 | 11 |
| Average Cd-content of Raw Phosphates | - | 1-3 | ~20 | 13-22 | > 30 | ~65 | 60-120 | ~23 | ~6 | 8 | ~6 | |

* share of German N-P-K fertilizer imports.

Source: UNITED NATIONS, 1987; Table 2.3; Table 2.5.

8

P- and N-P-K-fertilizer imports of Germany will probably not deviate significantly from the domestically produced fertilizers. The only supplier with somewhat higher Cadmium concentrations may be France which still imports highly contaminated Raw Phosphates from Tunesia, Togo, and Senegal.


## 2.3 THE CADMIUM LOAD OF PHOSPHATE FERTILIZERS

The transport of Cadmium through Phosphate fertilizers into agricultural land and its subsequent transport through the soil depends among other things on the quantity which is consumed and on the concentration of Cadmium in the fertilizer. The latter is not only influenced by the regional source of the raw material, it also depends on the processing of the raw Phosphates, in particular whether any processes for the removal of Cadmium are applied.

Phosphate fertilizer is produced from Raw Phosphate which through grinding and chemical processes is converted into Phosphoric acid. This, in turn, is the basic material for most of the different kinds of Phosphate fertilizers (FAYARD 1988). During this process waste materials - mainly gypsum - are removed such that the Cadmium content of the Phosphoric acid is higher than that of the Phosphate ore (see Table 2.3). Depending on the process technique for producing Phosphoric acid, the waste materials contains 20% to 50% of the Cadmium (ELGERSMA ET AL. 1991) such that it is practically impossible to deduct from the Cadmium content of the raw material its exact concentration in the fertilizer.

Without considering any removal activities, the inflow of Cadmium through imports of Raw Phosphates has been falling throughout the 1980s. Given the import data and the average concentrations of Cadmium by the country of origin, one can estimate that in 1980 about 38t of Cadmium have entered Germany through imports. By 1988 this amount has been reduced to about 11 t (Table 2.7). The overall reduction of raw Phosphate imports as well as the elimination of mainly African imports with high Cadmium contents are responsible for this reduction of Cadmium flows from domestically produced fertilizers.

Since only about 34% of the German consumption of Phosphate fertilizer is domestically produced, the Cadmium load of Phosphate fertilizers in Germany is to a large extent determined by the Cadmium contamination of imported fertilizers. 90% of the imports are compound fertilizers and the remaining single nutrient fertilizers consist to a large extent

Table 2.7 — Cadmium Inflow through Imports of Raw Phosphates in Germany (1980 -1988; kg Cd)

| | Average Cd-Content (ppm) | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 |
|---|---|---|---|---|---|---|---|---|---|---|
| USA (+Puerto Rico) | 8 | 11544 | 656 | 7240 | 7512 | 6624 | 6784 | 5744 | 4904 | 3968 |
| Israel | 23 | 3059 | 2369 | 3703 | 3841 | 4416 | 4025 | 3588 | 3611 | 4048 |
| South-African Custom Union | 2 | - | 128 | 12 | 122 | 334 | 400 | 514 | 380 | 408 |
| USSR | 0,5 | 179 | 194 | - | - | - | - | 10 | - | 38 |
| Morocco | 16 | 5424 | 7424 | - | - | 352 | 192 | 3584 | 4832 | 2528 |
| Algeria | 20 | 80 | - | - | - | 80 | 440 | 920 | 1020 | 560 |
| Tunesia | 30 | - | - | - | 480 | 240 | - | 120 | - | - |
| Senegal | 75 | 6825 | - | - | - | - | 4200 | - | - | - |
| Togo | 62 | 10540 | 5704 | 2790 | 1798 | 3286 | 868 | 434 | 992 | - |
| Jordan | 7 | - | - | - | 21 | - | 70 | 259 | 21 | 21 |
| Syria | 8 | 28 | 152 | - | - | - | - | - | - | - |
| Unidentified | (*) | - | - | 4050 | 4066 | 3230 | 3015 | 505 | 440 | - |
| Total | | 37679 | 24627 | 17795 | 17840 | 18562 | 19994 | 15678 | 16200 | 11163 |

(*) Cd-content set to 5 ppm. Most of the imports are probably from the USSR.

Source: Computed from tables 2.2 and 2.3 as imports weighted by average Cadmium contents and United Nations. Commodity trade statistics.

of Thomas Phosphates. Therefore, it is mainly the Cadmium content of the compound fertilizer imports which may contribute to the inflow of Cadmium into Germany. It has been shown above that the Cadmium load of the German compound fertilizer imports is likely to be similar to that of the domestically produced. If one extrapolates the Cadmium load through the German supplies to that of the net imports, then the total input of Cadmium into Germany through fertilizers should amount to approximately 32 t/a. This is significantly less than the quantities of 48.8 t/a which are estimated by BÖHM/SCHÄFERS (1990) who have based their number on rather high average Cadmium contents of the Raw Phosphates.

## 2.4. REMOVAL OF CADMIUM FROM PHOSPHATE FERTILIZERS

The inflow of Cadmium into the soil through Phosphate fertilizers can be reduced in three different ways:

- Raw materials with lower Cadmium content can be used in the production of fertilizers.
- Less Phosphate fertilizers can be consumed in agriculture.

10

- Cadmium can be removed from the Phosphates.

The first option has been partially used with the reduction of raw phosphate imports from African countries as has been described above and the second option has also materialized - willingly or unwillingly - as it is evident from the declining consumption. The removal of Cadmium from the raw phosphates has not been used so far.

Several processes for the extraction of Cadmium in the production of Phosphate fertilizer are available today (SAUERBECK 1982):

1. Calcination of Raw Phosphates
   (80-90% Cd reduction; Energy Intensive)

2. Extraction from Phosphoric Acid
   2.1 Ion Exchange
   2.2 Wet Extraction with a Solvent
   2.3 Active Carbon
   2.4 Electrolytic Process
   2.5 Chemical Separation

Whereas the removal from raw phosphate through high-temperature processes turned out to be too costly, most of the separation processes for phosphoric acids were not designed for all types of acids with different Phosphate and Cadmium contents or had problems with the disposal of the removed Cadmium. A report by BECKER (1989) concluded that only the extraction process from wet phosphoric acid by a solvent could be considered sufficiently universal and cost efficient.

The wet extraction process has by now been developed to large scale applicability and a plant with a capacity of 70,000 t $P_2O_5$ p.a. has already been built. It consists of three processing steps:

1. Extraction of Cadmium from wet process phosphoric acid by an inmiscible solvent phase;

2. Reextraction of Cadmium from the loaded solvent phase by an aequeous salt solution;

3. Working up of the Cadmium-containing aqueous salt solution and transfer of the extracted cadmium into a concentrate, suitable for disposal (CHEMISCHE FABRIK BUDENHEIM 1991).

Figure 2.4 — CFB-Process for the Removal of Cadmium from Wet Phosphoric Acid
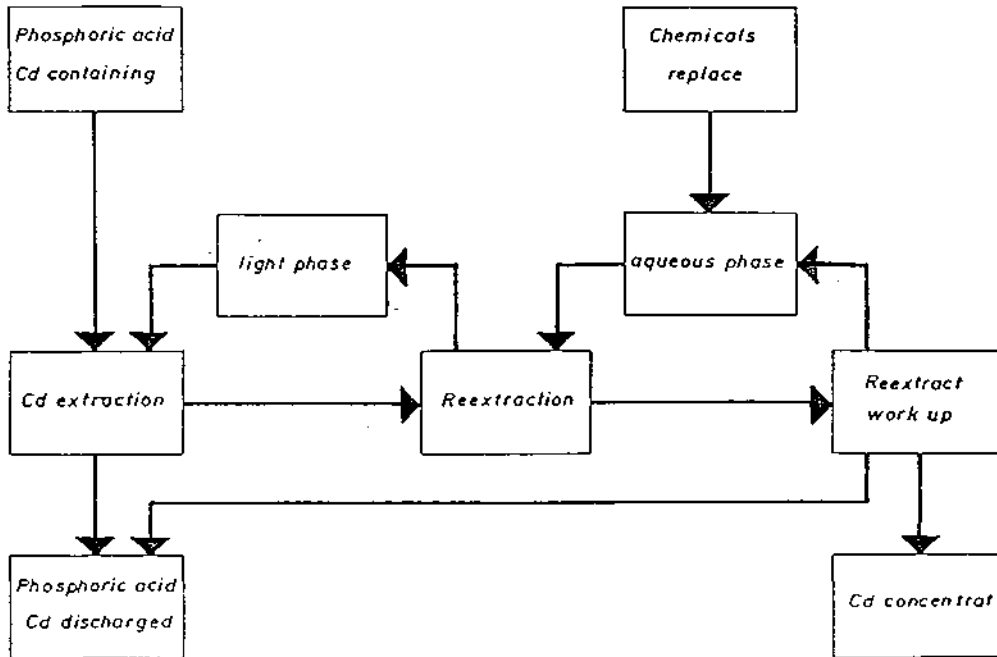


Source: CHEMISCHE FABRIK BUDENHEIM (1991).

The reduction to a three step process has reduced the technical complexity and lowered costs. A study on Cadmium extraction processes for Phosphoric acid (BECKER 1989) concludes that technologies have been developed which allow the removal of Cadmium on an industrial scale and at reasonably low costs. Among those the "Budenheim Process" seems to have several advantages vis à vis other processes. E.g., it can process Phosphoric acids from different sources with a wide range of contaminations.[1]

The "Budenheim Process" has by far the lowest set up costs; a unit with the capacity of 1,000 t $P_2O_5$ per day has unit fix costs of 0.92 ECU/t $P_2O_5$ compared to between 2.54 and 6.76 ECU/ t $P_2O_5$ for the alternative processes (BECKER, 1989). Variable unit costs in terms of the quantity of $P_2O_5$ depend on a variety of factors such that even a relatively narrow range of values can not be given. Table 2.9 gives four examples of costs where the processed materials varies in terms of the $P_2O_5$ content of the Phosphoric acid, in terms of the Cadmium content of the raw acid, and in terms of the reduction of the

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[1] The technical details are described in a report to the Minister of Science and Technology (FRANKENFELD/RUSCHKE 1985).

Cadmium[2]. Unfortunately one can not deduct from these informations a cost function in terms of the degree of Cadmium reduction.

Table 2.8 — Unit Costs of Removing Cadmium from Phosphoric Acid in the "Budenheim Process"

| | | Type of Phosphoric Acid | | | |
| | | Florida | Morocco | N. Carolina | Togo |
|---|---|---|---|---|---|
| Cd Content | mg/kg | 6 | 18 | 33 | 37 |
| $P_2O_5$ Content | % | 29.6 | 57.0 | 53.4 | 26.0 |
| Cd Reduction | mg/kg | 5 | 14 | 28 | 36 |
| Remaining Cd | mg/kg | 1 | 4 | 5 | 1 |
| Cost per t $P_2O_5$ | DM | 7.30* | 4.74 | 6.84 | 8.91 |
| Cost per kg Cd removed | DM | 429.41* | 189.60 | 131.54 | 64.10 |

* Cost without Cleaning Step of Organic Material.

Source: FRANKENFELD/RUSCHKE 1985.

From the information in Table 2.8 a number of important conclusions can be drawn, however.

• The higher the original Cadmium content of the acid, the lower the variable cost of reduction in terms of the quantity of Cadmium removed, i.e., separating one kilogramm of Cadmium from acid from Togo with 37 mg Cd/kg costs only 64.10 DM compared to costs of 429.41 DM for removing the same amount from the Florida acid with a contamination of only 6 mg Cd/kg.

• Different reduction percentages can be achieved through a variation of the extraction steps. It is in general possible to achieve a reduction to below 1 mg Cd/kg. There is no clear relationsship between reduction costs and the degree of removal since the $P_2O_5$ content seems to exert a stronger influence - with rising costs for lower $P_2O_5$ contents of the acid - than the variation in removal rates. FRANKENFELD/RUSCHKE

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2  An additional complication is due to the high content of organic material in the Florida Phosphate which requires a separate processing step which almost doubles the unit costs.

(1985) therefore recommend to place the Cadmium extraction as late as possible in the processing chain of the Phosphoric Acid.

- The removal costs in terms of the quantity of $P_2O_5$ clearly favour relatively low reduction percentages; the least expensive examples are the reductions from 18 to 4 mg Cd/kg (Morocco) and from 33 to 5 mg Cd/kg (North Carolina). From the viewpoint of the Phosphate fertilizer producer only the Cadmium extraction from high to a medium contamination seems economical.

- From an overall economic perspective the results of the experiments presented in Table 2.8 suggest that the costs of reduction - measured in DM per kilogramm of removed Cadmium - the more fall, the larger is the total amount of Cadmium removed. Not only the fixed costs but also the declining variable costs contribute to this result which represents a downward sloping average cost curve. Such scale effects indicate that - seen from the perspective of the damage prevented - it is economical to reduce Cadmium to concentrations of as low as 1 mg Cd/kg.

- If one compares the costs of removing Cadmium from Phosphate fertilizers to those of removing other depositions of Cadmium on the soils, there is probably no other policy which could be as inexpensive as this one. E.g., the reduction of diffuse atmospheric depositions is much more expensive. Emissions from large coal-fired industrial furnaces could be reduced through more advanced dust filters, yet their cost of removing one kilogramm of Cadmium are in the range of DM 4,000 to 6,000 (KLEPPER/MICHAELIS 1992). For thermal Zinc refining reduction costs are in the range of DM 2,000 to 2,600 (ibd.). It is therefore clear that removing Cadmium from Phosphate fertilizers is an extremely inexpensive option for reducing the load of Cadmium on soils.

- The price effect of a Cadmium removal in Phosphate fertilizers would also be quite moderate. If one takes a price of around 1,500 DM/t $P_2O_5$ for fertilizer (STATISTISCHES BUNDESAMT 1991; SCHINDLER 1986), then additional costs of between DM 5 and DM 20 amount to price increases of far below two percent.

## 3. SEWAGE SLUDGE

### 3.1 PRODUCTION AND CONSUMPTION OF SEWAGE SLUDGE

An important input of toxic materials to agricultural soils comes from the application of sewage sludge. It is hardly possible, however, to determine how much of it is actually applied in a specific area. The amount of raw sludge produced in Germany in 1987 was approximately 85 mio m³, i.e., about 4 mio t of dry substance. Table 3.1 summarizes the composition by the sectors producing the sludge. Unfortunately the use of this raw sludge is not well documented. Especially the fate of industrial sewage sludge is practically unknown. For sewage sludge from public facilities LOLL (1989) estimates that 19% of the 50 mio m³ raw sludge are used in the agricultural sector (see Figure 3.1). This would amount to 667 thousand t/a (dry substance), resp. 14.5 mio m³ . Whether industrial sewage sludge is also used in agriculture seems to be unknown. Since these sludges usually have higher metal concentrations (see below) it is more likely that the bulk of sludge used in agriculture comes from the public waste water treatment facilities.

Table 3.1 — Production of Raw Sludge in West Germany 1987

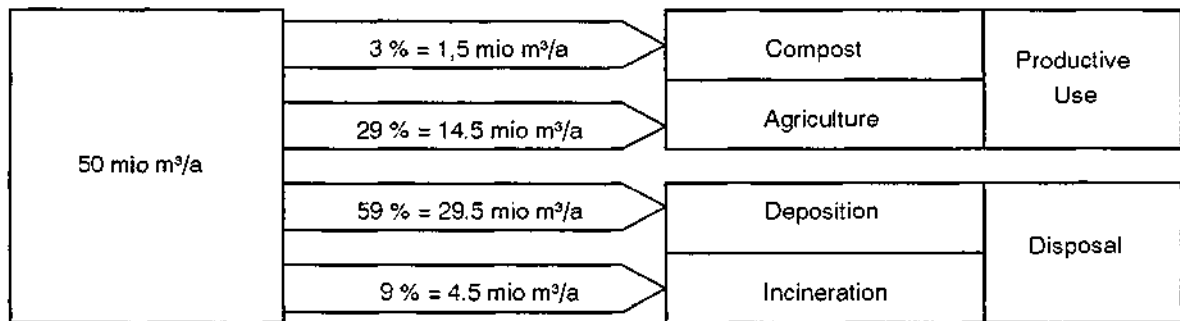|  | Volume (mio m³) | Weight (mio t dry substance) |
|---|---|---|
| Public Sewage Treatment | 51.7 | 2.4 |
| Mining Industry | 10.5 | 0.5 |
| Manufacturing | 22.7 | 1.1 |

Source: SACHVERSTÄNDIGENRAT (1990).

The application of sewage sludge on agricultural soils is regulated by the "Klärschlammverordnung" (1982), the "Ordinance on Sewage Sludge". It controls the maximum allowable concentration of heavy metals in the sewage sludge, their maximum allowable concentration in the soil, and the total amount of sludge which can be applied on the land. Not more than 20mg/kg of Cadmium are permitted in sewage sludge; however, it can be applied only on soils with less than 3 mgcd/kg. This has the consequence that sewage sludge can not be used near urban areas and close to industrial centers since these soils already show a contamination of Cadmium beyond the permitted level. In addition, not more than 5 t/ha of sewage sludge may be applied over a three year period. A survey of 7,400 samples of sewage sludge has revealed that

concentrations remain far below the limit - about 4 mg/kg on average with only 1.6% of the samples exceeding the legal limit (SCHEFFER/SCHACHTSCHABEL 1989).

Unfortunately, it is unknown how much sewage sludge is applied on a specific area. One can therefore only give a rough indication of the possible ranges of Cadmium depositions through an orderly use of sewage sludge in agriculture. Given the average

Figure 3.1 — Consumption of Sewage Sludge from Municipal Waste Water Treatment Plants

| 50 mio m³/a | 3 % = 1,5 mio m³/a | Compost | Productive Use |
| | 29 % = 14.5 mio m³/a | Agriculture | |
| | 59 % = 29.5 mio m³/a | Deposition | Disposal |
| | 9 % = 4.5 mio m³/a | Incineration | |

Source: LOLL (1989).

concentration of Cadmium of 4 mg/kg in the sludge, a farmer who uses the allowed 5 t/ha in a three year period could at most add about 7 g/ha Cd to his soil per year. The maximum amount would come to 33 g/ha Cd if the legal limit of 20 mg/kg Cd in the sludge were to be reached. The overall load of Cadmium on agricultural soils through the application of sewage sludge can be estimated to amount to not more than 2.3 t/a (BÖHM/SCHÄFERS 1990).

The environmental impact of adding sewage sludge to agricultural soils is, however, not as straightforward as one might expect. There is no one-to-one correspondence between the Cadmium load and the environmental effects - be it the contamination of agricultural products or the further transport of Cadmium into other media. Sewage sludge adds organic material which is able to accumulate some of the heavy metals and to contain it tightly in its molecular structure. It has been found that the Cadmium content of crops has even fallen after the application of sewage sludge because of this process of absorption (FEUEREISSEN 1986). Since sewage sludge is slightly basic it raises the pH of the soil and this reduces the uptake of Cadmium - and Zinc - by the different crops (ibd.). These effects slow down the potential health threat of Cadmium contamination in food, and at the same time this rise of the pH also reduces the washout of Cadmium (see also section 6).

## 3.2 Sources of Cadmium in Sewage Sludge

The Cadmium contamination of agricultural soils through the application of sewage sludge can be reduced either through the substitution of sewage sludge by other fertilizers or by reducing the Cadmium load of the sewage sludge inside the treatment facility. This would, however, amount to reducing the fallout of dissolved Cadmium in the treated water thereby increasing the Cadmium load of the water discharged into the rivers. Finally measures could be taken which limit the Cadmium content in the waste water entering the treatment facilities in which the sewage sludge is produced. This option would first require an identification of the sources of Cadmium in the waste water stream and secondly the investigation of technically feasible and economically rational strategies for reducing the emissions at the respective sources. For the state of Hesse the material flow of Cadmium in the water and in particular into the waste water treatment facilities has been estimated (NOLTE 1987).

Figure 3.2 summarizes the quantities of Cadmium which are transported in the different water flows for the state of Hesse and it identifies the sources from which the Cadmium enters waste water and runoff in the early 1980s. However, these sources do not include those industrial waste waters which are treated in industrial water treatment facilities. It becomes clear that the diffuse inputs into the runoff from the deposition of dust, through rain, corrosion and traffic contribute comparatively little to the Cadmium load of waste waters. Of the total deposition of about 1 t Cd/a from these sources somewhat less than a third enters soils and the groundwater directly, whereas the rest is collected and treated in waste water treatment facilities. The major contribution to the Cadmium load in these treatment facilities, however, comes from industrial waste waters which amounts to 3.46 t Cd/a.

The numbers of NOLTE (1989) are derived from the emission situation in the early 1980s and would - if they were extrapolated - result in rather high emissions of Cadmium for Germany overall. This may be true for the time for which Noltes study was performed. Since KLEPPER/MICHAELIS (1991) did find a drastic reduction of emission since that period, the absolute size of the numbers in Figure 3.2 are most likely too high for the present time. The composition of the emissions, on the other side, may not have change as much such that the relative contributions from the different sources may still be reliable.

The Cadmium in the sewage sludge originates to about 80% from industrial waste waters, to about 9% from household waste waters, and to roughly 11% from those flows of diffuse sources which are caught in the public sewer systems from surfaced areas

such as roads, houses, etc. Those inputs of Cadmium are then approximately equally divided between treated water flows entering rivers and lakes and sewage sludge which is partly deposited in landfills or on agricultural soils.

Figure 3.2 — Cadmium in the Waste Water
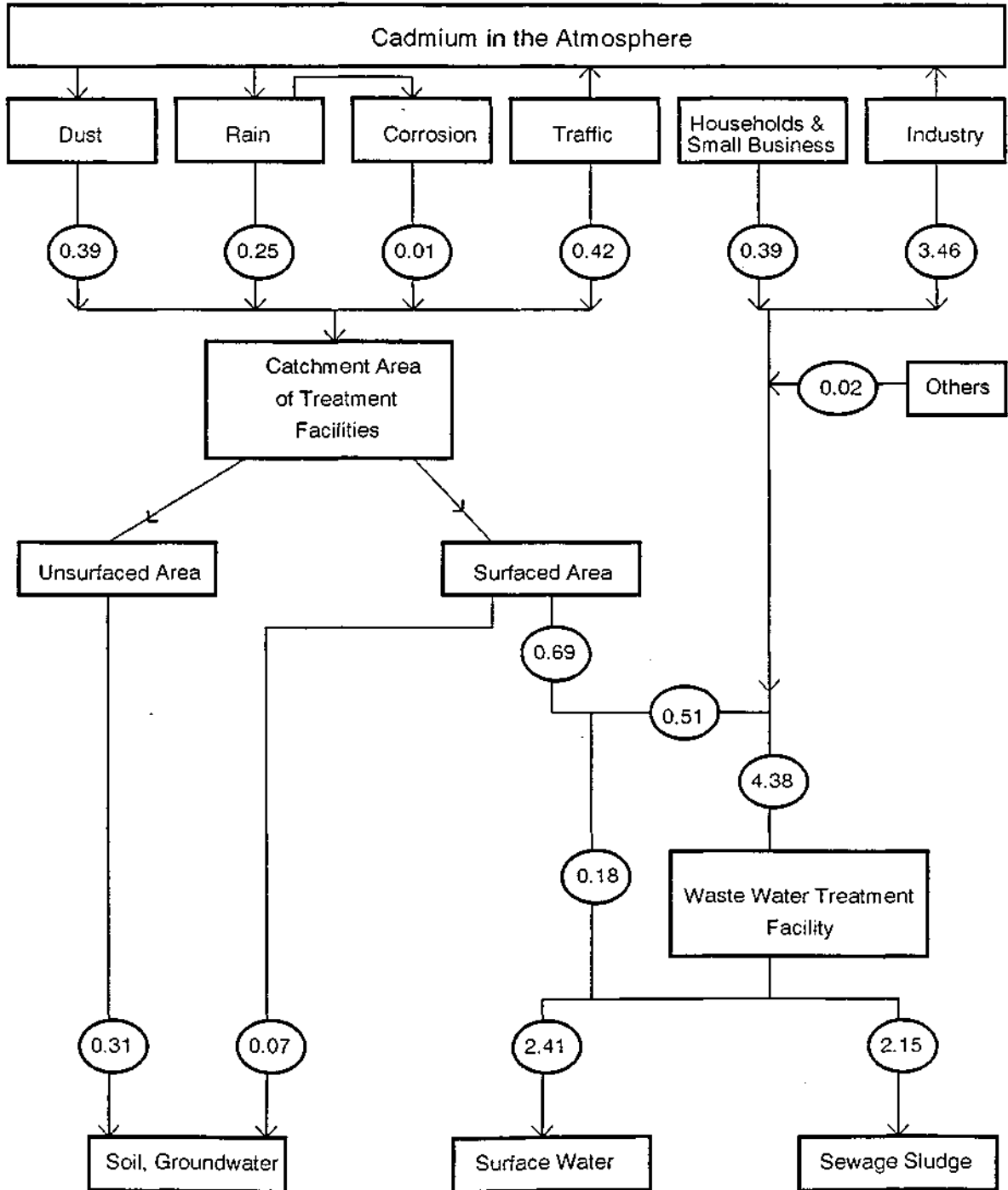
If one wants to reduce the Cadmium content of the waste water streams from communal treatment facilities or of the sewage sludge one needs to concentrate on the original sources of the Cadmium, i.e. industrial emissions, both aqueous and airborne. A study on aqueous Cadmium emissions in the Rhine River Basin has found a drastic reduction of industrial emissions between 1983/84 and 1988 from around 30 t Cd/a to 3 t Cd/a (ELGERSMA 1991). Although only a part of industrial waste waters is treated in municipal treatment facilities one can expect a significant reduction of Cadmium in these facilities as well. Airborne Cadmium emissions which are the source of the diffuse depositions in the runoff are estimated to have been cut in half between 1982 and the early 1990s (KLEPPER/MICHAELIS 1991) such that the waste water flows from surfaced areas which carry deposited dust and rain will also have lower Cadmium concentrations today.


## 4. AIR-BORNE DEPOSITION OF CADMIUM

Practically all emissions of particulates into the air will eventually become deposited in the water or on land. In the previous chapter some of those airborne depositions have been mentioned which contribute to the contamination of sewage sludge. Yet, they constitute only a small fraction of the deposition as only the deposition on surfaced areas enters waste water treatment facilities. The unsurfaced areas also take up a considerable part of the Cadmium load which was emitted into the air.

The geographical pattern of the deposition of Cadmium is extremely complex such that only a number of factors can be mentioned which determine this pattern. Specific conditions of the emitting sources - e.g., the length of the chimney, the size of the particles on which the Cadmium is bound, or the chemical condition of the Cadmium - determine the transport of particles into different layers of the atmosphere. General atmospheric and geographical factors determine how far and in which direction the Cadmium is transported after leaving the emitting source. Consequently, the pattern of deposition can hardly be predicted; it is clear, however, that one can not expect a homogeneous pattern of deposition of Cadmium on soils, neither geographically nor over time. Since these stochastic patterns could only be simulated in regional climate models from which results are not available at the moment, some features which influence the quantity of emissions as well as some characteristics of the deposition will be presented here.

Figure 4.1 summarizes the total airborne emissions of Cadmium for the year 1982 and presents an estimate of emissions for the early 1990s by major sectors of the economy. The quantitatively most important emissions into the air come from industrial sources, in particular the iron, steel, and metal industries as well as the ceramics industry and those large combustion facilities which are burning coal. Consequently, most emissions are concentrated in urban areas, in particular in industrial centers with important iron and steel or metal industries. Studies on the contamination of soils indicate that Cadmium emitted from these facilities seems to become deposited to a significant degree in their vicinity. Therefore, the Cadmium load on soils in different locations varies strongly. Whereas rural areas experience depositions of 1.5 to 3 g/ha per year, this number rises to between 3 and 35 g/ha in urban areas. In the vicinity of metal and steel industries depositions of 40 to 100 g/ha have been found (SCHEFFER/SCHACHTSCHABEL 1989). The highest depositions clearly point towards the metal industries; however, since the figures mentioned in SCHEFFER/SCHACHTSCHABEL (1989) relate to the early

Figure 4.1 — Cadmium Emissions into the Air 1982 and Early 1990's - Best Guess"
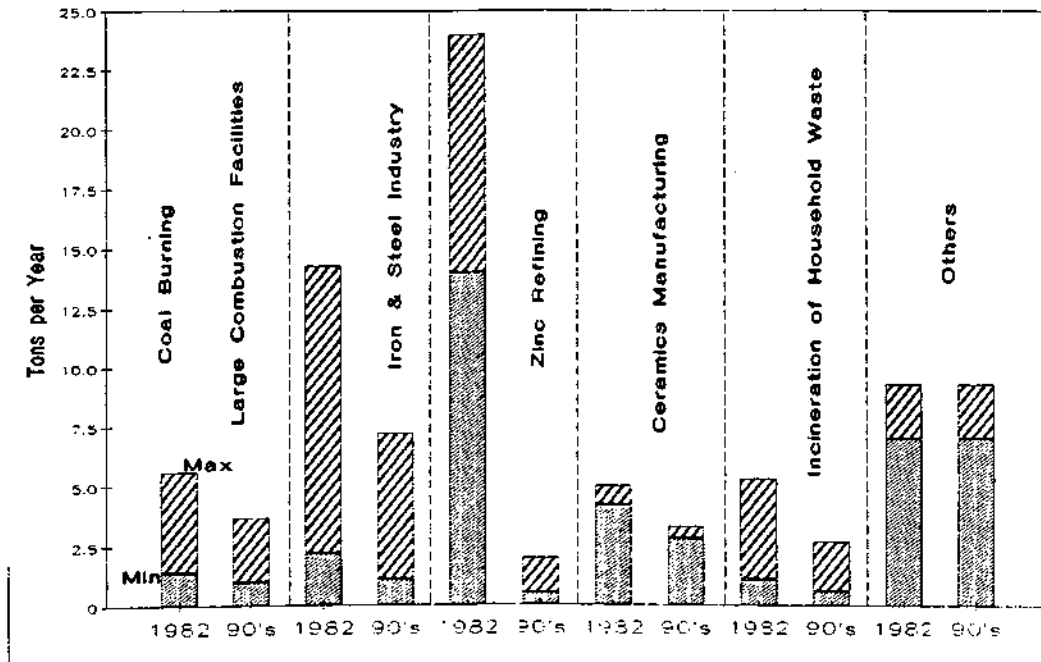


Source: UMWELTBUNDESAMT 1991; OWN CALCULATIONS.

20

1980s the relative contribution of different sources may have changed by now and sincethe overall emissions of the metal industries have been significantly reduced (Figure 4.1) the depositions in their vicinity are most likely much lower today.

The overall airborne emissions of Cadmium which the Umweltbundesamt (1991) has estimated to amount to between 25.9 and 58.9 t/a in 1982 have probably been reduced to about 13 to 23.6 t/a in the early 1990s (see KLEPPER/MICHAELIS 1991). For the deposition of Cadmium on the land one would need to possess information about the aerial transport of those emissions beyond the borders of Germany as well as the aerial imports into Germany which are probably of significant size (see section 5). Although a sound procedure for estimating the overall amount of Cadmium which is deposited on German soils is not possible at the moment, SAUERBECK (1982) gives an estimate of 30 t/a which in relation to the likely emissions in 1982 seems reasonable. Given the emissions reduction which has been achieved in the meantime, today's Cadmium depositions may be as low as 15 t/a, however with large regional and local variations.

The deposition in urban and industrial areas can not only be attributed to industrial emissions. Locally high concentrations of Cadmium in cities and along roads point to the short range deposition of Cadmium from automobiles. Abraded particles from car brakes, tires and exhaust from fuels contribute to the contamination of soils near roads. These emissions are deposited very close to the source, since Cadmium concentrations of soils directly at the roadside are as high as 3 mg/kg but drop to 1 mg/kg in a distance of only 4 meters (SCHEFFER/SCHACHTSCHABEL 1989). High concentrations in urban areas, e.g., in parks and gardens, may therefore be more attributable to accumulated depositions of past use of fuels such as coal for domestic heating.

## 5. TOTAL DEPOSITION OF CADMIUM

The previous three chapters on Cadmium depositions through Phosphate fertilizers, through sewage sludge, and through airborne emissions which are washed out by rain or which fall out - as Cadmium is bound on dust particles - have already revealed how complex and diverse the processes and determinants of the deposition of Cadmium and the accumulation in the soil are. For the overall deposition of Cadmium on soils a last factor should be added, which contributes large amounts of Cadmium to the soil, but only in very isolated spots. From the total Cadmium flow in the economy the dominating part is incorporated in products (see KLEPPER/MICHAELIS 1991 and 1992) which eventually are turned into waste. In addition, the unintentional use of Cadmium produces

industrial waste such as rubble and slack. All these wastes are deposited in landfills, and an estimate of BÖHM/SCHÄFERS (1990) indicates that sizable quantities must eventually become deposited in landfills. From a total of 300 tons of Cadmium in municipal waste about two thirds are deposited in landfills, whereas the rest is incinerated (ibd.). However, these activities in many cases produce little or no harmful environmental effects - e.g., Cadmium in plastic products is tightly bound and can not be dissolved and washed out - and even if there is a chance for contamination it is of a local nature. In the following, these Cadmium loads onto soils will be ignored.

Among the three sources of Cadmium which contribute to the contamination of soils none becomes evenly spread over the land. It is therefore impossible to predict the Cadmium load which is deposited on a particular area. One can only characterize ranges of likely quantities of deposition from the different sources on characteristic areas. Possible categories could be:

1. Rural areas without the application of sewage sludge or Phosphate fertilizers.
2. Rural areas with sewage sludge application.
3. Rural areas with Phosphate fertilizer use.
4. Rural areas with the application of Phosphate fertilizer and sewage sludge.
5. Industrial and urban areas.

In the first case only diffuse Cadmium depositions from airborne emissions can add to the already existing stock of Cadmium in the soil. Such depositions are measured to be in the range of 1.5 - 3 g/ha per year in rural areas (SCHEFFER/SCHACHTSCHABEL 1989). Given the German emissions of Cadmium amounting to between 26 t and 59 t per year in the comparable time period of the early 1980s, of the deposition of 1.5 - 3 g Cd/ha each year only about 1.0 - 2.0 g Cd/ha would come from German sources. If one would extrapolate this relationship to the emission situation of today, then the deposition of Cadmium from German sources would be around 0.5 - 1.0 g Cd/ha and the overall load would be 1.0 - 2.0 g Cd/ha, i.e., by about 30% less than in the early 1980s. This estimated share of German emissions is still strongly overestimated because a nonnegligible part of the emissions become deposited in urban areas where depositions are up to ten times higher than in rural areas.

The pattern of deposition varies due to atmospheric conditions and the location of emitting sources. Since the Cadmium in airborne emissions is bound on dust particles one can expect a correlation between the geographical distribution of the deposition of dust and the pattern of the Cadmium load. Regions with larger dust deposition are the eastern border of West Germany - mainly due to the atmospheric import from the former GDR and Czechoslovakia -, Nordrhein-Westfalen with its high concentration of metal

industries, and the Rhein-Main-area (UMWELTBUNDESAMT 1989). The rural eastern border regions will probably import significant amounts of Cadmium (see section 4). In the urban areas with a large agglomoration of industries the depositions can go up to 35 g Cd/ha per year and from 40 - 100 g Cd/ha if there are metal industries in the vicinity. Other rural regions, however, may have negligible amounts of airborne Cadmium depositions.

In rural areas where sewage sludge is also applied, the Cadmium load on agricultural soils can increase. Since this depends on the amount of sewage sludge used per hectare, one can only compute the possible maximum load of Cadmium which would need to be added to the airborne deposition. Given an average concentration of 4 mg Cd/kg in sewage sludge, a farmer can - according to the Klärschlammverordnung - add no more than 7 g Cd/ha to the soil (see section 3). Consequently, the Cadmium load to rural areas with the application of sewage sludge can be at most 8 - 10 g Cd/ha. It will be much lower in most cases, however.

In the third case of rural areas with only the deposition of Cadmium through the use of Phosphate fertilizers, it has been shown (section 2.1) that the quantity of Cadmium contained in those fertilizers which are consumed in Germany amounts to about 32 t/a. Statistically this would result in a deposition of less than 2.5 g Cd/ha per year on soils in agricultural use. The actual deposition on a specific area, however, mainly depends on the type of crop grown and on the the specific Cadmium content of the fertilizer. Nothing is known about variations in the Cadmium content of Phosphate fertilizer, but the fertilizer industry has promised to remain below 40 mg Cd/kg $P_2O_5$. Average Phosphate use in agriculture varies often between 40 - 100 kg $P_2O_5$/ha (SCHINDLER 1986) such that the actual Cadmium load is at most 1.6 - 4 g Cd/ha per year thus resulting in an overall yearly load on such agricultural land of 2.6 - 7 g Cd/ha.

The fourth case concerns the Cadmium deposition through the combined use of sewage sludge and fertilizer. Sewage sludge is applied mainly for adding organic substance to the soil (FILIPINSKY 1992b), but it also carries nutrients such that the use of minerals can be reduced somewhat. Since the nutrient content of sewage sludge varies widely, these savings can hardly be predicted. However, a combined use of both is likely. The overall yearly load of Cadmium to those soils could then be as high as 9 - 13 g Cd/ha.

The Cadmium deposition in urban and industrial areas can mainly be attributed to three sources. There is the deposition of the long-range transport of dust contaminated with Cadmium which is probably quite low. Then there is the deposition of locally emitted Cadmium from traffic and from heating - i.e., coal fired small scale heating systems.

Those two seem to contribute significantly to the measured depositions of up to 35 g Cd/ha/a in urban areas (SCHEFFER/SCHACHTSCHABEL 1989). On agricultural land which in urban areas is often used for horticulture one would have to add depositions from Phosphate fertilizers. These loads may also be significant because the fertilizer dosage in horticulture is relatively high thus adding up to 4 g Cd/ha/a to the atmospheric deposition. Sewage sludge can not be applied in those areas since the Klärschlammverordnung prohibits its use on contaminated soils.

## 6. CADMIUM DYNAMICS IN THE SOIL

In the previous sections the different paths have been described through which Cadmium is transported before it becomes deposited in the soil. However, this is not the final medium in which Cadmium remains locked in. It can become transported further into rivers, lakes or groundwater and finally the oceans, and it can be taken up by plants. The processes which determine this Cadmium transport are complex and it is only intended in this section to indicate in which direction and in which relationship the transport is likely to take place and what the most important factors influencing this transport may be. Figure 6.1 illustrates the different media in which Cadmium can be transported back and forth after it has been deposited on the soil and before it ends up in the groundwater or the ocean.

Figure 6.1 — Cadmium Transport in the Soil



24
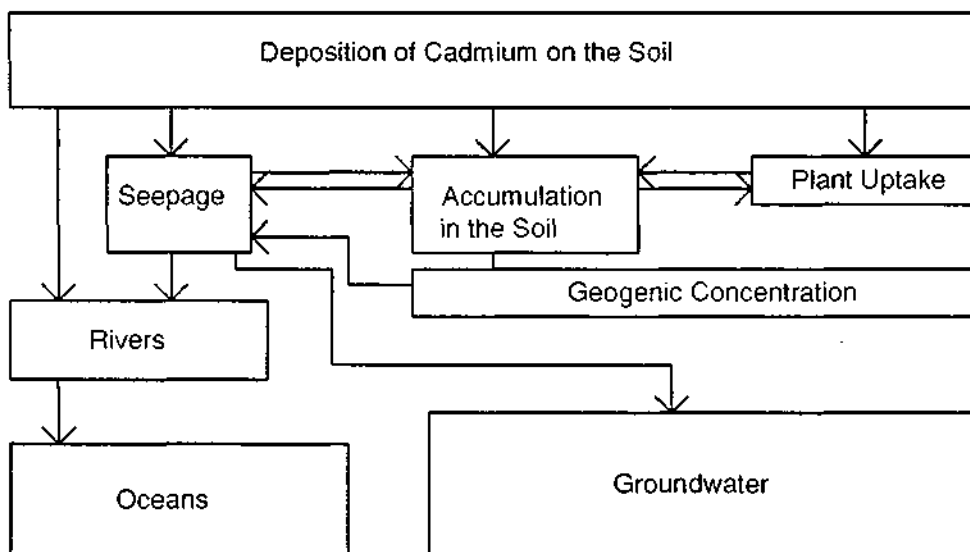
The chemical and physical processes determining these transports are presented here in a grossly simplified fashion. The major factors determining the fate of Cadmium in the soil are

- the concentration of Cadmium in the soil,
- the composition of different components of the soil,
- the pH of the soil, and
- electrolytic conditions.

These factors influence whether Cadmium is in a condition where it is either securely stored in the soil, or is adsorbed to specific materials - but with the potential for becoming subject to desorption processes -, or it is in a solvent phase (FÖRSTNER 1992; PETERS 1990). Since Cadmium only becomes a potential threat if it is available for plants or can be washed out, the factors which determine the amount of Cadmium in the solvent and in the exchangeable phase are of particular importance. Among the above mentioned factors influencing adsorption and desorption processes between dissolved and exchangeable Cadmium the pH turned out to be the most important (HERMS 1989; PETERS 1990).

Given these processes, the total contamination of soils with Cadmium at a particular point in time is the result of

- the accumulation through historical depositions,
- the natural background load of Cadmium, and
- the soil conditions which determine adsorption and desorption processes over time.

Therefore, the current depositions do not reflect the overall contamination of particular soils and regions, and even a simple adding up of historical depositions would be inaccurate. The Cadmium content of soils as a result of these historical processes varies widely; SCHEFFER/SCHACHTSCHABEL (1989) report an average content of 0.1 mg/kg which can in specific areas go up to 3 mg/kg. Anthropogenic emissions have lead to contents of up to 200 mg/kg in one area where centuries of ore mining have resulted in dangerously toxic concentrations. The usual concentration, however, is about 40 mg/kg in the vicinity of Cadmium emitting factories, around 3 mg/kg right at congested roads, and between 0.5 and 5 mg/kg in city parks and gardens. In rural areas the Cadmium contents of soils vary around 0.1 mg/kg such that the anthropogenic contribution can hardly be distinguished from the background load. However, since Cadmium still is deposited thus leading to a doubling of the concentration of 0.1 mg/kg over a 20 to 40 year period policy measures are still needed in order to avoid a long-term affect on as

yet practically clean soils. In addition, even such low Cadmium concentrations may under specific circumstances create environmental problems as will be shown below.

As long as Cadmium is bound to particles it is unlikely to create environmental damages, but in the solvent phase it can be accumulated in plants or become washed out. The share of Cadmium in the solvent phase depends on a number of factors. One of them is the concentration of Cadmium in the soil. This is important since in soils with given characteristics the distribution of Cadmium in the adsorbed phase relative to the solvent phase varies with the total Cadmium content. With an increasing Cadmium load the concentration of the Cadmium in the solution increases overproportionally, i.e. the potential threat to the water as well as to plants increases exponentially with the Cadmium concentration (DE HAAN / VAN RIEMSDIJK 1989). In addition, the anthropogenic Cadmium is often supplied in a solvent phase or, if it enters the soil as a dry deposition, can change into the solvent phase more easily than geogenic Cadmium (SAUERBECK 1986; MIEHLICH/GRÖNGRÖFT 1989; GOLWER 1989). According to FILIPINSKI (1992a), the solubility of anthropogenic Cadmium is twice as high as that of geogenic Cadmium.

One of the decisive factors determining the mobility of Cadmium in the soil is pH. The sorption capacity of colloids in the soil depends on the pH. Whereas other heavy metals are less sensitive to a decline in the pH, the sorption capacity of Cadmium decreases strongly when the pH falls below 4.5 (DVWK 1988; HERMS 1991). For a pH between 4 and 7.7 it was found; that the sorption capacity increases two to three times with a one point increase in the pH (JENSEN/BRO-RASMUSSEN 1992). A pH of 4.5 seems to represent the critical level beyond which Cadmium becomes increasingly dissolved. SAUERBECK (1985) even speaks of an exponential relationship between dissolved Cadmium and a pH below 4.5.

The mobility of Cadmium ions, i.e., their movement with the water through the soil, also depends on the cation exchange capacity of the soil which varies directly not only with the amounts of clay and organic matter but also with the pH (SCHEFFER/SCHACHTSCHABEL 1989; DVWK 1988). Another way through which the distribution of Cadmium between the solid phase, the plant uptake and the leachate is influenced, is the inflow of chlorides into the soil. The adsorption of Cadmium decreases with increasing Cadmium-Chloride complexation and these stabil complexes are water soluble (DE HAAN/VAN RIEMSDIJK 1989), so that they will easily become washed out.

All these interacting factors determine the composition of Cadmium between the solid and solvent phase and therefore its further transport through the soil, either from the

upper soil downward and eventually into the groundwater or into the plants. A calculation of DE HAAN/VAN RIEMSDIJK (1989) shows (see Table 6.1) that a particular Cadmium concentration in the solvent phase, i.e., the potential wash out, can be achieved through widely varying Cadmium concentrations in the soil depending on the soil conditions. E.g., the EC standard for drinking water of 5 mg/l can be met in some soils only with Cadmium concentrations far below the natural background contamination of 0.1 mg/kg whereas in heavily polluted soils but with favourable conditions this goal can be easily met. Apparently, the fate of Cadmium in the soil and its potential environmental threat either through plant uptake or through wash out and transport into the groundwater or rivers and lakes depends much more on the soil conditions than on the Cadmium concentration in the soil.

Table 6.1 — Calculated Cadmium Content in the Soil (ppm) as a Function of Soil Properties and Dissolved Cadmium

| Index of Soil Properties | Measured Cadmium Concentration in Soil Solution | | | |
|---|---|---|---|---|
| | 1.5 mg / l | 2.5 mg / l | 5 mg / l | 10 mg / l |
| 0.001 | 0.001 | 0.002 | 0.004 | 0.006 |
| 0.01 | 0.01 | 0.02 | 0.04 | 0.06 |
| 0.1 | 0.1 | 0.2 | 0.4 | 0.6 |
| 0.3 | 0.4 | 0.6 | 1.1 | 0.9 |
| 0.5 | 0.7 | 1.0 | 1.8 | 3.2 |
| 0.9 | 1.2 | 1.9 | 3.3 | 5.7 |
| 6 | 8.3 | 12.5 | 21.7 | 37.9 |

Source: DE HAAN/VAN RIEMSDIJK, 1989.

These findings have interesting implications for policies intended to reduce environmental threats of Cadmium. Since the soil properties - and in particular the pH - have such a strong influence on the desorption of Cadmium, the prospect for reducing the negative environmental effects of Cadmium depositions seems to be better rooted in activities which increase the adsorption capacity of the soil than in reducing Cadmium emissions which eventually will become deposited on soils. A small increase in the pH or the application of lime may have a much stronger impact on the adsorption than, say, a 50% reduction in emissions of which only a small fraction actually enters soils with critical conditions for solving Cadmium. In addition, the environmental threat of Phosphate fertilizers which are contaminated with Cadmium is much smaller than other depositions since agricultural soils are kept at a pH high enough to prevent any significant desorption of Cadmium.[3]

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[3] An exception may occur on sandy soils with low adsorption capacities.

One form of transport of Cadmium has not been mentioned so far: the soil transport through erosion. Without doubt, soil erosion leads to a relocation of large amounts of material. Most of this material is most likely only relocated locally, e.g., downhill into the valleys, but some will also be washed out into rivers. It is quite likely that this erosion is responsible for a considerable part of the Cadmium load of rivers and for the accumulation in the bed of a valley. The total quantity of eroded soil has only been estimated for the state of Bavaria with about 14 mio. tons per year (UMWELTBUNDESAMT 1989). For the whole of Germany no numbers are availlable. If one would take the lowest Cadmium concentration of agricultural soils, i.e., 0.1 mg/kg, a total of 1.4 t of Cadmium would be relocated in Bavaria alone every year. If one assumes an average soil loss of 13 - 16 t/ha (SCHEFFER/SCHACHTSCHABEL 1989), then the total loss in Germany on agricultural soils would amount to 176 - 217 mio. t/a, i.e., to a Cadmium relocation of approximately 18 - 22 t Cd/a. How much of this amount will end up in rivers which transport it towards the ocean can hardly be assessed.

The amount of dredged material in the major rivers can give a very rough indication of the dimensions which may be involved in this transport. In the mid 1980s in Germany dredgings of about 40 mio. $m^3$/a have been taken place (SRU 1990). Cadmium concentrations in sediments are reported for the 1970s with values between 1.5 and 40 ppm (dry substance) (ibd.), but since the yearly Cadmium loads have been drastically decreased in the last two decades, these figures will be much lower today. In the Elbe, the Weser, and the Ems Cadmium concentrations in the sediment did vary between 1 and 4 ppm (dry substance) in 1987 (NORDSEE 1989) and around 3 ppm in the Rhine at the Dutch border (SRU 1990). If one assumes an average Cadmium concentration of 2 ppm in the dredged material, then roughly 10 t of Cadmium will be dredged every year.

Unfortunately, these 10 t Cd/a can not indicate very well the loads which are transported. First of all, one misses the sediment transport in rivers which leaves Germany. Secondly, 88% of the dredged material is again dumped into the rivers at different locations (SRU 1990) such that it is not clear whether it may be dredged again in a later period or wether it is transported away. Nevertheless the dimension of the Cadmium load in the sediment together with the likely quantities of eroded soils indicate that a considerable part of the unidentified Cadmium transport in rivers which have been mentioned in the introduction may come from eroded material. This, of course, would mean that there is little potential for reducing these aqueous Cadmium loads besides measures to prevent soil erosion.

## 7. CONCLUSIONS

The environmental threat of Cadmium can only be assessed after the complex paths through which it is transported from the emitting source to the place where it produces the damage have been identified. In this paper the main focus has been on the sources and the fate of Cadmium which is deposited on the soil and then further transported into plants, the groundwater, or rivers. The Cadmium load on German soils shows a wide regional variation with heavy depositions and concentrations in the vicinity of industrial centers. The short-range transport of air-borne Cadmium emissions and the relatively small other sources of Cadmium depositions, i.e., Phosphate fertilizers and sewage sludge, are responsible for this uneven distribution.

For assessing the likely economic costs of the negative environmental effects through the Cadmium depositions from different sources, the regional pattern of these emissions needs to be taken into account. Also, the evaluation of potential preventive measures can only be discussed in such a framework. Figure 7.1 summarizes the contribution of the different emitting sources to the potential hazards in different areas. It shows that in urban and industrial areas the depositions of local emissions are the most important sources of soil contamination. Consequently the largest reduction in the Cadmium load could be achieved through measures directed towards local emitters. On land in agricultural production sewage sludge may provide the most important input of Cadmium. Its environmental threat, however, depends on the type of soil, i.e., its pH and its organic matter. Cadmium depositions through long-range atmospheric transport and through Phosphate fertilizer are of less importance. Although forests receive little depositions in absolute terms they are rather sensitive to the atmospheric depositions since the rain often has a pH as low as 4 thus supporting the wash out of heavy metals as well as the uptake in the plants. The contamination of water in rivers is extremely small today such that health threats are unlikely. Only the accumulation of sediments in estuaries and especially the Wadden Seas has lead over time to potential environmental hazards. Since in Germany the aqueous point emissions have been reduced significantly, the most important input probably comes from the deposition of long-range transports of dust and the quantity of water which even at low Cadmium concentrations carries quite large absolute quantities of Cadmium.

The environmental threat from Cadmium which is deposited through different channels as shown in Figure 7.1 relates to the most important impact areas. For the identification of measures to reduce these environmental impacts, however, the potential to reduce the different emissions as well as their likely costs need to be set in relation to the environmental damages which are avoided. Unfortunately, in many cases little is known

about the costs of abatement; the technical options can be identified, however. The technical and practical feasibility as well as the likely costs of reducing the Cadmium load in the different categories of deposition are summarized in Figure 7.2. In assessing the potential for reducing Cadmium depositions, the original emitting sources and the economic costs of reducing these emissions at the source need to be identified.

Figure 7.1 — The Potential Environmental Threat through the Cadmium Transport

| | Urban and Industrial areas | Rural Agricultural Land | Forests | Water |
|---|---|---|---|---|
| Fertilizer | some | some | none | little |
| Sewage Sludge | none | (important) | none | none |
| Long-range Atmospheric Transport | some | some | important | important |
| Local Atmospheric Transport | important | none | none | some |

As described in section 2, Cadmium can by now be removed from Phosphate fertilizer relatively easy and at low costs. However, significant reductions of the Cadmium deposition can only be expected on agricultural soils in rural as well as in urban areas. Yet, the percentage contribution to the deposition in urban areas is relatively small. Fertilizer is the only Cadmium source which is clearly identifiable and where its removal is technically straightforward. In the case of the other depositions this can not be done as easily.

The Cadmium load of the sewage sludge will in many cases not be identifiable as long as the diverse group of dischargers into waste water treatment facilities do not need to declare the substances contained in their waste water. It is therefore at the moment impossible to assess reduction potentials at the point of the discharger. The only remaining option is to reduce the use of sewage sludge in agriculture. This alternative would have additional costs in the form of additional purchases of fertilizer and of costs to increase the humus content of the soil. In addition, the sewage sludge needs either to be disposed of either in landfills or it needs to be incinerated. Both options, however, rechannel the Cadmium from a direct application on agricultural soils to air-borne

emissions and depositions in landfills. Reducing the Cadmium transport into the soil through a reduction of the use of sewage sludge will only lower the load on rural soils which are not heavily contaminated at the moment.

Figure 7.2 — Likely Potential and Costs for Reducing the Cadmium Deposition in Germany*

| | Urban and Industrial Areas | Rural Agricultural Land | Forests | Water |
|---|---|---|---|---|
| Fertilizer | good<br>low cost | good<br>low cost | none<br>- | little<br>- |
| Sewage Sludge | none<br>- | some<br>little direct costs | none<br>- | none<br>- |
| Long-range Atmospheric Transport | little<br>high costs | little<br>high costs | good<br>high costs | good<br>high costs |
| Local Atmospheric Transport | little<br>unknown costs | none<br>- | none<br>- | little<br>unknown costs |

* The upper entry in each cell denotes the likely technical potential; the lower entry the likely removal costs.

Not the largest deposition per hectare but the most widespread is from long-range atmospheric transport. The reduction potential in the different industry sectors varies considerably as is discussed in KLEPPER/MICHAELIS (1992). Since the regulation on air emissions of the large emittors, e.g. large scale incinerators, or the steel and metal industries, is already relatively tight, additional reductions which may significantly reduce these atmospheric depositions may be rather costly. And for that deposition, which is imported via air from abroad no measures can be taken anyway.

The quantitatively most important deposition in urban and industrial areas originates from industrial emissions and from automobile traffic. A further reduction of industrial emissions could have considerable costs if the regulations of the TA-Luft (Technical Ordinance on Air Emissions) are already met by the companies. Reducing emissions from traffic means basically reducing the traffic volumes with all the political difficulties involved in such decisions.

Direct damages from the Cadmium contamination of soils could at the moment only occur on a few specific localities with a long history of accumulation of Cadmium. The damage through plant uptake is usually prevented by the prohibition to grow food on these soils. Although a complete assessment of the costs of alternative measures can not be made, the present regulation is likely to be the most economical one, since a clearing of soils from the historical accumulation of Cadmium is technically infeasible. An alternative, at least for some soils, could consist of measures to increase the bonding capacity of the soil. An increase in the pH of acidic soils would reduce the environmental threat, also an increase in the organic content of the soil would reduce the amount of Cadmium which is available for plant uptake.

Similar arguments are valid for the damage created by Cadmium through wash-out and subsequent transport into the groundwater or rivers. In these cases, soil conditions are probably more important than the Cadmium concentration in the soils. Model calculations make evident that even in soils with only a geogenic Cadmium load but unfavourable soil conditions with respect to the adsorption capacity, the Cadmium desorption can be as high as that in heavily contaminated soils (section 6). In these cases the only policy option consists in raising the adsorption capacity of the affected soils through, e.g., the adding of organic material (home grown manures, green manuring), or liming. In this respect the supply of organic material through sewage sludge should not be underestimated.

As far as erosion is concerned it is possible that significant amounts of Cadmium may be transported into costal waters. Possibly these transports contribute to a large extent to the overall load of Cadmium which is transported in rivers. A reduction of these loads could either be achieved through measures to reduce soil erosion or through a reduction of the Cadmium content of soil under the threat of erosion. The option to reduce the Cadmium deposition on these soils would have little impact since the share of newly emitted anthropogenic Cadmium in these soils is probably quite small such that only in the very long run a reduction of Cadmium in the sediments can be expected.

The assessment of the transport of Cadmium from emission sources to diffuse depositions has shown that a simple and straightforward policy to reduce the environmental damage through Cadmium can not be formulated. A clearly identifiable emission source can cause anything from almost none to serious damage depending on the fate of the Cadmium once it has left the emitting source. Therefore, the relationship between emissions and environmental impact needs to be assessed in every case, be it the regional or the sectoral peculiarity which influences this relationship. Consequently, any attempt which wants to go beyond the crude identification of Cadmium flows and

their prevention as it has been presented here, will need to rely on a careful ecological balancing of the use of Cadmium as an intentional as well as an unintentional input in economic processes.

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